A BASIC UNDERSTANDING OF THE MECHANICS OF ROLLING MILL ROLLS

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PREFACE TO THE 1st REVISION

I published this e-book in March 2003, for free downloads from ESW homepage http://www.esw.co.at.

Immediately some friends and also myself found some spelling - of course - and even worse, real errors, sorry. Some colleagues claimed, “my material toughness” was not precise enough, and they made proposals for improvement. So I tried to eliminate (reduce) errors and to do definitions better.

In April 20003, I joined the conference ROLLS 2003 in Birmingham, GB, and some presentations stimulated me to re-think and re-write chapter 4.6. “Roll Damage Caused by Fatigue”. The description of the impact of "particle cleanliness" on sup-surface starting, particularly "crumply" (high cycle) fatigue spalling was so far missing in this chapter totally.

After the first release of this book, I was hoping for more stimulations and proposals for improvements, corrections, supplementations and additions by friends, customers, competitors or … Indeed, I am grateful for any comment - this helps to make it better - but in fact, there have been only very few messages. This leaves me waiting for more feedback.

I expect to edit some more re-written chapters later. Especially I am waiting for results from "roll cooling simulation" to give my theory of fire-cracks more background. Secondary scale on hot strip and the impact on wear is another issue. Stresses from Hertzian pressure in 4-high cold mill back up rolls were measured years ago, the results were never published, but of high interest - also, maybe later.

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1. PREFACE / INTRODUCTION

Rolls are tools used in rolling mills to reduce the cross section of metal stock. The weight of rolls may vary from a few kilograms up to 250 tonnes.

Under rolling conditions the contact area between roll and stock suffers wear, the other parts of a roll - body and necks - have to be considered as normal parts of designed components under high load. This means that necks should not experience plastic deformation or fatigue. However, loads in a mill are not clearly and precisely defined. Of course, there are rules to calculate the maximum stress in rolls caused by design limits for maximum separation force, torque, Hertzian pressure etc, but these criteria are valid only under so called “normal rolling conditions” and even these change continuously with progressive wear in the contact zone.

Besides “normal rolling conditions” - a stable, theoretical assumption - mills experience many different changes in rolling conditions. After a roll change or a mill stop rolls need some time to return to stable thermal conditions, every new bar entering the mill creates an impact, ... and sometimes there are really severe rolling accidents, due to faults by operators, weak rolled materials with internal defects, or because of other problems in a mill such as a power cut, mechanical problems of transportation or in the water cooling system. Problems of this kind can never really be calculated but they have a detrimental effect on all rolling schedules including stresses in the roll.

As regards “abnormal” rolling conditions - which are more or less very “normal” for rolling mills - roll damage often occurs with consequences for the mill and the rolled product. Evidently the reasons of roll failure have to be discussed and determined (or vice versa) to reduce the risk of repeated roll damage and its consequences, or indeed to eliminate the risk completely. These investigations are discussed internally but frequently the roll supplier is asked to give his opinion and in most cases claims are made when roll damage occurs. Obviously rolling conditions in a wide sense are discussed as well as roll quality; discussions are often very controversial and can become heated due to misunderstandings resulting from divergent knowledge and information of the partners.

During the course of my 25-year-long experience of endless discussions about rolls, roll application and roll failures with customers and fellow colleagues from other roll producers I found my performance often miserable or worse, frequently due to a lack of common understanding of the basic material science of my subject. There are many articles available on various subjects concerning material science but these papers all discuss theories, details, assumptions, possibilities and differing parameters without revealing the basic information needed for careful everyday applications.

Surprisingly there is almost no literature available on rolls, the best I know is *Rolls for the Metalworking Industries* [1]. Moreover, in many topics I do not agree with the general understanding and interpretation of the subject matter.

The idea for this book was born after experiencing some such unpleasant discussions. It seemed to me that it could be very helpful to combine as many necessary facts and information as possible in order to broaden the understanding of “rolls und loads”. But the rules of material science are of course not limited to rolls alone and are also useful for any other component of a machine. The wear parameters in the gap, the contact area of hot rolled material during rolling may be unique but neck loads and contact stress in all other applications (cold rolling, back up rolls) have similarities in other components.

Therefore I hope this book will be useful in giving a general understanding of especially big components - large cross sections - which might suffer from damage for various reasons.

My intention with this book is to make everything as simple as possible and I will not deal with all the detailed parameters. Of course this contains the risk that I am not as precise as some people might wish. But we need facts: there are some laws of nature and if a customer asks all roll suppliers for the "Poisson ratio" or figures of heat conductivity for a material, then the best is that he should receive the same kind of answer from everybody.

Most of the scientific information presented is state-of-the-art but some articles and information are not really widespread or known. Maybe they do not seem scientific enough, perhaps too easy - especially my understanding of static strength and fatigue as a function of Vickers hardness and microstructure - some articles have never been published in this form before, for instance *Hydrogen- induced Failures of Rolls*.

In chapter 3 of this book I try to deliver basic information on material science, on the application of important figures and on the reliability of these figures.

Chapter 4 of the book concentrates on rolls. Here we again have to consider the conditions of roll failures. However, I will not include any details about roll making - the expertise of roll making is a different and very secret story which is not necessary for us to be able to understand rolls.

Of course the understanding of material science is applicable in any type of construction, in any steel part; rolls are just "my" example.

I hope that in future many discussions will be easier thanks to the information contained in this book.

I am grateful to everybody who has helped me to understand rolls and I appreciate any additional hints to improve my knowledge of rolls.

I should like to thank especially Dr. Karl Heinz Ziehenberger, who helped me with the text-editing and in compiling the illustrations and literature. I am also grateful to some colleagues from ESW for careful proofreading and discussions, as well as to my brother-in-law, graduate engineer G. Alberti, who gave me many hints on how to do things better.

2. WHERE DO WE COME FROM AND WHERE WE ARE GOING?

2.1. GENERAL OVERVIEW

Most technically used basic metals (iron, aluminium, magnesium, titanium) and most alloying elements (silicon, manganese, chromium, nickel, molybdenum, tungsten …) are found in nature in a chemical stable form as ore (oxides or other chemical compounds, only carbon is found in a pure state as coal or as carbon hydrides). Only precious metals such as gold are found in nature as pure metal.

To acquire technically useful metals and their alloys ore has to be reduced (and alloyed) and primarily shaped by casting or sintering. These processes are suitable only for achieving an almost finished shape for “small” compact parts. For other products the primarily shaped metal needs secondary forming: forging and in case one dimension of the product is very much bigger than the others, then the secondary forming is done in a rolling machine, a rolling mill with cylindrical tools, the rolls.

While casting and forging are old technologies going back more than 3 000 years, rolling assumed major importance in the industrialized world during the 19th century. Initially steel was the only product to be rolled to profiles (rails, beams, channels, rounds) but since about 1930 flat products (sheet and strip) have become increasingly dominant.

Profiles and flats are hot rolled (the latter to a minimum size). Thin flat products are finished by cold rolling for various reasons, e.g. to achieve a better shape and profile, because of mechanical properties, surface conditions, etc.

In the recent past rolling technology was improved and changed dramatically but rolls have always remained the critical part of rolling mills. So the development of roll qualities and roll-making technology had to follow the development of rolling technology, they had a mutual influence.

Rolling mill industries rely on capital investment and so big industrial groups in increasing concentration were created. On the other hand the roll industry remained in the hands of small, mostly privately owned companies which are creative, innovative, care about their very special product and are capable of implementing new developments rapidly. The roll industry is based on people and not on capital.

While the demand for rolled products continues to grow, the need for rolls is decreasing due to improved rolling technology and better roll qualities (see chapter 5), and the market situation for rolls is undergoing changes.

2.2. HISTORICAL DEVELOPMENT OF ROLLING MILLS

Leonardo da Vinci invented the first rolling mill but a few centuries passed before rolling mills became important for the steel industry in the 19th century. Initially more long products than sheet were rolled; today the opposite is true.

Mass production of flat products, "hot strip mills", were developed in America in the first half of the 20th century and became widespread throughout the world after the second world war.

To produce flat steel more efficiently and economically some major developments dramatically changed the manufacturing technology. The goal was and continues to be the reduction of energy, man power, financial investment, etc., thereby lowering production costs but at the same time increasing yield (relation of weight of good finished strip to weight of material before rolling) and strip quality.

To begin with slabs were cast in iron chill moulds, later in continuous cast slabs (160 - 300 mm thick). Result: no more slabbing mills. Then thin slab casters (35 - 80 mm thick) - no more roughing stands. Now, at the beginning of 21st century, the first industrial strip casters - invented 150 years ago - go on stream with only one stand, one pass for the production of wide hot strip. In the conventional hot strip mills the minimum strip thickness rolled was (1,5) 2 mm. In thin-slab continuous-cast rolling mills the strip rolled thickness is below 1 mm and the strip caster aims to cast between 2 and 1 mm.

In the past it used to take weeks to produce coiled strip from iron ore. Now, in thin-slab continuous-cast mills - most start with scrap in electric arc furnaces - the time between melting and coiling is less than a day. Strip is rolled in one heat which means that after melting, the material cools down completely only after rolling is finished.

To achieve a better shape of flat products new technologies were being developed all the time like (work- or back-up) roll bending, 6 high stands, continuous variable crown (CVC) and all these changes had a great impact on the load distribution on the rolls.

A similar development took place for long products: casting blooms in iron chill moulds; continuous casting of pre-shaped bars (dog bones) - no more breakdown mills; and more and more long products are rolled in “universal mills” instead of traditional open mills with grooved rolls, usually one pass - one groove.

Of course mills for cold rolling and their technology were also improved. New mills were developed to obtain “better strip” - six high mills, continuous variable crown, inflatable back-up rolls, etc. and continuous-continuous (endless) rolling.

Steel markets are very competitive and over a long period the absolute prices per tonne for rolled products are falling despite inflation, changing energy costs, manpower etc. Companies which do not introduce new technical developments will in the long run face problems.

Illustration 1 shows some features of different types of mill stands.

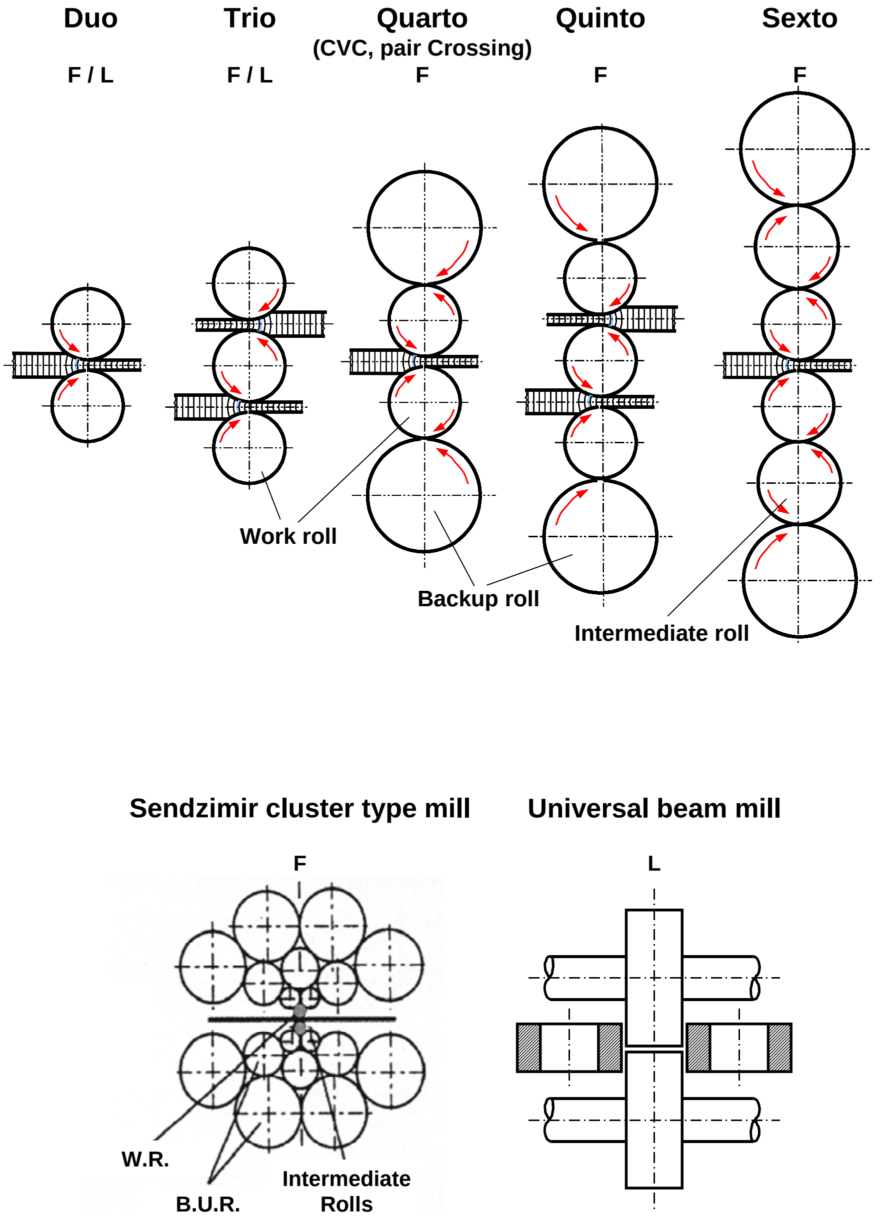


Illustration 1: Variation of mill stands with different specific load and stress distribution;
F – Flat products, L – Long products

2.3. HISTORICAL DEVELOPMENT OF MATERIALS USED IN ROLLING MILLS

In the 19th century basically unalloyed grey iron - modified only by various carbon equivalents and different cooling rates (grey iron chill moulds, or sand moulds) - and forged steel was used for rolls. The cast iron grades varied from “mild - hard”, to “half - hard“, to “clear chill”, where the barrel showed a white iron layer (free of graphite) and grey iron core and necks due to reduced cooling rate; this type of roll was used for flat rolling without any roll cooling in “sheet mills”, as long “sheet - mills” existed (end of 20th century). Later on cast steel rolls were developed with a carbon content up to 2.4 %, with and without graphite, and are still produced today.

Around 1930 “Indefinite Chill Double Poured (ICDP)” rolls were invented for hot rolling, especially for work rolls in finishing mills of hot strip mills, which were also used for many other applications such as roughing stands of hot strip mills and work rolls in plate mills. This grade was to become the world standard for many years with very limited variations. Until today no other material could replace this grade for some applications. In the late 1990s finally ICDP enhanced with carbide improved roll performance and started a new phase for this old grade, still successfully in use today in work rolls for early finishing stands of finishing hot strip mills (replacing high chromium iron and HSS - see further down) and for plate mills.

Around 1950 nodular iron was invented and introduced into roll manufacturing, unalloyed as well as frequently (Cr) Ni, Mo-alloyed, giving good wear resistance and strength at the same time.

The use of “high chromium iron” (2 - 3% C, 15 - 20% Cr) and later on “high chromium steel” (1 - 2% C, 10 - 15% Cr) brought new materials, with high wear resistance and “forgiveness” into rolls. But this was only one major step towards greater productivity of rolls.

In 1985 by starting “High-Speed-Tool Steel (HSS)” materials were introduced into rolls and evolved the so-called “Semi-Tool-Steel” grades. After initial problems all changes brought new opportunities for better roll performance. After the introduction of new grades to the mills it was often necessary to change or improve rolling conditions. However, after some time rolls also improved and there were no further problems with new grades, only a better performance!

All these roll grades are used for flat and long products. Additionally tiny rolls to produce wire rod use new, even more high-tech grades: sintered carbide is state-of-the-art, and ceramic rolls are also in trial use. However, for manufacturing these types of rolls there are still limitations in terms of size; equipment for bigger parts is not yet available.

Forged steel rolls were also improved for cold rolling to give higher hardness penetration after heat treatment by increasing the content of alloying elements. Basically the chromium content was increased from 2% to 5% and changed to (mainly) induction hardening. Chromium plating of work rolls after grinding and “shot blasting” increased the life of the necessary surface roughness.

In reality rolls are tools for metal forming, therefore the development of suitable roll materials goes hand in hand with the development of other cutting and non-cutting tools in metal industries. Rolls are relatively large tools with an extended life but ultimately they are only tools.

A summary of materials in use for the production of rolls is presented in table 1.

Material	Hypo-eutectic steel	Semi - HSS	Adamite (Hyper-eutectic steel)	HSS (high speed steel)	High Chrome Steel	Graphitic cast steel	CC (Chlear Chill)	GHM ("Cast Carbide")	ICDP	Carbide Enhanced ICDP	High Chrome Iron	Nodular Cast Iron	(Mild Hard / Half Hard – old grades of grey iron)	Sintered Carbide	Ceramic
In Use Since	1870	1995	1920	1990	1980	1950	1870	2000	1930	1995	1965	1960	1850	1970	2000
C [%]	0.4 - 1.0		1 - 2.2				2 - 4							8 - 15	---
Si [%]	0.3 - 1.0		0.4 - 0.8			0.8 - 2.0	0.4 - 1.0					1 - 3		---	Si_3N_4
Σ (Cr, Mn, Mo, Ni, Co) [%]	1 - 6	5 - 8	< 4	< 6	8 - 12	2 - 5	---	2 - 10	6 - 9		14 - 22	3 - 6	< 3	5 – 15 (Co)	---
Σ (V, W, Ti, Nb) [%]	< 0.5	5 - 10	< 0.5	8 - 15	< 0.5 ?	< 0.5 ?	---	30	---	1 - 4	< 0.5 ?	---	---	70 - 90	---
Carbide content [%]	0 - 2	2 - 5	6 - 15	3 - 5	10 - 20	5 - 15	40 - 50	30 - 40	30- 40		20-30	1 - 15	5 - 15	70 - 100	---
Graphite	---	---	---	---	✓ ---	✓ ✓	---	---	✓	✓	--- ---	✓	✓	---	---
Barrel hardness [HV]	180 - 700	500 - 700	300 - 450	600 - 750	500 - 700	300 - 450	500 - 650	600 - 900	600 - 700		500 - 700	280 - 500	250 - 450	1300-1800	2200
Forged (F), Cast (C)	F / C	C (F)	C ((F))	C, F, others	C	C ((F))	C	C	C	C	C (and others)	C	C	other	other
Mono casting (M) Compound casting (C)	M (C)	C	M	C (M)	C	M (C)	M	M	C	C	C (M)	M	M	Sleeves	Sleeves
Market importance/consumption (from 0 to 10, 10 is max.)	10	3	4 ↘	? ↑	4 - 7 ↘	2 - 3 ↘	1	?	7 - 8 (10)		8 - 9 ↘	3 - 4 ↘	0	2 - 5	?
	W.R. , CSM, B.U.R. for HSM / CSM, break down mills; …	Hot Rolling Roughers, F1, F2, ? Break down, Universal ??	Long Products	W.R. in HSM, Long Products, Wire, Rod Mills	W.R. HSM, Rougher, F1, F2…	Heavy Sections Mills, Roughers in HSM, Long Products	Sheet mills (almost out), Sleeves of small diameter	?	W.R. HSM, PM, ST,…		W.R. in HSM	Long Products		Max 450 diameter	Max diameter ?

🟧 WORK ROLLS FOR HOT ROLLING STRIP AND PLATE
🟩 ROLLS FOR LONG PRODUCTS
🟦 RECENT NEW MATERIALS

Table 1: Material used for rolling mill rolls

3. BASIC BUT IMPORTANT KNOWLEDGE FROM MATERIAL SCIENCE

3.1. HARDNESS

3.1.1. INTRODUCTION

Hardness is worth discussing as the first of all mechanical properties:

- measuring hardness is fast
- measuring hardness is cheap
- equipment to measure hardness is reasonable and available almost everywhere
- there are good correlations between hardness and other mechanical properties - at least for the same type of material (same composition, microstructure…)
- many people believe in hardness figures

I have the following special reasons:

- correct hardness readings are very difficult to obtain
- hardness by itself does not give many right answers
- hardness is misunderstood and misinterpreted by many people
- the linear relation of hardness to other properties is always limited to a certain degree
- hardness without more information about the material tested (microstructure) is often misleading.

As regards roll materials with a wide variation of compositions and structures (see chapter 2.3.), hardness can be more confusing than helpful and it is often the case that talking about hardness leads to endless but useless discussions. The main problem with rolls is that as long as a roll does not disintegrate there is really no other property that can be checked.

Rolls should be evaluated by performance figures, but these figures are only available at the end of a roll life - and this figure is not available for preliminary inspections. Roll hardness problems will be discussed in greater detail in chapter 4.3.

Material hardness of is very essential - however the measurement-value of hardness is the most abused, falsely misinterpreted figure in material science. The worst case is to use hardness without a basic understanding of material properties for specifications, and then (knowing nothing of the importance of the influences of the properties or manufacturing and heat treatment proceedings) reducing the range of hardness variation.

Generations of roll makers and roll users have discussed the hardness controversy without ever reaching any consensus. However, these discussions were useless because they very seldom met real needs or provided a solution to any problem. They became "dummy arguments", windmills.

In any case hardness is very important for material science and we will often come back to hardness in the following chapters. We feel it is necessary to discuss hardness in greater detail, even though there are many books and thousands of articles covering this subject. I will try to provide easy statements which will - I hope - be accepted by most readers.

3.1.2. PRINCIPLES OF HARDNESS READINGS

There are national and international standards for various hardness reading methods, but these are not always applicable on hardness readings on rolls. For this reason, there is no need to discuss these standards here. In this chapter, we will describe the principles of various methods before we will take care for the special problems of rolls in chapter 3.1.4.

When a "very hard particle" is pressed into a surface it will result in an intrusion. The load of pressure divided by the area of the intrusion is a figure for hardness, called "Vickers Hardness" (HV) when the very hard particle is a specially shaped diamond. It is called "Brinell Hardness" (HB) when the very hard particle is a Tungsten-Carbide ball. If the depth of penetration starting at an initial load to a maximum load is measured (easy for electronic reading, good for automation), then it is called "Rockwell Hardness" (HRC).

When a weight drops on the surface of a specimen it loses energy due to plastic deformation of the specimen - "hardness" - and the weight rebounds more slowly than when it falls down ("Equotip Hardness") and reaches less height than it started off at ("Shore Hardness"). These methods are used with different materials and together with the different shapes of noses of the falling weights give a wide variety of standard hardness readings.

There are many more methods of hardness testing but basically all induce plastic deformation on the surface of the specimen. The dynamic testing (Shore, Equotip) is influenced additionally by the young modules of the specimen, tested material and maybe by the damping capacity as well - who knows?

For scientific purposes Vickers Hardness is very popular and has some clear advantages

- it is (almost) independent of the load, pressure
- the tested area is clearly determined and controlled optically under the necessary magnification of the microscope
- it is applicable for soft and very hard materials
- it also allows separate testing of the various structures and phases of a material.

And last but not least many mechanical properties have - in certain limits or ranges - a linear relationship to the Vickers Hardness. This is one of the reasons why I will use only "HV" in the following chapters so as not to start to confuse myself.

However, these linear relations are always only valid for <u>one</u> “type of material”. This has to be discussed in more detail in the chapters 3.2. ff, strength, wear etc.

The factor A in the relation:

$$p = A \cdot HV + B$$

(where p might be any property and B is another constant) is often related to microstructure and/or chemical composition. Let us take one very well known example: Steel and grey iron of the same hardness have a different tensile strength; in this example A = 3.5 ± 0.1 for steel and A = 1.0 ± 0.2 for grey iron, B = 0 for both materials.

The distribution of hardness versus the cross section of a component is sometimes of high interest, especially for surface-treated components or for heat-treated parts of heavy cross section. However, this information can never be obtained non-destructively with standard measuring methods.

Hardness is only one parameter to characterise a material - more information is always needed to understand the material properties.

3.1.3. HARDNESS CONVERSION

There is a great demand for conversion tables, from one system to another because "Vickers Hardness" is not easy to employ in everyday measuring procedures (the load of the Vickers diamond, usually 300N (30 kg) – HV 30, has to be over-compensated mechanically so that the load really presses the diamond into the specimen) and many people want to check hardness without too much work with other methods.

Many conversion tables are published by roll makers, standard organisations and others but nobody tells us how the tables are established, whether they are taken from samples (too small for rebound hardness) or from big rolls, where nobody can overcome the surface problems and these vary heavily with the depth of penetration during hardness readings. Different tables never fit together and - from what I have seen so far - they do not show the ranges, the variations in measuring and so they are not reliable. And of course there is not a zero-to-zero conversion, therefore these tables create more confusion than true conversion. However, if the people who use these tables understood a little bit of "error calculus", they would give up the conversions immediately and would never use these “confusion tables” again.

3.1.4. FUNDAMENTAL PROBLEMS OF HARDNESS READINGS

Surface hardness, and only surface hardness of a component can be measured non-destructively, is often - particularly with rolls - used to check material properties by the more or less well known relations between hardness and tensile-, fatigue-strength, wear etc.

The 2-dimensional surface is taken representatively
for the 3-dimensional volume behind the surface…..

….. but most components have hardness gradients due to
macroscopic and microscopic variations close to the surface.

The *macroscopic gradient*, well known for rolls, is caused by *casting* - decreasing solidification speed with increasing distance from the surface - and by *heat treatment* - decreasing cooling speed with increasing distance from the surface at quenching in relation to TTT-curves (time-temperature-transformation curve). Two examples: 1. Indefinite chill work rolls are called “indefinite”, because their fall in hardness is continuous but cannot be clearly defined. 2. After a slow gradient at the beginning the fall in hardness of forged work rolls for cold strip mills is very sharp. This defines the hardness depth and can be influenced by steel composition and heat treatment methods.

The surface itself is prone to everything, every form of mishandling: oxidation, corrosion, work-hardening, local tempering by burning (grinding or whatever), decarburisation during heat treatment, etc. All these reactions may cause *microscopic gradients at the surface, positive or negative.*

Work-hardening (see chapter 3.2.) is strictly related to hardness, that means the influence of work-hardening increases the greater the hardness of the material is. Below 250 HV work-hardening has almost no influence on hardness, but beyond 400 HV (and most barrel surfaces of rolls have a greater hardness) work-hardening assumes a major influence (see also chapter 4.3.). Work-hardening is normally caused by machining on the lathe whereby the amount of work-hardening depends on the geometry of the cutting tool and is not always removed by grinding.

Surface tempering by grinding changes the microstructure and lowers the hardness. Of course this can only happen with hardened materials; where originally martensite or retained austenite exists, there is no tempering of ferrite or pearlite. Again we have the same problem as before, all extremely hard materials (like rolls) are very sensitive to surface tempering. (To be more precise: only the matrix of microstructures containing carbide can be influenced by work-hardening or tempering, carbides are not changed, but these materials containing carbide usually have a more or less martensitic structure anyway.)

In case finished ground large components (like rolls) of high hardness are checked for hardness they may show the influence of work-hardening from the lathe and or of tempering due to “wrong” grinding. Surface hardness may have deviations from “real material hardness” up to 50 HV. The only way to measure the “right” hardness is to etch electro-chemically an area into the barrel after rough machining and to measure hardness on the bottom of this area, at least 3 to 4 mm below the initial surface. Whether this is useful or not will be discussed in chapter 4.3.

Even the preparation of a sample carries high risks: how was the specimen gained, cut out of the works piece? If it was done with a cutting disc then at least one millimetre has to be ground off very carefully with high water cooling to eliminate the tempering effect. If the specimen was cut out with a saw it is even worse and work-hardening may extend even further. You have to eliminate the influenced surface and re-check again and again until test results are stable.

Very often the *variation of hardness readings* is underestimated. Rolls with a barrel surface of some square metres made of quenched materials with steep tempering curves always show a wide variation of hardness - even though the tempering furnaces are excellent with very accurate temperatures (± 5°C) - because the barrel temperatures during heat treatment are not as accurate all the time. And after the rolls have been in service for some time in a hot strip mill the hardness distribution on the barrel will be changed anyway by tempering in contact with the hot rolled material (see chapter 4.3.)

Variation of hardness is in many cases greater than the specified range of hardness. Only if averages are averaged some times, then the figures might fit! (See chapter 4.3. and 4.11.).

The real problem is that some people believe this is the only property that can be measured and specified with a narrow range but this is absolutely unrealistic and not necessary at all.

Hardness readings are important for roll-makers to prove that the manufacturing process was well done, and they might be of some interest for roll users if they always test their rolls under the same conditions to ensure that they are operating safely. (See chapter 4.3.).

3.2. MATERIAL PROPERTIES FROM STATIC TESTING

3.2.1. ELASTIC DEFORMATIONS

Machine parts, components and tools (rolls) should work safely and always without unexpected breakage or deformations. There are many rules about how to design a component in this respect, but it is necessary to know the loads applied to the component and to understand the material properties. In most cases, when a component fails it is a result of fatigue after crack initiation and crack propagation under alternating loads. Notches, stress raisers have a high impact on strength. In the following chapters we will deal with fatigue and fracture mechanics, which allow the safety of components with already formed cracks to be calculated.

However, the most common material mechanical properties for comparing different materials are gained from so called “static” tests, with slowly increasing load and/or strain. These tests give figures to limit elastic deformation, maximum stress, ductility and the mechanical constants for Hook’s law (Young’s modulus E and coefficient of transversal contraction μ). Normally these tests are performed with one-dimensional stress (three-dimensional strain) in straight test bars and only as an exception with three-dimensional stress and notched test bars.

The three-dimensional elastic (no plastic deformations) stress-strain relation is described by tensors with many constants and only under very special assumptions (homogeneous and isotropic material) therefore these equations can be reduced to the general Hook's law.

$$\varepsilon_1 = \frac{1}{E}\{\sigma_1 - \mu(\sigma_2 + \sigma_3)\}$$

$$\varepsilon_2 = \frac{1}{E}\{\sigma_2 - \mu(\sigma_3 + \sigma_1)\}$$

$$\varepsilon_3 = \frac{1}{E}\{\sigma_1 - \mu(\sigma_2 + \sigma_3)\}$$

simply using two constants

E = Young's modulus

μ = Poisson ratio

In case $\sigma_1 = \sigma_2 = o$, the tests with straight bars, we get

$$\varepsilon_1 = \frac{\sigma_1}{E}$$

$$\varepsilon_2 = -\mu\frac{\sigma_1}{E}; \qquad \varepsilon_3 = -\mu\frac{\sigma_1}{E}; \qquad \varepsilon_2 = \varepsilon_3$$

and finally

$$\mu = -\frac{\varepsilon_2}{\varepsilon_1}$$

The Young's modulus for ferritic, bainitic, martensitic steel is more or less independent of the content of alloying elements and heat treatment conditions

$$E_{Steel} = 210\,000 \text{ N/mm}^2 \pm 3\ \%$$

The Young's modulus of austenitic steel is

$$E_{aust.\ Steel} = 180\,000 \text{ N/mm}^2 \pm 3\ \%$$

The Poisson ratio for *pure elastic* deformation is a constant

$$\mu = 0.3$$

In case of only *pure plastic* deformation and the assumption that volume of the material is constant, the Poisson ratio becomes the maximum

$$\mu = 0.5$$

Crossing the limit of elasticity, we will observe more or less work hardening plus plastic deformation and the Poisson ratio will shift from 0.3 to 0.5.

For normal construction parts plastic deformations are not allowed and the poisson ratio is a constant for most metals and especially for steel, independent of the content of alloying elements and heat treatment condition.

One exception for Young's modulus and Poisson ratio and even more mechanical properties is grey iron with lamellar graphite and because this material behaves totally differently from the others (and it is used in rolls very often) we have to discuss this separately in chapter 3.2.3.

Ductile iron - grey iron with nodular graphite - almost follows the laws of "normal" steel. Only Young's modulus is slightly lower ($E = 175\,000 \text{ N/mm}^2$, ± 5 %).

3.2.2. TENSILE TEST

3.2.2.1. TENSILE TEST WITH STRAIGHT TEST BAR

The tensile test is measured as an engineering stress-strain curve, where stress is always calculated and related to the initial cross section. Illustration 2 give results for / of

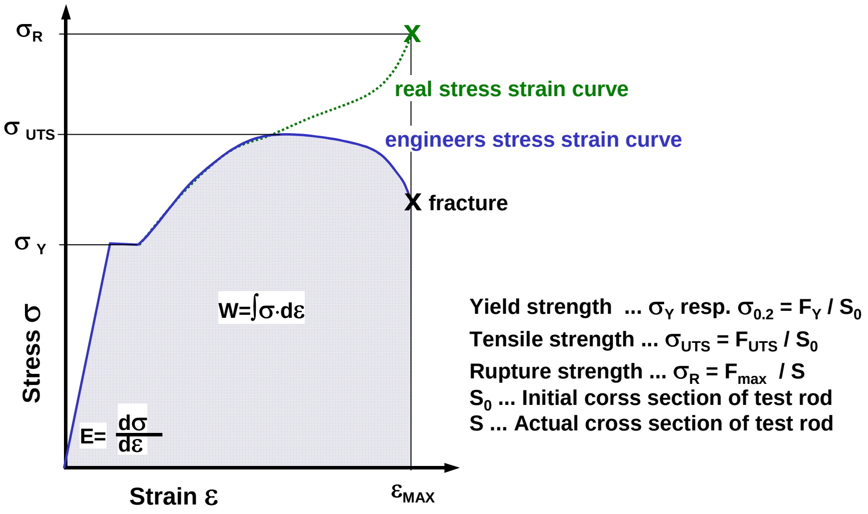
- limit of elasticity: yield strength
- maximum stress (s.a.): tensile strength - the stress when the sample really breaks after local neck down, slim down. The breakage load divided by the actual cross section is called failure strength - but this value is of no general interest.

and furthermore

- the gradient of the stress-strain-curve beyond the yield strength determines the work hardening

and

- max. strain is the indication of ductility, normally however ductility is measured differently on the sample as a percentage elongation and/or as the reduction of area at the place of fracture in a percentage as well.



Yield strength ... σ_Y resp. $\sigma_{0.2} = F_Y / S_0$
Tensile strength ... $\sigma_{UTS} = F_{UTS} / S_0$
Rupture strength ... $\sigma_R = F_{max} / S$
S_0 ... Initial corss section of test rod
S ... Actual cross section of test rod

Illustration 2: Stress strain diagram for tensile test

Tensile tests are carried out strictly under the following conditions:

$\sigma_1 \neq 0; \qquad \sigma_2 = \sigma_3 = 0$

$\varepsilon_1, \varepsilon_2, \varepsilon_3 \neq 0$

which is a very uninteresting stress condition in engineering design, though we have to take the above results of tensile tests with some reserve, indeed caution. Construction parts used for multiple purposes should not be loaded beyond the limit of elasticity because they would change their shape! However, tensile tests give figures so that different materials can be compared especially for loads beyond the limit of elasticity, which is called ductility. Elongation and reduction of area are easily gained in tensile tests and allow to rate the “ductility” of materials. Sophisticated engineers use the impact test (preferable in a wide range of temperature) with notched specimens to rate “ductility”, but this test is not very helpful for “material of low ductility” – as most roll materials are. “Fracture toughness” used in fracture mechanics, see chapter 3.4., is somehow different from “ductility” but helpful to explain crack propagation in pre-cracked construction parts or specimens under static or alternating loads; however this figure is difficult to gain, has a strange physical dimension and is not the same as what we mean with “ductility”.

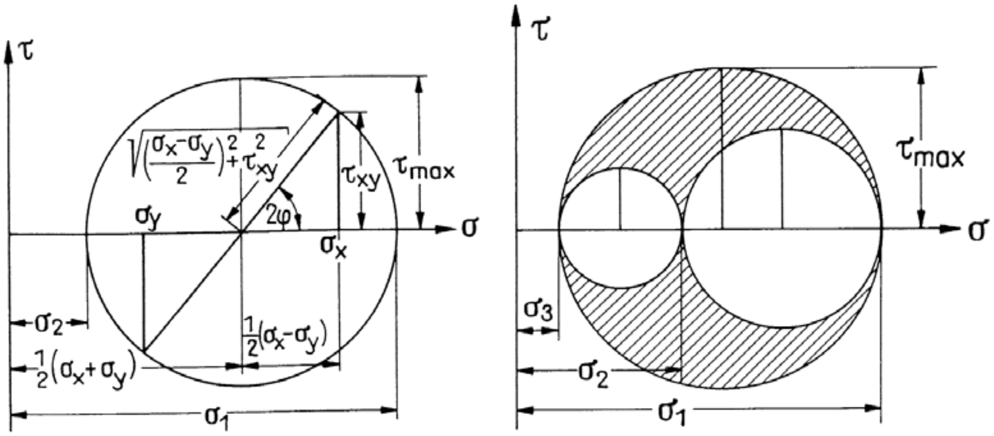
To calculate the limits of elasticity or the max. stress or strain before breakage in real construction parts under load (that is for almost all applications) there are a number of hypotheses to calculate maximum shear stress, which take all stresses (zero or different from zero ,$\sigma_1 \neq 0$) into consideration. One of these hypotheses is Mohr’s shear stress hypothesis which says that plastic deformation occurs when the shear stress exceeds a certain limit. The shear stress is calculated from:

$$\tau_{i,k} = \frac{1}{2} \cdot (\sigma_i - \sigma_k)$$

and

$$\tau_{max} = \frac{1}{2} \cdot (\sigma_{max} - \sigma_{min})$$

Illustration 3 shows the situation for a two-dimensional stress (σ_1, $\sigma_2 \neq 0$, $\sigma_3 = 0$) and for a three -dimensional stress situation (σ_1, σ_2, $\sigma_3 \neq 0$).



σ_1, $\sigma_2 \neq 0$, $\sigma_3 = 0$

σ_1, σ_2, $\sigma_3 \neq 0$

Illustration 3: Mohr's Shear stress circle for 2- and 3-dimensional stress situation

In case of $\sigma_{max} = - \sigma_{min}$, τ_{max} is big and plastic deformation occurs "easily". These are the conditions of "cold-rolling", otherwise the strip could not deform and may break.

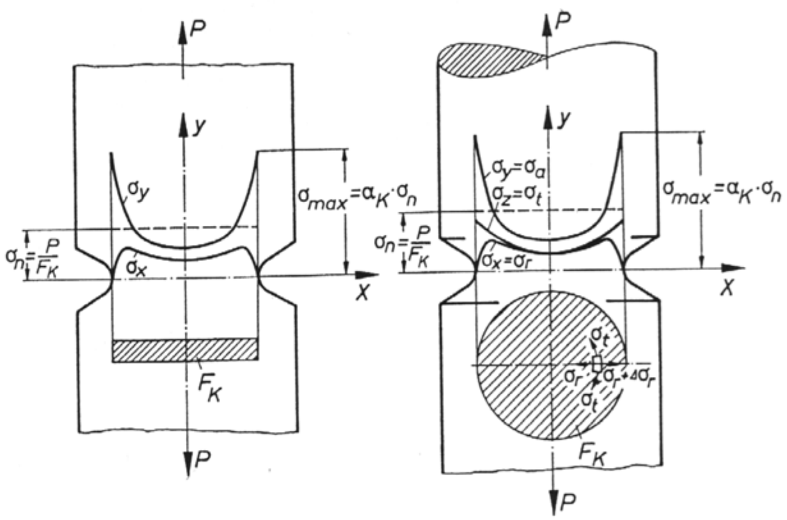
For understanding roll damage by brittle breakage (fire cracks etc.) often under ordinary strain, the hypothesis of breakage due to maximum principal stress is very much recommended, the fracture is always orthogonal to principle stress.

Incidentally, roll core material does not need ductility but sufficient high strength because the core is always under a hydrostatic stress situation: $\sigma_1 = \sigma_2 = \sigma_3 \rightarrow \tau = 0 \rightarrow$ no plastic deformation …

... and the results of tensile testing only give figures for comparison for different materials gained under the same conditions of testing.

3.2.2.2. TENSILE TEST WITH NOTCHED TEST BAR

When using notched specimens we leave the conditions to gain material properties, because the assumption $\sigma_1 \neq 0$, $\sigma_2 = \sigma_3 = 0$ is no longer valid. In the cross section of notched specimens there is a 3-dimensional stress situation (2-dimensional of course at the surface on the ground of the notch). Due to the stress situation all stresses have the same operational sign, constriction is hindered because of reduced maximum shear stress.



flat test piece

round test piece

Illustration 4: Stress situation in notched flat- and round test piece [2]

In the case of brittle material (like glass) the specimen breaks as soon the stress peak reaches "tensile stress" (on the bottom of the notch).

In case the material is ductile plastic strain will start under load at the bottom of the groove and continue towards the centre (Illustration 5). Due to reduced contraction the maximum load at breakage might be much higher than with straight specimens, (Illustration 6) -breakage starts at the centre of the specimen!

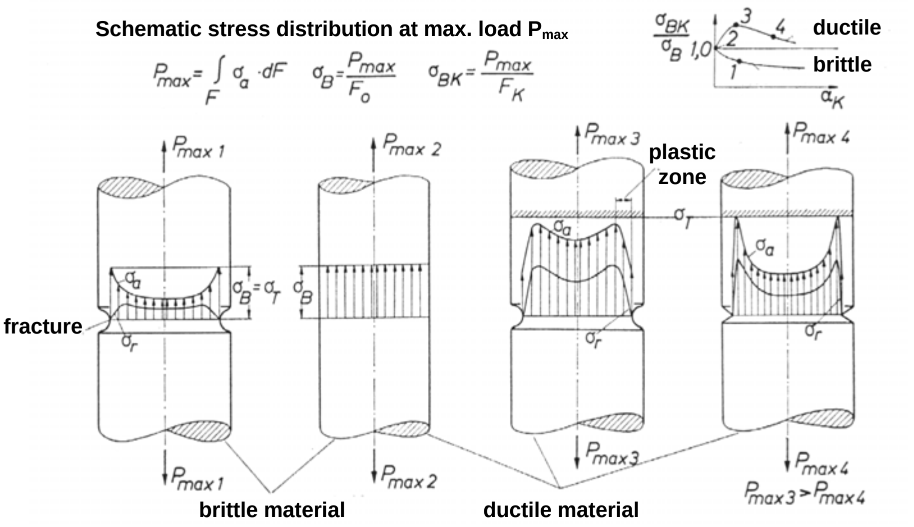


Illustration 5: Schematic stress distribution in notched test specimen of brittle and ductile materials under tension at max. load P_{max} [2]

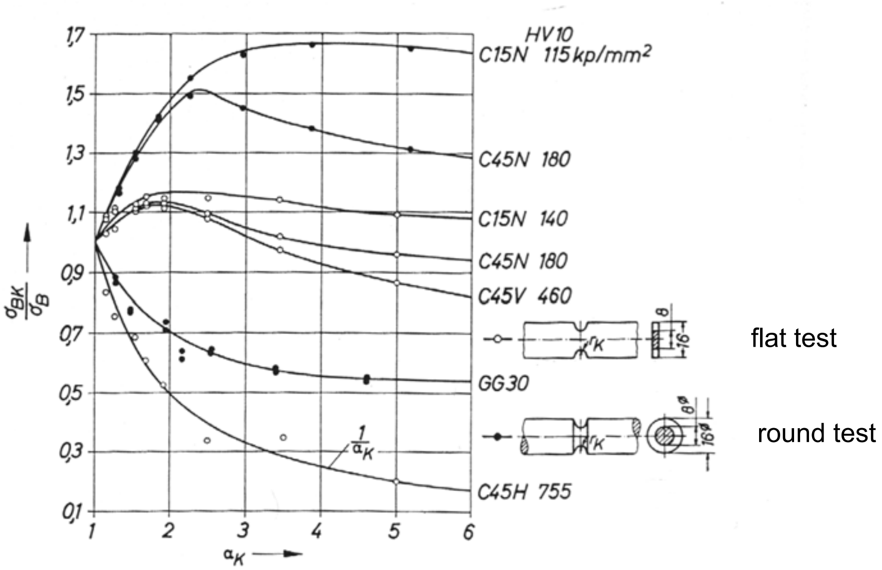


Illustration 6: Strength of notched specimen σ_{BK} related to stress of unnotched test specimen σ_B as function of stress concentration factor α_K for various materials [2]

In fact the relation of strength of notched specimen to that of straight specimen of the same material indicates the ductility very nicely.

3.2.3. TENSILE TESTS USING GREY IRON WITH LAMELLAR GRAPHITE SPECIMENS

So far we have discussed homogeneous, isotropic material. Grey iron, extreme with lamellar graphite is no longer homogeneous, it becomes heterogeneous.

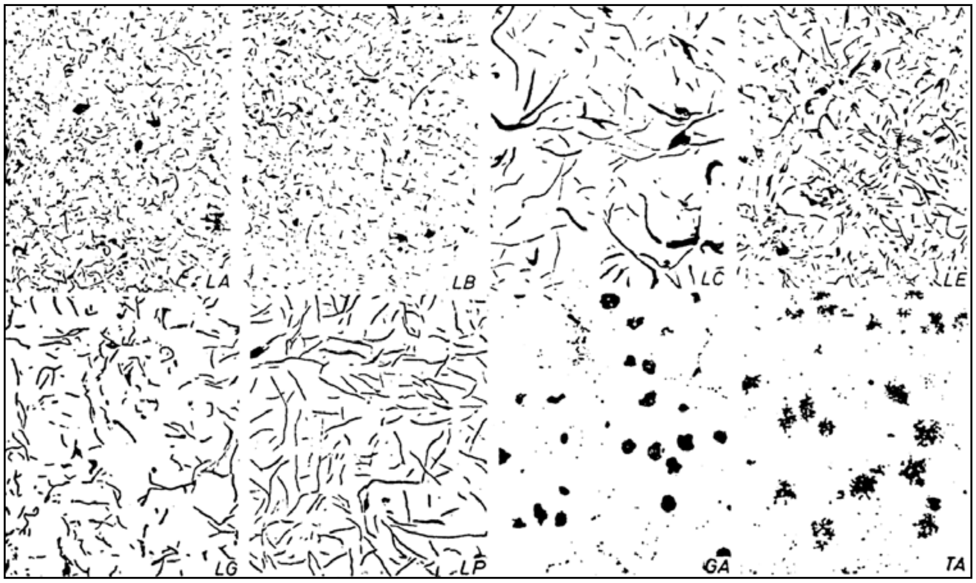


Illustration 7: Microstructure of different types of grey cast iron [3]

Within a matrix of "steel" a high number of graphite particles of various size and shape are distributed. The Young’s modulus of graphite is very low compared to steel so actually graphite does not carry any load or stress. For example if graphite were to be replaced by air or a vacuum, it would not change the mechanics of grey iron.

Every graphite particle has to be considered as a notch in steel, so grey iron is a multiple notched material like foam. Notches induce 3-dimensional stress (!) and the stress-carrying cross section is reduced by the graphite as well. Whenever load is applied on grey iron there are stress peaks at the ground of every notch (graphite particles), followed by plastic strain. Sooner or later more and more cracks perpendicular to the highest principal stress in the matrix at the notches are initiated. Due to the 3-dimensional stress, constriction/contraction is hindered everywhere in the specimen, even the testbar is macroscopically considered as straight. And the values of the test bar increase due to plastic deformation and cracks.

This effect has a high impact on the stress-strain-curve in tensile tests: Young’s modulus, the spring rate of the material, changes continuously with increasing load due to local plastic deformation and the micro cracks in the matrix. The volume of the material is not only elastically deformed but it increases also by stress, making it absolutely different from any homogeneous materials.

Consequently the stress-strain-curve, Illustration 8, looks different:

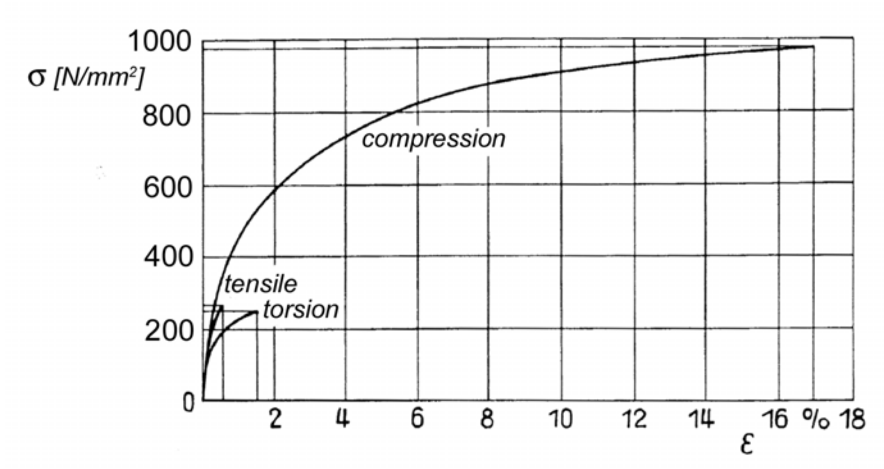


Illustration 8: Stress strain curves of grey cast iron with lamellar graphite [4]

- There is no real elastic deformation; there is no longer a linear function of stress versus strain.
- E_0, Young’s modulus at load zero, is increasingly reduced at E_0 under load, Illustration 9.
- After relief of load the length of the test bar is increased, Young’s modulus is decreased.
- Transversal contraction is very small and decreases with increasing load, Illustration 10.
- No necking appears before breakage.
- Tensile strength is very limited (= 350 N/mm^2) for grey iron with lamellar graphite.
- The material becomes increasingly anisotropic with unidirectional load. (The Young’s modulus decreases in the direction of the greatest principle stress, while it remains unchanged in the perpendicular direction).

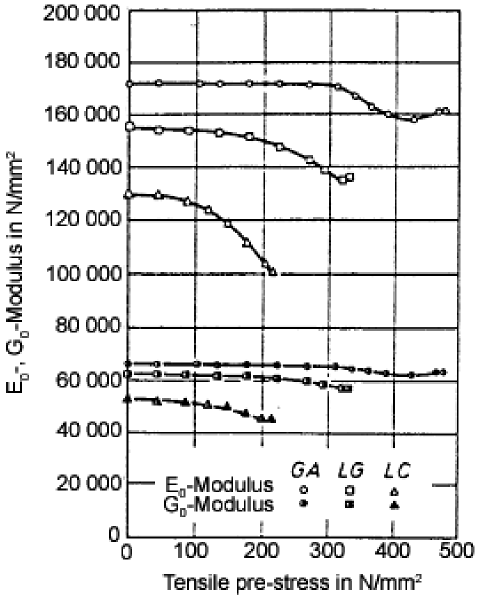


Illustration 9: Changing E_0- G_0-Modulus with tensile pre-stress [4]; GA, LG, LC … different types of grey cast iron – the graphite morphology is represented in Illustration 7.

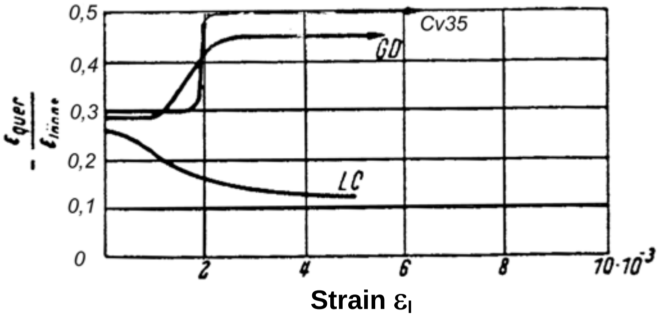


Illustration 10: Transverse contraction versus elongation for specimen of steel (Cv-35), nodular iron (GD) and grey iron with coarse lamellar graphite (LG) [4], graphite morphology see also Illustration 7.

Useful remarks:

Young's modulus can be examined, inspected by ultrasonic testing [5] with very low loads (or with resonance vibration method).

Sound velocity in materials is a function of Young's modulus, E, Poisson ratio μ, and density, ρ,

$$c_l = \sqrt{\frac{E}{\rho} \cdot \frac{(1-\mu)}{(1+\mu)\cdot(1-2\mu)}}$$ for longitudinal waves

For steel c_l = 5900 m/sec.

for grey iron 3500 ≤ c_l ≤ 5000 m/sec.

for ductile iron 5300 ≤ c_l ≤ 5700 m/sec.

For grey iron with lamellar graphite the sound velocity c_l has an (almost) linear relationship to the "degree of saturation" S_c

$$S_c = \frac{C}{4.23 - 0.31 \cdot Si - 0.275 \cdot P}$$

The easiest way to measure the sound velocity c_x is to adjust the impulse-echo-US equipment to the sound velocity of steel c to measure the virtual thickness d_x of the sample and to relate it to the real thickness d.

$$c_x = c \cdot \frac{d}{d_x}$$ (accuracy ≈ ± 1 %)

This measuring method can be very helpful to test whether the treatment for ductile iron was successful or not and/or to determine pre-cracked, overloaded parts of grey iron with lamellar graphite (reduced Young's modulus) before catastrophic damage may happen (see chapter 4.6.2.1. - "Heavy spalls ...").

3.2.4. TENSILE STRENGTH

To compare different construction materials there is an old tradition of talking about “tensile strength” even so this is not a significant figure for any design calculation (see above "Tensile Test"). The result of measuring tensile strength includes - just to repeat it once more - elastic and plastic deformation, work-hardening and necking.

For homogeneous, isotropic materials including low and higher alloyed steels used for any construction, independent (up to certain limits) of the state of heat treatment there is a linear function between tensile strength Rm and hardness H (measured in Vickers penetration Hardness).

$$R_m = 3{,}5\ HV\ [N/mm^2]$$

However, there is an upper limit for this function, because the harder the steel becomes, the more brittle it will be and finally the smallest inhomogeneity - like non-metallic inclusions - will deliver a stress raiser for final breakage. Additionally slight bending of the specimen during testing cannot be compensated by plastic deformation. This means the maximum tensile strength is given by the cleanliness of steel.

Illustration 11 shows tensile strength versus hardness for 3 different kinds of steel, curve A represents super-clean bearing steel (1% C, 1.5 Cr) B and C cast steel (0.80 C, 2% Mn, 1.5 Cr) where B is significantly better as regards percentage purity (particle cleanliness).

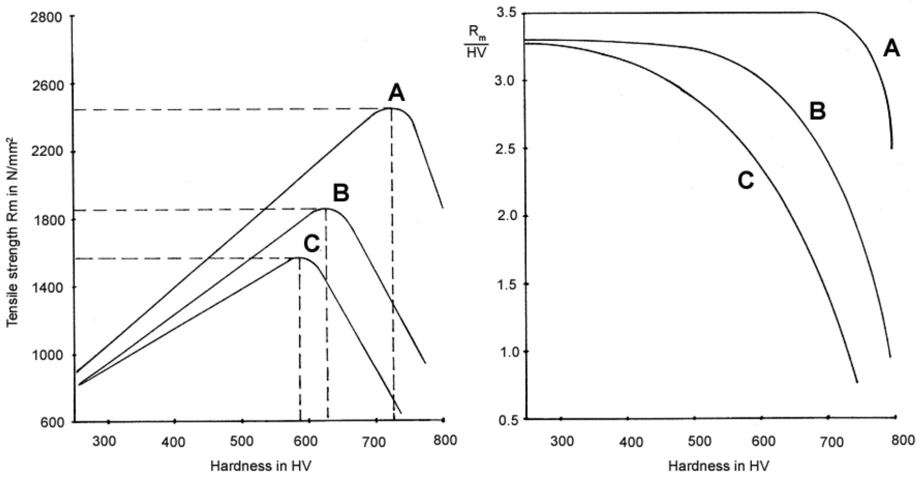


Illustration 11: The optimum mechanical properties of each steel depends on hardness

In cases where hardness exceeds the optimum, tensile strength drops dramatically; the tensile stress hardness relation decreases. It is well known that with increasing strength the ductility decreases (see chapter 3.2.2. for definition), but beyond the optimum it becomes catastrophic, with further increasing hardness strength and ductility fall drastically. We have to bear this in mind whenever someone argues that “greater hardness is better”, this is only valid to the optimum, which is strongly related to the material in use.

Heterogeneous materials - like grey iron, graphitic cast steel - do have lower tensile strength than homogeneous steel of the same hardness, however even for these materials tensile strength increases with hardness up to a certain level. The reduction of tensile strength is heavily influenced by the shape - much more than by the quantity or size - of the inclusions.

The tensile-strength / hardness ratio is a significant characteristic of the material (Illustration 12).

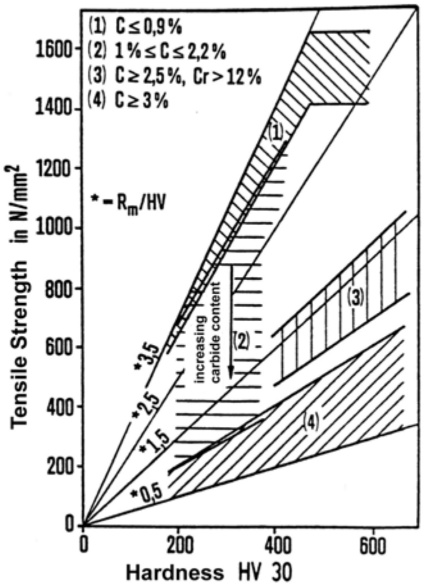


Illustration 12: The tensile strength increase with hardness - but carbides, graphite and impurities lower the tensile strength

$\frac{R_m}{HV} \leq 3.5$	hypo eutectoid steel
$2.7 \leq \frac{R_m}{HV} \leq 2.9$	carbide free cast iron with nodular graphite
$1.5 \leq \frac{R_m}{HV} \leq 3.0$	hypereutectoid steel, graphitic cast steel, nodular iron roll materials etc.
$1.0 \leq \frac{R_m}{HV} \leq 1.5$	grey iron with lamellar graphite

3.2.5. WORK-HARDENING

Work hardening of rolls only concerns the barrel surface, where it may create some problems.

The background of work hardening is that all plastic deformations of steel lead to an increase in hardness and to a reduction of ductility at the same time.

To measure the amount of work hardening and to investigate work hardening in relation to other properties the tensile test is useful, Illustration 13 give the necessary definitions. Illustration 14 shows results of tensile tests. Illustration 15 and Illustration 16 demonstrate how work hardening increases with increasing hardness of test material.

In any case, these diagrams give “work hardening” not in terms of hardness but in terms of increasing limits of elasticity due to plastic deformation – but it is clearly understood, that the limit of elasticity is a linear function of hardness (for each steel grade)!!

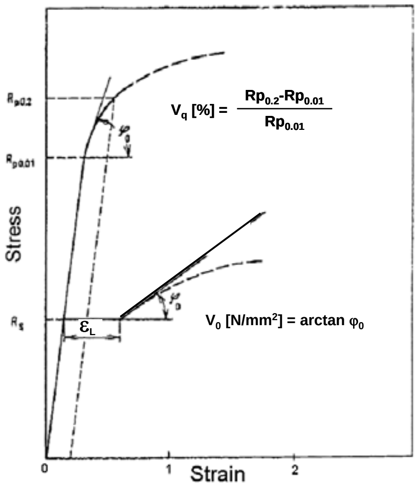


Illustration 13: **Stress strain diagram for tensile test; definition of modulus V_0 and coefficient of work hardening V_q**

ε_L ... yielding (Lüders elongation) [6]

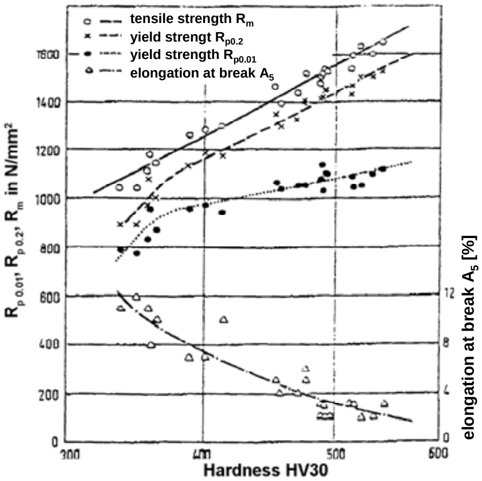


Illustration 14: **Mechanical properties of heat-treated tool steel versus hardness after various tempering temperatures [6]**

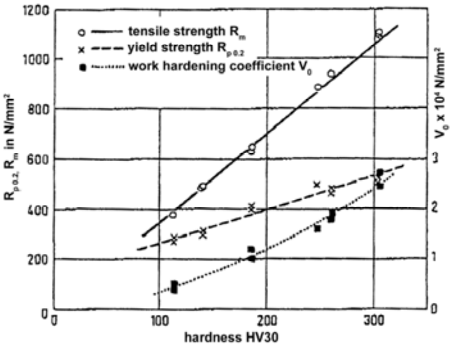


Illustration 15: Modulus of work hardening V_0 versus the hardness of carbon steels in normalized conditions [6]

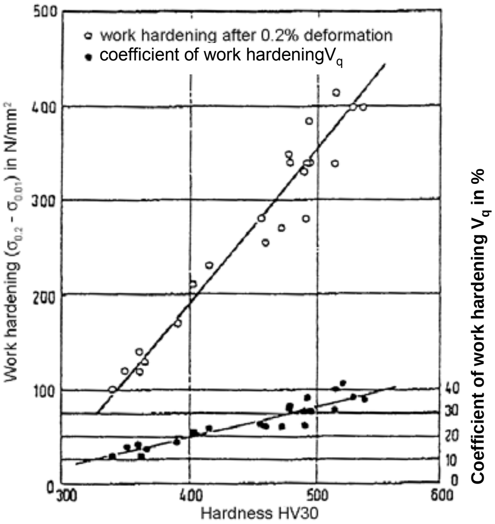


Illustration 16: Absolute and relative coefficient of work-hardening - as a function of hardness derived from Illustration 14

And it is to remind again, that with increasing limit of elasticity the ductility - the remaining capability for plastic deformation - is decreasing.

Soft, mild steel shows an almost elastic-plastic deformation curve with hardly any work hardening. However, work hardening increases with the initial hardness of steel. Of course the very hard surface of rolls - the most critical is that of back-up rolls with very long campaigns in the mill - after being in service often show an increase of hardness, because some parts really suffered plastic deformations. This might occur in areas of highest rolling pressure or locally due to “strip on the roll” or because something else passed inadvertently through the gap.

One of the ideas of regrinding back-up rolls - besides re-establishing the right, original shape – is to eliminate work hardening from the surface. In case this is not done correctly - and all mill people want to reduce stock removal to improve roll performance in terms of tonnes rolled per millimetre of roll life - then the next local overload, which cannot always be excluded, may create an initial crack due to a lack of ductility and the crack may end up in a spall, thus causing an early termination of the roll's life.

Work hardening of back-up rolls in cold strip mills is more critical than in hot strip mills, because "cold" strip on a roll is normally the hardest material in the stand and will not take necessary plastic deformation - so the back-up roll - the "softest" partner has to take it with all possible consequences. Hot strip is always soft and easy to deform and it will fall off the roll before it becomes cold and hard.

Rolling mills require rolls with less wear (chapter 3.5.) to keep the rolls for longer campaigns in service. This process was successfully achieved in recent times with back-up rolls for hot strip mills, by changing the steel grade from 2% chromium to 5 % at a significantly higher hardness. In fact: due to less wear the pressure in the gap between back-up and work rolls became much more stable, with no more highly loaded areas after centre wear of back-up rolls. Furthermore, the 5% chromium-high hard rolls used to have a significantly higher level of residual stresses, which reduces shear stress, plastic deformation, work-hardening and crack propagation in case of initial cracks. However, because of the already reduced ductility compared with "soft" traditional back-up rolls it is highly recommended to watch work-hardening carefully because in case of local overload the remaining ductility is very limited and cracks may lead to catastrophic spalls.

Whenever there is a work-hardening problem we have to distinguish strictly:

↳ whether we can avoid plastic deformation, with steel of higher strength, by higher hardness, higher limit of elasticity. If so, it is fine, helpful and the right thing to do.

↳ or whether steel has to submit to plastic deformations due to accidental overload. In this case high hardness is counter-productive, absolutely wrong and will lead to catastrophic failure (this is one of the most misinterpreted theories in roll discussions).

3.2.6. COMPRESSION STRENGTH

In rolling mills very high pressure is applied, especially between work rolls and back-up rolls. This Hertz's pressure - even under normal rolling conditions - is often much higher than the tensile-/ compression- strength of roll materials and sometimes even more than double the limit of elasticity. If rolling accidents occur the pressure, which is hard to calculate, is much higher than normal.

Plastic deformations, intrusions should not happen to the surface of rolls and this is especially critical for work-rolls (chapter 3.2.5.). The reason why under these high pressures there are normally no plastic deformations - the surfaces appear nice and intrusion-free - is based on the fact that plastic deformations only occur if the shear stress exceeds a critical size. Shear stress is, however, a result of a 3-dimensional stress situation. In the roll gap the roll surface is <u>always</u> in a 3-dimensional compression stress situation. With the formula of Mohr it is shown that the maximum shear stress is only 30% of the maximum Hertz'ian pressure, 17.

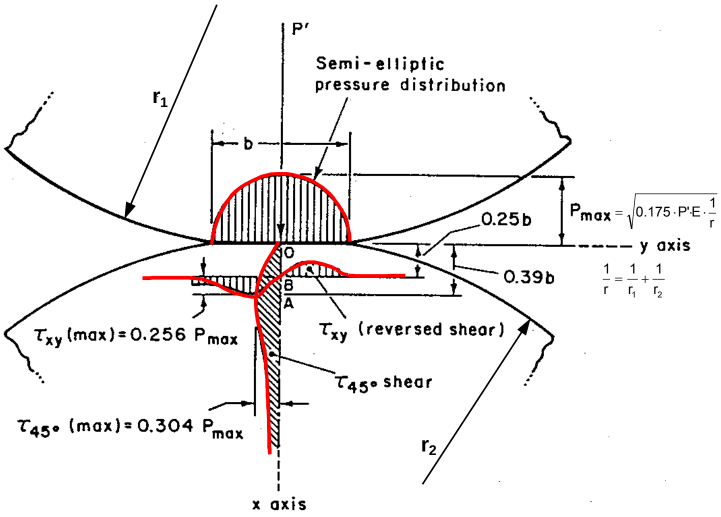


Illustration 17: Magnitude and distribution of major stresses at the zone of contact between work and back-up rolls [7]

In addition rolls close to the surface always have compressive residual stresses and these reduce the shear stress and also help to avoid plastic deformations and intrusions.

In the case of rolling accidents with very high local mechanical overloads (for instance: “strip on the roll”) there has to be plastic deformation somewhere, the shear stress will exceed all limits, and most frequently the back-up roll (the “softest” part in cold rolling mills) will show intrusions. But, see 17, the maximum shear stress is “sub-surface” and in case of overload this might be the starting point – sub-surface – where a spall may start!

Nevertheless the discussion concerning intrusions is often concentrated on compression strength with very strange theories. However, compression strength, gained under one- dimensional stress conditions - and transversal plastic deformations are very strongly related to hardness, independent of the material, no matter whether steel or grey iron with nodular or lamellar graphite.

For different reasons measurement of compression strength is much more complicated than a tensile test:

- sometimes, for example with very ductile material, the sample will not break easily - it just flattens to a coin
- the friction on both ends of the sample should be considered
- breakage is only considered to be correct if the sample has a certain shape, the length/height H to diameter D ratio must especially fit into certain limits

$$1.5 \leq \frac{H}{D} \leq 2.5$$

To achieve this means that large samples with too high a ductility value have to be deformed, remachined, deformed, remachined ... until breakage happens.

However, nobody needs to carry out any more experimental work because the rule to calculate compressive strength exists and is simple and valid for all kinds of material, ranging from mild to very hard steel, from grey iron to tungsten carbide, and is always valid!

$$\boxed{R_{\text{compr.}} = 3{,}5 * HV}$$

There it is. The only open question is, where do we find a unidirectional stress situation, where we need this figure?? For sure not in any roll application!

3.2.7. TORSIONAL STRENGTH

To roll material in a rolling mill the rolls are driven in 4-high-mills for flat products - normally the work rolls but in some exceptions the back-up rolls - and the torque has to be transmitted from the motor by a spindle to the wobbler of the rolls without breakage. Experience shows that torque has to be considered as a static load - and only in case of emergency is the value of torque really high - because torque is constant for the length of a bar (max: low-cycle fatigue) – I never saw fatigue-neck damage due to torque, unlike roll bending (where the necks should be safe against fatigue).

Torque roll neck breakage happens very seldom and only by a single major overload due to a rolling accident. Rolls should break first because they are the cheapest and can be most easily replaced in the combination motor - spindle - roll. So, in a layout of a mill, torque strength of roll necks has to be orientated on the static torque strength of roll materials.

There are not too many institutions or laboratories which actually do measure shear strength. There is some literature available to understand stress situations and how to relate shear strength to tensile strength.

Only thin-walled pipes give almost linear stresses under torsional load and the stress situation is bi-directional ($\sigma_1 = - \sigma_2$, $\sigma_3 = 0$). Special equipment is necessary to test shear strength. Because $\tau_{max} = (\sigma_1 - \sigma_2) / 2$ and in shear test $\tau_{max} = \sigma_1 = - \sigma_2$, plastic deformation is always very high.

However, there is no special need to work more on this problem, because it has been proved that shear strength is almost the same as tensile strength.

So whenever a figure for torque strength is needed, it can be taken to be the same as tensile strength.

$$\boxed{\tau_b \approx R_m}$$

3.3. *FATIGUE*

3.3.1. HISTORICAL BACKGROUND

Most failures and breakages of construction parts happen due to fatigue, so this matter is of high interest for all engineers, much more than the static strength of material. All fatigue breakages are brittle, with almost no macroscopic plastic deformation.

Topography of fatigue failures always show a starting point (crack initiating), many lines of rest and a final brittle fracture. Fatigue cracks always propagate perpendicular to the greatest principle stress. The well-known Illustration 18 helps to identify the loads which caused a fatigue failure.

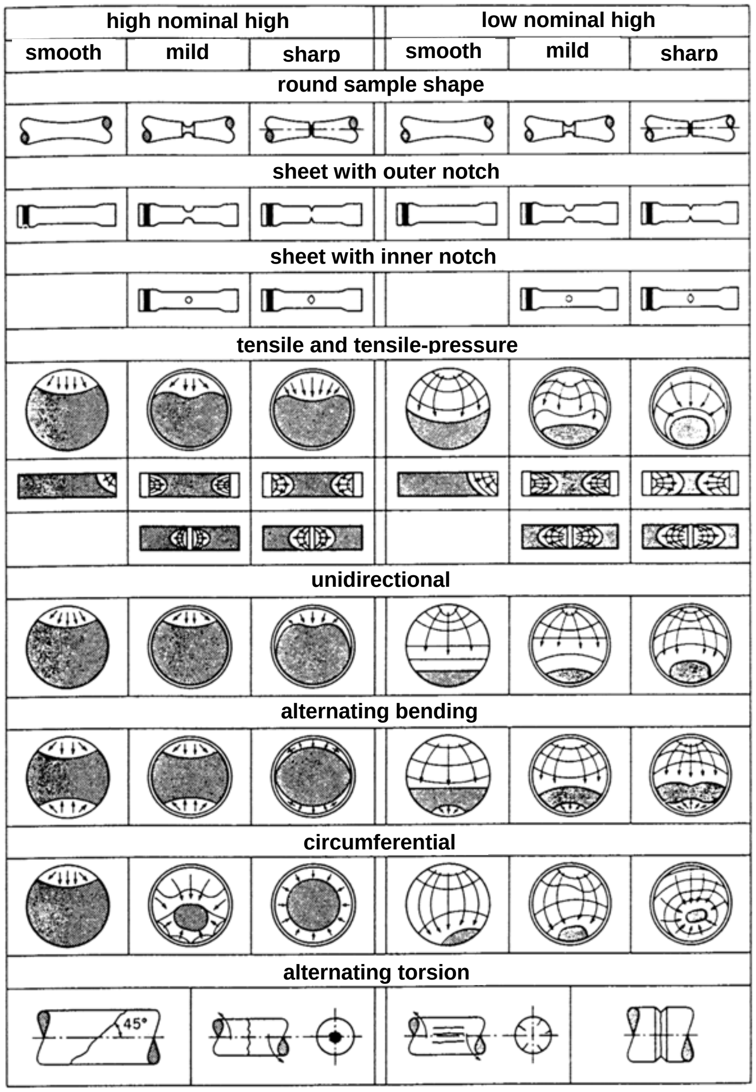


Illustration 18: Topography of fatigue and stress

Fatigue testing started by Wöhler at the end of 19th century after the first fatigue failures of railroad parts were observed. The same testing procedure is still used today even though fatigue is much better understood nowadays through the theories of fracture mechanics, which we will briefly explain in the next chapter. (Not really the theory but basic understanding and useful applications).

However, Wöhler's test procedure, a single stage endurance test, is still helpful today because tests are easy to carry out and the result allows many phenomena to be understood, explained and interpreted. The testing method and the results are useful for comparing different materials and for studying the influence of different parameters on fatigue.

Fatigue is also studied under changing loads, but this procedure is often applied to machine parts in full size - mainly for mass production parts like cars - and it is not possible to establish general rules for other applications from the results.

Rotating bending fatigue tests are most frequently used; the testing machines are easily designed (low price equipment), the testing frequency is high and so results are obtained in a relatively short time.

One test bar after the other rotates with a given load/bending moment till it breaks. The maximum stress where the samples of steel survive 10^7 (for aluminium 10^8 are necessary) revolutions is called fatigue strength. At higher stress levels samples fail at a lower number of revolutions, "low cycle fatigue". In case the samples are tested in aggressive media, we talk about “corrosion fatigue” with no fatigue limit and the rotating frequency - time - has a high impact on the results (because corrosion, diffusion is time dependent).

Before a test bar breaks, the fatigue crack starts (initiation always at a stress raiser) and propagates revolution by revolution – step by step; there are some statistics available to discuss details, however this means "theory" not practical application. Anyway, to determine a Wöhler's line for one material a minimum of 12 specimens are needed.

Notches have a high impact on fatigue test results: the fatigue strength of a notched sample is always lower than that of a straight, unnotched sample; **low** cycle fatigue for ductile material is vice versa, because for 1 cycle the Wöhler line starts with tensile strength, and tensile strength of notched bars is often higher than the tensile strength of straight bars (see "Tensile Test with notched Test Bars, 3.2.2.2"), Illustration 19.

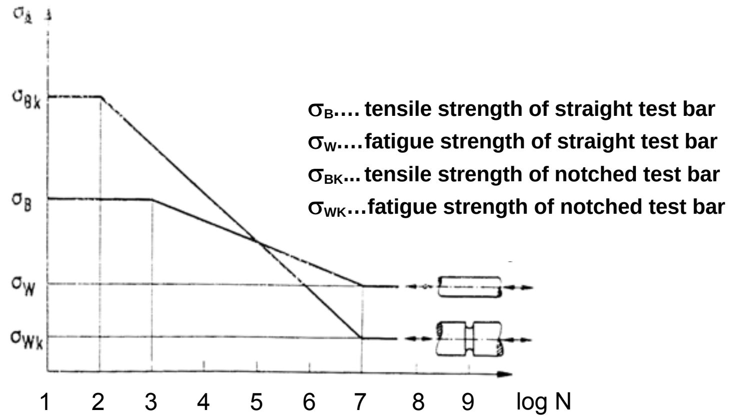


Illustration 19: Wöhler-diagram for straight and notched test bars of the same material

3.3.2. FATIGUE STRENGTH

After more than 100 years of fatigue testing very many results are available for statistical evaluation, even if one excludes all very special research studies on special questions.

It turned out that for homogeneous, isotropic steel - similar to tensile strength - bending fatigue strength (on air) σ_{bw} has a linear relationship to hardness (HV), up to a limit of approx. 500 HV, and luckily that is valid for notched samples as well, Illustration 20, and beyond this hardness fatigue strength may drop, however there are many factors which influence fatigue but basically the material becomes increasingly brittle and sensitive to notches, and very small stress raisers help to initiate a crack, and cracks under the same repeated load propagate.

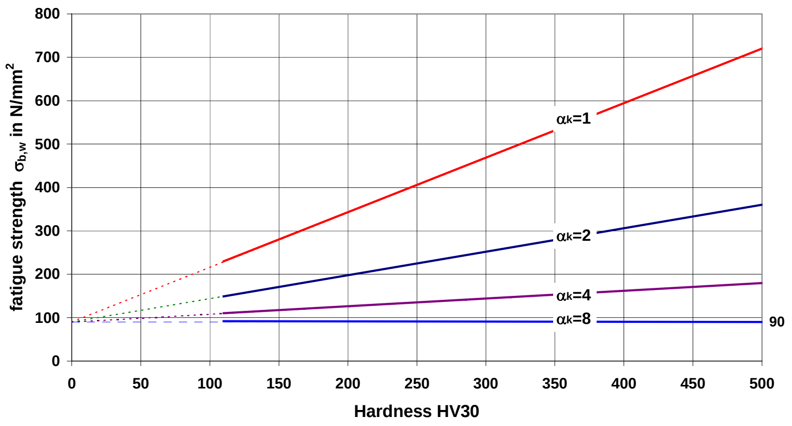


Illustration 20: Rotating bending fatigue strength of steel (C < 0.8%)

The graph in Illustration 20 shows very clearly that high strength material only helps to increase fatigue in the case of straight, smooth, notch-free construction parts. With very sharp notches - $\alpha_K = 8$ is very sharp (and also a miserable engineering design) - fatigue is independent of the hardness or of the tensile strength of the steel and vice versa. Normal “good” designs show notch factors about 2 or less, but even with this figure in cases of fatigue problems with parts it is more adequate to improve the design or manufacturing methods, see 3.3.3., instead of changing to higher strength material, for many reasons.

Rotating bending fatigue values are always higher than tensile/compression fatigue strength. However rotating bending is the most general reason of fatigue failures of machine parts.

In case of heterogeneous material like grey iron, graphitic cast steel, or hyper-eutectoid steel - fatigue strength is lower than that of homogeneous steel of the same hardness, the coarser the shape of inclusion, the lower fatigue strength will be. However even for "very lamellar" graphite in grey iron no fatigue strength less than 60-70 N/mm^2 was ever reported without or with notches.

Illustration 21 shows a similar graph as the previous Illustration, but this time for different materials, all figures for straight test bars ($\alpha_K = 1$).

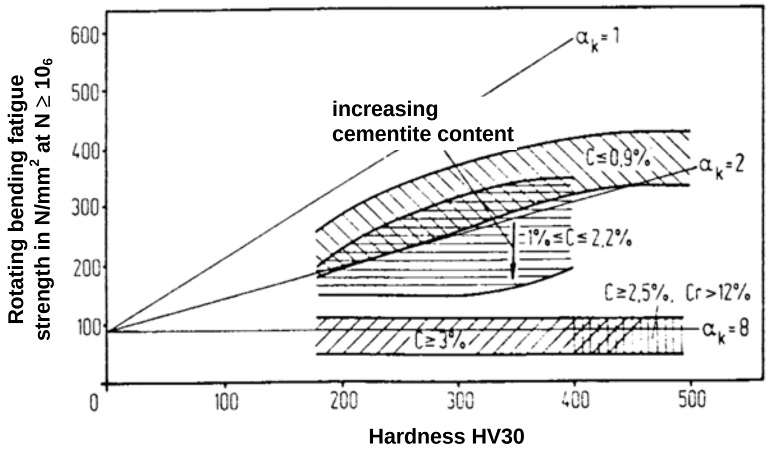


Illustration 21: Alternate strength measured on notch free test rods with Ø10 mm, specimen taken out from rolls with a barrel diameter ≥ 500 mm; limit curves for smooth ($\alpha_K = 1$) and notched ($\alpha_K = 2$ or $\alpha_K = 8$) test rods with Ø10 mm made of deformed and annealed steel

And sometimes engineers can be lucky: notches have less impact on the fatigue strength of these materials compared to high tech steel. This means in reality - even for these low strength heterogeneous materials in miserably designed parts with sharp notches - fatigue never falls below 60 N/mm^2. The miracle of low sensitivity of grey iron to notches can be explained with the non linear stress-strain-curve.

3.3.3. THE IMPACT OF PRE-STRESS/RESIDUAL STRESS ON FATIGUE STRENGTH

Residual stress operates as pre-stress! We will show that pre-stress (mainly compression pre-stress) has high impact on all notched or pre-cracked components. Rolls rely on residual stresses and roll makers expertise should include (heat treatment) procedures to create compressive residual stresses for high stressed areas, where required, and they should be capable of keeping tensile residual stresses - to compensate compression - low enough to minimize risks of breakage of any kind.

So far all results presented in chapter 3.3.2. are valid for rotating bending fatigue where the mean stress is zero (0). In reality this is not necessarily the only way of loading construction parts, often alternating stress is superimposed by a static stress pre-stress. All fatigue strength results for steel - without and with tension or compression pre-stress (mean stress ≠ 0) - are put together to build up a Smith-Diagram (or Haigh-Diagram), Illustration 22.

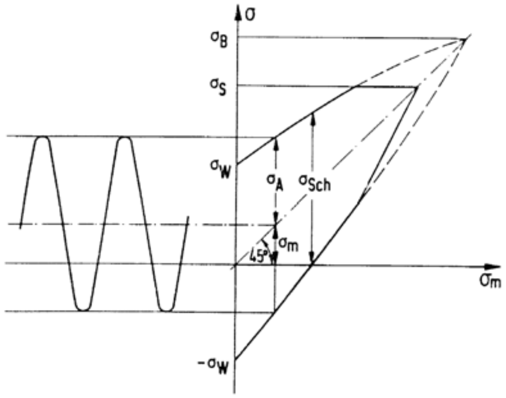


Illustration 22: Smith diagram (straight test bar)

It is evident that there is almost basically no influence of pre-stress on the fatigue strength of straight/un-notched specimens or construction parts. However, there is always a high impact on the fatigue strength of notched parts and fatigue failures always happen at notches, the place of highest stress !!

As was shown in Illustration 20 fatigue strength of notched bars - pre-stress zero - is reduced, but this reduced fatigue strength does not change fundamentally when tension pre-stress operates. And because the upper limit of stress amplitude is governed by the static limit of elasticity, the maximum allowed tension pre-stress for notched bars is higher than that for straight bars. (This is the explanation why and how screw bolt always with a high notch factor under high tension pre-stress, operates).

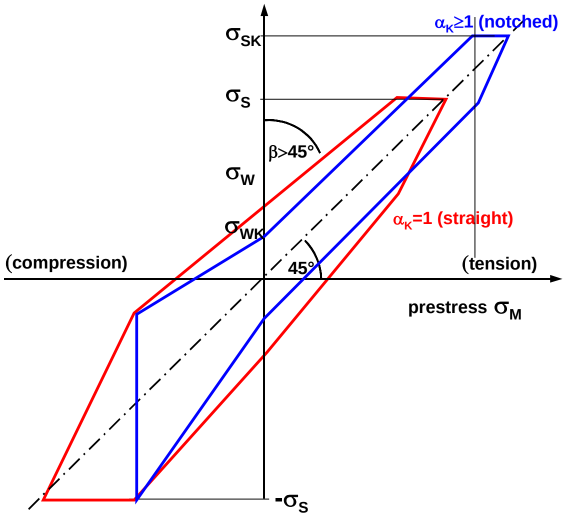


Illustration 23: Smith diagram for notched test bars of steel

> Compression pre-stress - if high enough - may compensate the influence of notches completely.

The Smith Diagram of grey iron with lamellar graphite, Illustration 24, looks somewhat different from that of steel as pre-stress on straight bars has a high impact on fatigue, and this is true for tension and compression pre-stress. However notches in grey iron parts do not reduce fatigue strength so heavily as they do effect fatigue strength of steel parts [4].

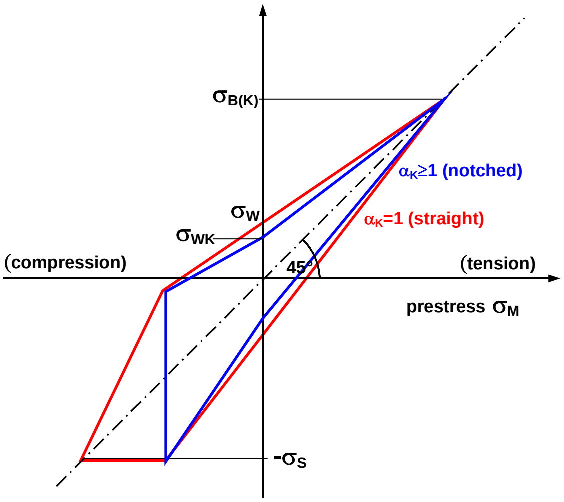


Illustration 24: Smith diagram of straight and notched test bars of grey iron with lamellar graphite

The goal is always to set up compression residual stresses at notched areas. Cold work-hardening, metallurgical processes (carburizing, nitrieding) or others do have high gradients and these methods are useful only for relatively small components, for bigger ones it does help only to avoid a bad surface finishing influence - but fatigue will be unchanged and the initial fatigue crack will start sub-surface. For heavy, large cross sections residual compression stresses of great depth are required and can be achieved only by appropriate heat treatment.

3.4. FRACTURE MECHANICS

Classic mechanics only deals with straight or notched construction parts and allows us to calculate stresses and strength, however it does not take cracks into consideration, nor does it not allow us to calculate crack initiation, crack propagation and final failures under alternating loads. Classic mechanics expects that safely designed constructions never should develop cracks and should never fail.

However, in reality nowadays we have to live with cracks and especially with rolls we have to deal with cracks every day. Fracture mechanics were developed to have a tool to calculate the breakage risk of construction parts or tools like rolls with existing cracks. There are always "cracks", it is just the question of definition that should be the deviation from homogeneity; it might be a "real crack" of the size of some or many mm or just a non-metallic inclusion in steel.

Fracture mechanics offers mathematical systems to calculate crack propagation and final failure of construction parts with cracks. There are many theories and much literature is available on fracture mechanics, but we will not go into detailed theories. It is almost impossible to compress these into a few pages, if it is done, it should be done correctly (for basic understanding see relevant literature). However, we will concentrate on the practical use of these mathematical calculations for application on parts of large cross sections. This may help to understand the increased risk with increasing crack depth - that is it. In reality we do not even know load distribution or mechanical properties in regions of highest load in large cross section parts - but we have to deal with cracks to avoid catastrophic failures.

The full theory of fracture mechanics has to include many parameters of materials and load conditions such as:

- all micro and macro mechanical properties of material (related to time, temperature and environment, specially elastic/plastic deformations)
- stress - strain situation at changing loads
- etc. etc.

For our purposes - to explain and calculate the risk of fracture in rolls, (chapter 4.6.) - we need only very basic information under the following conditions, (related to the size, the constant valid dimensions of rolls - plain strain conditions - and this reduces the calculations to easy equations):

- In load mode I, where the load operates perpendicular to a crack
- The loaded part is big, and no change of cross section is allowed - conditions of plain strain

A stress intensity factor is defined for the zone at the end of a crack of the length of 2a:

$$K_I = \sigma \cdot \sqrt{\pi \cdot a \cdot f(\frac{a}{d})}$$

(some formulas for easy calculation are given in Illustration 25).

- The dimension of K_I is $[\mathrm{MPa} \cdot \sqrt{\mathrm{m}}]$
- There is a critical value of K_I called K_{IC} - when this value is reached, breakage of the part happens. K_{IC} is a property of the material, some rough figures are available in relevant literature - to measure this needs special equipment and skills
- As long as the stress intensity factor K_I is below K_{IC} the crack may grow, propagate - but no fracture will occur

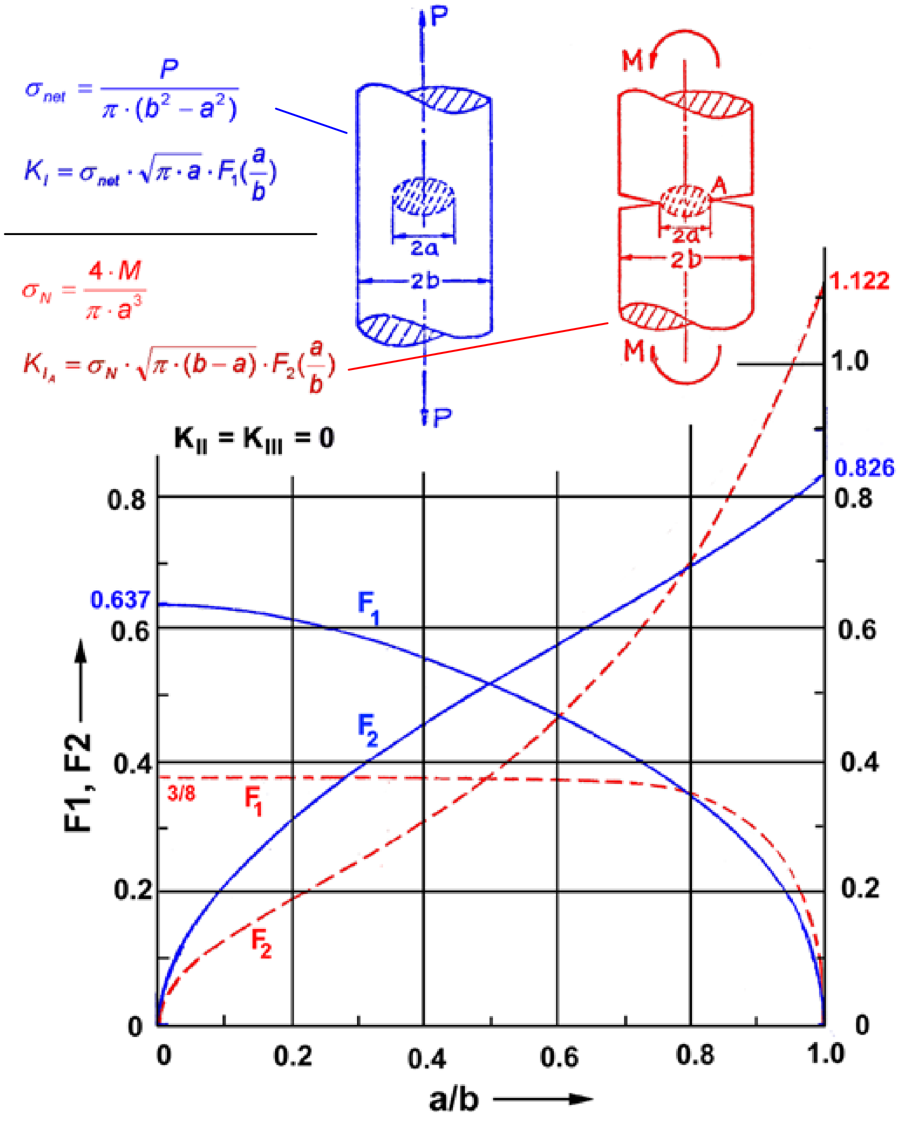


Illustration 25: Linear elastic fracture mechanics in uni-axial stress field;
continuous line – internal crack, dashed line – surface crack [8]

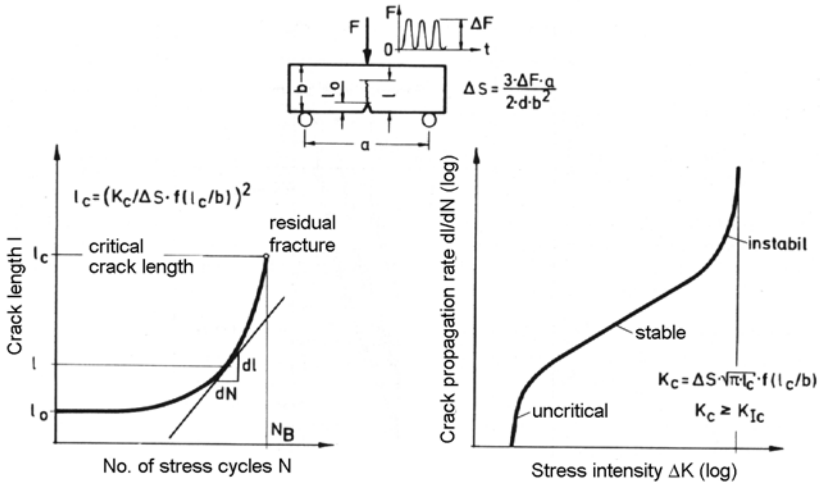


Illustration 26: Fracture mechanical material characteristics under fatigue load (schematic) [9]

Under alternating loads cracks propagate progressively. The crack propagation rate is strictly related to a ΔK-value, Illustration 26. ΔK is the difference between K_{max} and K_{min} during one load cycle and given by the stress amplitude $\Delta\sigma = \sigma_{max} - \sigma_{min}$. For a crack with the length of 2a it is as follows:

$$\Delta K_I = \Delta\sigma \cdot \sqrt{\pi \cdot a}$$

Illustration 26 (s.a.), shows crack propagation da/dN versus ΔK in double logarithmic scale, there are 3 different areas:

- 1st with very low, uncritical crack growth
- 2nd steady increase of crack propagation rate
- 3rd instable crack propagation and final fracture at ΔK equal K_{IC}.

The second part can – steady state increase of crack propagation rate - be expressed by

$$\frac{da}{dN} = \text{const.} \cdot (\Delta K)^n$$

Experimentally n was found to be between 3 and 4. The meaning of crack propagation speed in steps allows the stage of crack propagation to be determined and to avoid final failure.

Here is an example for the successful use of fracture mechanics: a number of 60’ x 80’ back-up rolls developed cracks in the fillet between neck and barrel, the part of the necks with the highest bending stress. The question was how to keep the risk of breakage in the mill/stand low but still use these rolls till they would reach scrap diameter. To find the critical crack depth, the calculations following the above shown formulas were made and the critical K_{IC}-value was estimated according to some figures from relevant literature, but a good safety factor was applied: As a result it was calculated that the critical crack depth would be beyond 100 mm. Then the actual crack depths were always measured after some runs/campaigns and so the crack propagation rate was under control. None of the back-up rolls in question reached a critical crack depth, none broke, the total used mm of roll life was worth the money value of 2.5 complete new rolls, and without fracture mechanics nobody would have taken the risk to run pre-cracked back-up rolls in a high performing mill.

3.5. WEAR

WEAR IS AN ISSUE OF PRINCIPAL IMPORTANCE FOR ROLLS, see chapter 4.8.

Wear is a wonderful subject, resulting in many papers, books, contributions to conferences. Wear is a never-ending story, new research results are published every day but in general it is very confusing. There are no standard test procedures. There are many proven test methods, but many parameters of influence - the number is infinite. And the combination of two or more of these additional parameters makes it even more confusing. It is not my intention here to try to compress all this knowledge into a few pages - this attempt would fail - but we will study a very limited number of graphs, which may help us to understand wear, especially for rolls used in rolling mills.

However, even in this narrow field of application the general understanding was absolutely misleading, indeed wrong, it looked like a paradox - an example will be presented in chapter 4.8.1.

The main problem is the unlimited number of parameters which influence wear:

- material to be tested: composition, microstructure, hardness, …
- the opposite material, the wear partner, which might be metal, ceramic, ...
- wear conditions like degree of slippage, pressure, speed, temperature, cooling systems etc.
- and interactive agents, like air, "water", lubricants, all kinds of corrosive agents ...

And all these parameters may vary very widely and so it is easy to understand that it is almost impossible to establish simple rules or laws to describe wear.

However we need some guidelines to improve wear resistance, when wear is a problem, and my guidelines have been proved to be helpful in developing better grades of material for rolls in rolling mills. So I will give my very personal rules and I would like to show where they were applied successfully and where they failed and why, and what was learned by these failures. I have to ask for your understanding, in that these experiences were based on rolls in rolling mills. In the end everybody has to go the route of "trial and error" but there is nothing wrong with that, in any case no real alternative is available.

KHRUSCHOV'S DIAGRAM

As there are so many parameters that influence wear, when studying wear for research purposes it is important to keep as many parameters as constant as possible:

- the same opposite material for all tests
- constant wear conditions: wear speed, pressure, temperature
- no interactive agents besides "air"
- the same slippage, relative speed between sample and opposite material
- and so on

The end result was a diagram by Khruschov, Illustration 27, which explains some principle relations between wear, hardness and the material composition.

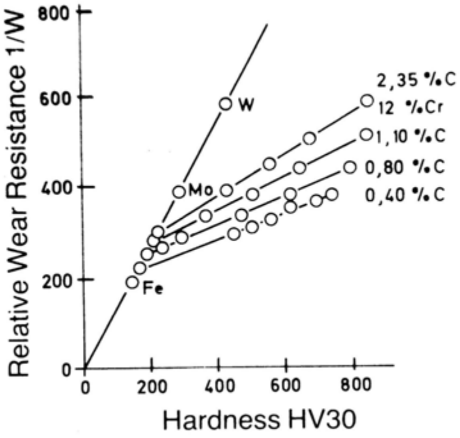


Illustration 27: Abrasive wear of metals and steel after Khruschov [10, 11]

Khruschov's diagram shows that the wear resistance of pure metals is linear and increases with hardness. For steel with a certain carbon content - where the hardness is varied by heat treatment - wear resistance increases with hardness but with a much slower gradient than for the pure metals. The initial wear resistance and the gradient increases with carbon content and even more with the content of carbon and the "right" alloying elements, preferably with elements which form carbides.

It is shown in chapter 3.2.4. that there is a maximum hardness for acceptable mechanical properties (untempered martensite is always "forbidden") for construction parts - and there are more restrictions (hardening, cracks, residual stresses, residual austenite ...) for hardness - so Khruschov's diagram finds for itself a logical upper limit of hardness for each material.

Some important conclusions from this diagram should always be kept in mind:

- At the same hardness, wear resistance increases with the content of carbon and alloying elements (Cr, V, Mo, W, V, Nb);
- The same wear resistance is reached at a lower hardness for materials with higher content of carbon and alloying elements;
- The potential increase of wear resistance with hardness is higher with a higher content of carbon and alloying elements.

WEAR AND HARDNESS

To repeat my understanding of wear again: hardness is really not a good issue to determine wear; the content of carbon and alloying elements and the microstructures are much more important. This is demonstrated even better in the next Illustration 28 taken from relevant literature, a paper on tool steels. It shows very nicely (of course always with the same wear parameters, conditions) that the wear resistance increases strongly with an increasing content of carbon and carbide, while the influence of hardness is marginal.

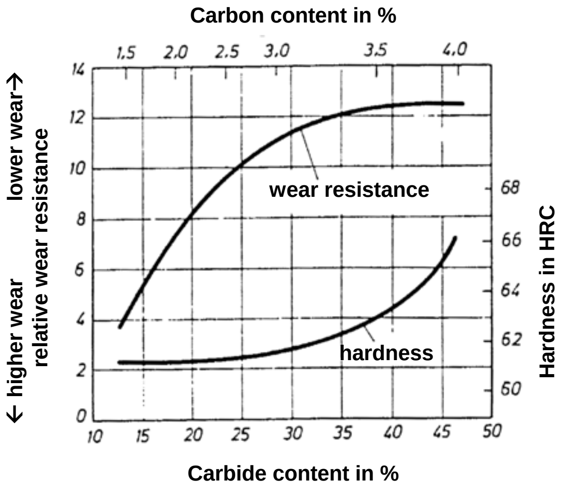


Illustration 28: Relationship between carbide content, or carbon content, hardness and wear resistance [12]

Illustration 29 shows how much wear is influenced by alloying elements. Here an “alloy equivalent” is formed, basically for carbide-forming elements, where the elements, which build up very hard carbides, are heavily weighted. Wear improves with increasing “alloy equivalent”, hardness is not even mentioned!

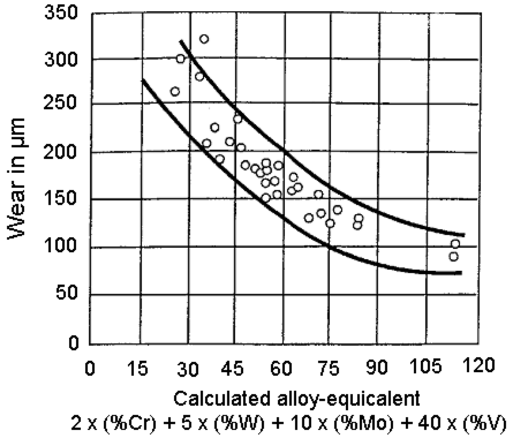


Illustration 29: Wear versus alloy equivalent (Range of alloys: 0.30-0.44 % C, 0.02-0.38 % Si, 0.31- 0.83 % Mn, 1.18-0.03 % Cr, 0.08-3.04 % Mo, 0.26-1.92 % V and 1.42-5.85 % W) [13]

This strong influence of very hard carbides on wear gives us the explanation for all "new" developments of materials which are exposed to wear, like tools of any kind and also rolls for rolling mills are included in this explanation as well.

We will return to this later on, when we discuss rolls more in detail, chapter 4.8.1.

3.6. FRICTION

To move one component relatively to another one, both pressed together by some load, a force is necessary. The amount of force depends on the surface conditions (shape, roughness) of both parts and on the coefficient of friction between the two partners.

In rolling mills there is always friction between rolls and rolled material in the rolling gap. The situation in a rolling gap is somehow very complicated: there is sliding in both directions, forward and backward extrusion with different continuously varying relative speed, and between the forward / backward extrusion there is static friction. In case the rolling speed is too high then extrusion goes only in one direction, static friction and “slippage” no longer occur and chatter of rolls is the next step, moving, non-moving, short time alternating bite and no-bite, chapter 4.8.3.

Separation force in a mill is calculated as force to reduce the cross section of rolled material plus friction between rolls and rolled material. And vice versa, it is state-of-the-art to calculate friction from the calculated and measured separating force. It was found (see chapter 4.8.3) that the friction changes during a rolling campaign.

This raised the discussion recently about the coefficient of friction of various roll materials but nobody discussed the most important aspect of friction, “the surface conditions” and the change of the roll surface during rolling, most significantly the fire-crack pattern.

CRM (Centrum Research de Metallurgie) published results of the coefficients of frictions for various roll materials measured under scientific conditions in the laboratory, Illustration 30. They found that there is no significant difference in the coefficient of friction for these materials – contrary to the results from the mills.

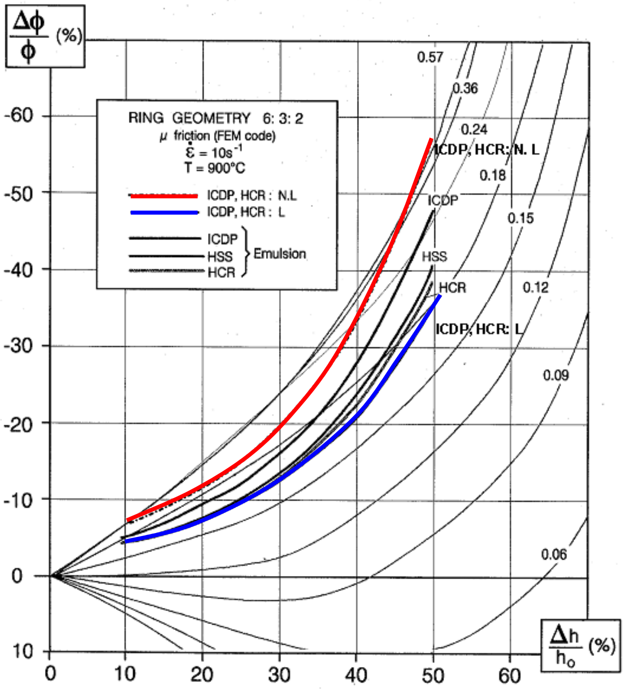


Illustration 30: Evolution of the coefficient of friction of different roll grades with and without lubrication (FEM-Coulomb model with barrelling; L. … lubricated, N.L. … non lubricated [14]

This proves that friction between roll and rolled material is basically a question of roll surface and not of the coefficient of friction between the materials. For curiosity's sake: even though there is no major difference in the coefficient of friction between different roll grades, some strange papers have already been published about how to solve this (non existent) problem metallurgically with some changes of microstructures.

The coefficient of friction of roll materials is not an issue of mayor interest for rolling mills but more work is needed on rolling conditions and how they influence the surface of rolls.

3.7. PHYSICAL PROPERTIES

Rolling mills that are fully computer controlled are based on rolling simulating models, which take many detailed parameters into account. The goal is to calculate the rolling gap - to achieve perfect rolled products - at any time of the rolling process, from the start after roll change through the period of warm-up of rolls to the stable rolling conditions. For this calculation many parameters and physical roll material properties are required and the roll makers are asked to provide these figures.

1. Young's modulus? This question is easy to answer for the materials used, but it does not give the right answer for double poured rolls with very different materials for shell and core (often made of grey iron). But the two different Young's moduli have to be combined. And the Young's modulus of the roll will change when the working layer/shell is reduced during roll life from new to scrap size of compound rolls. The remaining shell thickness at scrap size will vary from roll to roll too.
2. Poisson's ratio is well known, chapter 3.2.1., and it is always the same for technical materials most in use: 0.3 for elastic- and 0.5 for plastic deformation! Only for grey cast iron with lamellar graphite is everything very different (chapter 3.2.3.), but I am absolutely sure that only very few people ever took this strange obscurity into account!
3. Coefficient of thermal expansion? This coefficient is not just one figure for each material but a function of temperature, and it is almost a constant number for a small temperature range (20 to 100°C). Temperatures in a roll also change with time and local position.
4. Heat conductivity? To my knowledge no roll maker is capable of measuring heat conductivity - so this figure is taken from relevant literature, Illustration 31, for example. But this figure should always be the same for the same type of material - I wonder whether all roll makers will use the same source of wisdom.
5. Coefficient of heat transmission? This coefficient is indeed of high importance - but this question has not yet been asked! Heat transmission will be influenced strongly by the surface of rolled material and rolls. A very important question will be the existence and thickness of oxide layers, secondary scale etc. (see also chapter 4.5.) – but not even the question of how – and of what type of scale – these layers are formed.

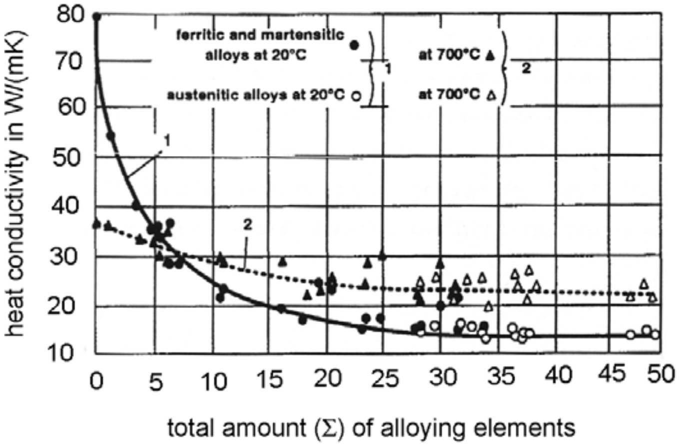


Illustration 31: Heat conductivity of iron base alloys at room temperature and elevated temperatures [13]

Instead of looking for some strange results without verification I feel that it would be much easier and more useful to try some random figures in a model and change parameters until the result fits the reading or result observed in a mill.

3.8. REMARKS ON MATERIALS USED FOR ROLLS

Table 1 showed the material used for rolling mill rolls. In the previous chapters 3.1. to 3.7. the laws of material science were presented and discussed, always taking account of their "limits" and useful application. Due to the high temperature gradients in the rolls during manufacturing (casting - solidification; heat treatment) rolls with a large cross section never consist of a uniform material with uniform properties. Even with a uniform composition there are different properties on the barrel surface, the necks and inside a roll. The properties of a roll can be controlled in different ways for various parts.

The stresses and their distribution in a roll due to the loads of the rolling process are very complex and vary widely. Some stresses have high gradients perpendicular to the roll surface - like Hertz'ian pressure or thermal stresses during rolling hot material and good roll cooling - some should simply be considered as the result of static loads - like torque from the driving motor. However all kinds of stresses may lead to roll damage, and wear is another big issue.

So - roll users want everlasting rolls and the maximum of all properties (greatest hardness, highest strength, no wear, best safety guarantee against all kinds of rolling accidents, ductility etc.) and roll makers do their very best to meet these requirements. Ultimately special new materials were developed just for use in rolling mill rolls and some well-known materials were adopted for rolls (like HSS), but they were never used before for any construction part or tool of similar dimensions.

The task is always to optimise the different properties, mainly strength, wear resistance and safety against fire-cracks and all sorts of damage due to rolling accidents. This process of optimising - basically choosing the right composition, heat treatment and manufacturing process -always has to bear in mind the soundness and safety against any failure of the entire roll, which means developing the right microstructure and controlling distribution and level of residual stresses.

The main parameters for controlling the properties of a roll are:

- ↳ mono-, or compound roll (roll design)
- ↳ chemical composition of the material
- ↳ casting : mould design, temperatures, weights, inoculation, down-cooling
- ↳ heat treatment

According to the microstructure of roll materials there are different groups of grades:

1. hypo-eutectoid steel
2. hyper-eutectoid steel, ADAMITE
3. graphitic hyper-eutectoid steels
4. high alloyed materials like High-Chrome, HSS, Semi HSS...
5. nodular iron
6. indefinite chill cast iron, ICDP
7. special materials, like sintered carbides, ceramics, GHM

The materials related to one of the groups 1, 2, 3 and 4 can be controlled / influenced widely by heat treatment, however the structure, shape, size and amount of primary carbides in rolls is more or less given after initial forming and is unchanged after heat treatment (contrary to "normal tools") The maximum temperature during heat treatment is in most cases restricted by the liquidus temperature of core material of compound rolls, most frequently ductile iron.

The amount of carbides increases with the content of carbon and carbide forming elements (Cr, Mo, Nb, V, W ...).

The materials related to one of the groups 3, 5 and 6 contain graphite which forms during solidification. Graphite has a high impact on the performance of the rolls during rolling. There are many theories about how graphite changes the properties of rolls, how it improves the rolling performance, however here we will simply list the advantages but not the theories (most of which have been proved wrong):

- graphite makes smaller, finer fire crack pattern / networks
- graphite reduces the risk of spalls after rolling accidents
- graphite creates a better and smoother surface of rolls and rolled products

Graphite is crucial in materials of high content and / or hard carbides (ICDP, nodular iron). Graphite has no impact on wear. Wear resistance is based mainly on the amount and hardness of carbides. There is no doubt that the form of carbides is of great importance for the risks of spalls and secondary damage of rolls after rolling accidents (in particular a real network of carbides increases the risks and a "non-continuous carbide” network, NCC reduces it).

However, it should not be forgotten that nodular iron and ICDP rolls need enough graphite to perform well, and this is more or less controlled by casting (temperatures, inoculation) rather than by composition. To create graphite by heat treatment is not helpful - trials in this direction failed.

Most graphitic materials do not require high temperature heat treatment, but, if any, only some kind of stress release or martensite tempering.

4. ROLLS

4.1. DEMAND FOR ROLLING-MILL ROLLS

Steel the is major metallic material used every day in our world, more than 700 million tonnes are produced world-wide every year and most of the steel is rolled for long or flat products.

Aluminium is an important metal as well and it is also rolled mainly for flat products (for cans, foils, airline parts and automobile industries). We are concerned mainly with rolling steel.

Rolls are tools which have to take all kinds of stresses, loads from normal and abnormal rolling and changing with roll wear during a rolling campaign. Rolls are required to carry out the heavy work of reduction necessary for hot and cold rolling. Rolls never should break, spall or wear - they should give excellent performance and never cause any problems. But all mills are capable of spoiling any roll; mills are strong and many operations - even in fully automated mills - can go wrong, chapter 4.5. and 4.6.

The loading of mill stands is very complex in most applications, chapter 4.10.:

- Torque from driving motors has to be transmitted
- Separating forces create mill stand deflection
- Stress can be raised by roll design and by the rolled products
- High Hertz's pressure - not equally distributed from one end of the barrel to the other - is effective during rolling flat products in 3 (4, 5, 6, or more) high mills
- The linear load (t/m) between roll and strip varies widely according to the material rolled and rolling schedule strategies
- There is always sliding and friction between roll and rolled material, varying extremely in section mill rolls, setting up different friction patterns.
- The roll surface is exposed to rapid changes in temperature (fire-cracks!)
- The environment in the roll gap may consist of various chemicals with or without mechanical parts, which may have a high impact on wear properties
- The surface conditions of a roll change during a rolling campaign by "polishing", "fire-cracks", "wear" etc.
- Even the shape of a roll is changed due to uneven wear.

Rolls are regularly redressed to rebuild the desired shape and to eliminate the worn, fire-cracked and fatigued surface, and they never last as long as roll users would like.

There is a long history of research and development of roll grades and progress continues. The final goal is always to increase the quality of finished rolled products (tolerances, surface) and at the same time to increase the length of campaigns, to improve roll performance and to reduce the risks of roll damage.

Rolls come in a wide variety of sizes, the smallest roll weighs only a few kilograms, the heaviest around 250t a piece, and the variety of grades used is also wide, from ductile iron to tungsten carbide, covering all kinds of tool steels and special steels, used only for rolls. For cold rolling forged steel is state-of-the-art, cast rolls are in use in many applications, and sintered tungsten carbide is used as well as “cladded” or ESR-rolls (see Table 1).

So as you can see, it is quite a task to give some general information on rolls. However, I hope it will be useful, even though this book is concerned mainly with hot and cold rolling of flat products - this is the field of my experience - but the laws of material science are applicable to all kinds of rolls.

At present relevant literature on rolls is very limited and I hope that this book can fill a vacuum. For general reference there are a few publications, but very frequently I found little real understanding of the special problems of roll mechanics. I have published a number of papers on special subjects, but here my experience is gathered in one book. Everybody should feel free to use and have access to relevant literature for more details.

Rolls in general are highly stressed tools which are subject to wear. There are specifications of rolls, specifications on mechanical properties, specifications following known or unknown standards. These specifications may be based on some research background or, as often as not, they simply follow the requirements of “Statistical Process Control” (SPC).

The grade of all rolls, the quality of rolls of all roll makers have to be justified by the use and performance of the rolls, if enough data are available. Ultimately the cost of rolls per ton of rolled steel is decisive. But roll makers and roll users have to know what they are doing, what they expect from rolls and how they should treat their tools.

Modern rolls are now designed to withstand normal rolling operations, and they do - but what happens, if rolling accidents are normal in operating a mill?? Then everybody is in trouble.

The choice of the optimum roll grade is a balance between performance and sensitivity to mill accidents!

4.2. REMARKS ON ROLL MAKING

There is a huge variety of rolls, applications, production procedures / technologies as well as of roll grades - and no standards exist. This is a field for the specialists. However, it is also a very small market. Most of the roll-makers run small companies (often less than 300 employees), the roll-users are often parts of big conglomerate giant steel (Alu-) companies - and rolls are only tools but necessary ones.

Under normal rolling conditions and without “roll problems” only a very limited number of specialists are responsible for the rolls, these important tools. But as soon as a roll disintegrates in the mills, for whatever reason, or perhaps the rolled product does not meet the requirements - everybody in the rolling mill immediately becomes a roll expert. And they all start discussing roll properties, roll making, roll testing and sometimes they forget that there has been a rolling accident - but it is always easy to blame others for a problem.

Rolls are
- Cast
- Forged
- Sintered (or Hot-Isostatic-Pressed; HIP)
- Produced by other methods

All technologies have their advantages, disadvantages, and limits for production. These limits may be caused by:
- Roll dimensions
- Roll grades (content of C-, alloying elements)
- Required hardness or wear resistance
- Manufacturing costs

There are of course areas that overlap, where rolls made by different technologies are available but there is no general maxim "cast better than forged" or vice versa. Competition is always tough and only the final result "cost of rolls in relation to steel rolled" influences the final decision. Conflicts often occur concerning back-up rolls, especially for hot rolling of flat products and some highly stressed section mill rolls (for instance for "pilings").

It is not roll making technology that is crucial - but the control of technology, the procedure always has to be under control. This depends on roll makers' care and understanding of his technology. This becomes evident by comparing the scrap rates of different companies - a well- kept secret - or any other quality figure. Reliability, reproducibility is not a question of roll making technology but just of procedural control.

For a long time the ratio of roll costs to tonnes of rolled material has been decreasing for various reasons:

- Better mill technology
- Better roll performance

but not for the reason of lower roll costs. To develop improved rolls with better performance grades and to introduce new manufacturing technologies roll makers have to earn money. "Low price" rolls are ultimately counterproductive!!

The expertise of roll-makers includes:

- Understanding the roll application (load, speed, roll cooling ...),
- Choice of optimum material
- Production of sound rolls without defects
- Choice of adequate heat treatment (strength, hardness, residual stresses ....)
- Ability to machine the rolls to meet the requirements of specifications and prints
- And last but not least the ability to follow changing requirements in the market place

In general roll-makers have to overcome some technical problems:

- Many rolls are damaged/destroyed in mills and a mutual understanding of the reasons for failures is required for long term co-operation between roll-user and roll-maker. Who is to blame for damage, who pays?? Technical research or a detective may find the answer - but the results must be agreed upon by everyone!
- The design load of rolls in a mill is never actually the random, the mean load. Normally rolls are subject to less stress than their design would allow - but in the case of rolling accidents stress may be much higher.
- Rolling conditions can be described in general [15], however they are never stable, they can change within each campaign from good to worse (wear) and frequently do.

- Some mills experience roll problems frequently (e.g. "edge spalling"/or "banding") and very similar mills do not have these kinds of problems. It is certainly not a roll problem - but the roll-maker is nevertheless asked to help to solve this problem, to sort it out. And even if two mills were exactly the same - they would be run differently, with different performance rates or kinds of problems.
- Rolls are rated by performance on the assumption that statistics equalise all different experiences of the roll during its life. But is that true? Can the performance be manipulated? Yes it can. It has been proved, maybe not on purpose - but by accident. Anyway: bad rolls are not always bad; good rolls not always good!

Enough complaints!

High-tech roll-makers try to increase the performance of their products continuously in order to stay in the market - but the roll market volume decreases, even with increasing steel- (and aluminium-) production volume, because the rolls perform better in the mill. Globally the number of roll-makers is declining - and some major roll-makers extend their market shares by acquiring other plants, chapter 5.

COMPOUND ROLLS

The design of rolls always has to take two absolutely different requirements into consideration

- Maximum strength to take separating forces, torque, high pressure between work- and back- up roll, etc.
- Maximum wear resistance in the contact area between roll and rolled material

As shown earlier, these properties cannot be achieved easily with one single material.

The solution of this dilemma is relatively easy for forged steel rolls used for cold flat rolling, by surface hardening of the barrel, (state-of-the-art until nowadays) and high-tech materials guarantee hardened zones large enough to reach the scrap diameter of work rolls without re-hardening. This applies - at a lower level of hardness - for differential hardened back-up rolls (forged or cast) as well.

However forgings are limited in the composition of the material, especially in carbon content. For the hot rolling of sections and flat products high carbon content turned out to be superior to "low" (≤ 1 %) carbon content. “Clear chill rolls” were for a long time a dominant solution. The chilled barrel of high carbon cast iron solidifies as white iron of high-carbides/cementite content, while the rest forms almost carbide-free grey iron with lamellar graphite. This leads to a high wear- resistance barrel surface area and relatively strong core and neck material. (However, most roll makers lost the manufacturing capability for this material because they changed their melting furnaces from open hearth to other equipment.)

To overcome this general problem of providing a high wear-resistant barrel / high strength material elsewhere - various technologies were developed. The common method for all these is to use different materials for the working zone of the barrel and the rest of the roll.

The most popular method to produce rolls with 2 or more different materials is the double pouring of cast rolls. Double pouring of cast rolls can be achieved by static casting, by the slide gate method, by spin-casting or by other high-tech methods. Spin-casting is becoming widespread throughout the world.

First the high alloyed material is cast into a chill mould and after solidification the other material is cast. Within certain limits materials vary greatly and can be used for shell and core materials, even grey iron - with lamellar or nodular graphite - is the most frequently used core material.

But as everybody knows double poured steel back-up rolls are also successful with steel core material of low carbon content. In any case from the view of solidification, the easy way is always when the carbon content is higher and therefore the liquid temperature of the core material is lower than that of the shell material.

For double poured rolls "the bond" is essential. This means the strength of the interface between shell- and core material, and because this area is prone to micro-structure irregularities of any kind, special procedures have been developed to assure the bond.

Different materials are used for the different requirements of the roll and therefore double-poured cast rolls "easily" control (hardness and) wear resistance of the working layer of the barrel - one material - and the mechanical strength of the rest of the roll - the other material - and the distribution of residual stresses.

I would just like to mention one argument which is frequently discussed: the "tough" core material. No "tough core materials" are needed; in the situation of plain strain for big cross sections plastic deformation is impossible. In reality what is required is strength and sound material - that is all! The core material is never capable of plastic deformation for stress relieving "due to" (I hate arguments but it is true) a permanent hydrostatic stress situation which does not allow plastic deformation, see chapter 3.2.2. (tensile test).

In case: $\sigma_1 = \sigma_2 = \sigma_3 \rightarrow \tau = 0.5 \cdot (\sigma_{max} - \sigma_{min}) \equiv 0$!!!

Another method for rolls of two different materials is to have rings fitted - shrunk, glued or mechanically fixed - on arbours. This has become outdated for back-up rolls but remains very successful for horizontal rolls of universal mills, for wire rod mills (small section mills as well) and other configurations.

Surface re-welding of rolls with high wear-resistant material has been tried since time immemorial but in most applications this method failed. Nevertheless for a few applications (edger roll, crushing roll for stones and minerals) it is still used successfully today.

"Cladding" is a very special method to cast high alloyed material on to a steel arbour. This method was developed in Japan and to my knowledge is in use only there.

4.3. HARDNESS OF ROLLS

Hardness in general and problems concerning measurement of hardness were treated in chapter 3.1. With rolls everything is worse because roll materials are extremely hard and therefore strongly influenced by work-hardening (on the lathe or the grinder) and tempering (on the grinder). For the impact of hardness on roll properties, especially on wear, see chapter 4.8. Some people even believe that “everything improves - the higher the hardness”. This has been proved to be incorrect. Sometimes the contrary is valid (chapter 3.2). Other parameters do have a higher impact on roll properties like composition (chapter 3.5), microstructure and residual stresses (chapter 4.4).

This chapter will deal with statistics and variations in hardness readings because this is an essential issue for all kinds of specifications and discussions on hardness.

The barrel surface of a “normal size” work roll for hot rolling (600mm < diameter < 800 mm; 1250 mm< barrel length < 2200 mm) has a total area of some square metres. For many reasons the hardness on this area is not uniform, but nobody really pays attention to that. A typical hardness distribution of a new, unused roll is shown in Illustration 32. After some runs in the mill the distribution becomes even worse (or better?), Illustration 33. The centre part of the roll, which has been in contact with hot strip, is now tempered, the hardness here decreased and is lower than at the edges of the barrel. The standard deviation increased and is by far larger than any specified tolerance. Usually specifications allow a range of 5 Shore, which is never met, but this is irrelevant - very good!

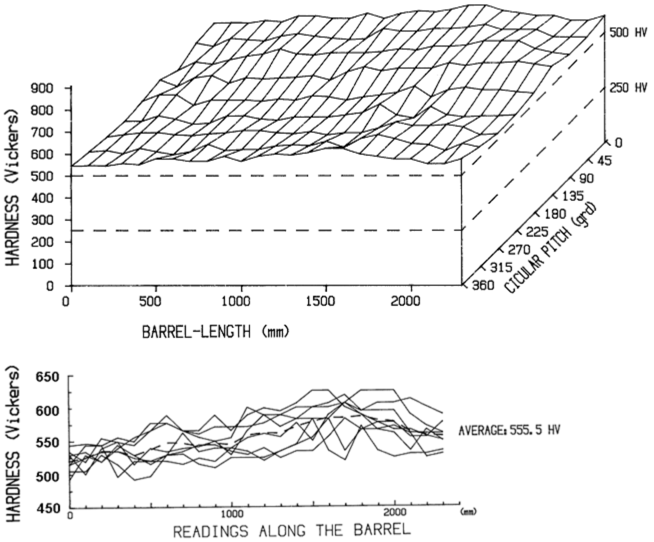


Illustration 32: Hardness distribution on the surface of a High-Chrome work roll for HSM, Ø759 x 2235 mm, average hardness = 555.5 ± 30.5 HV

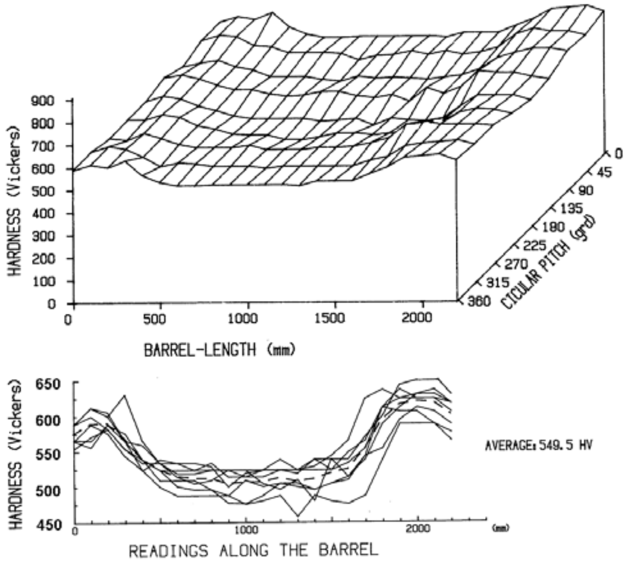


Illustration 33: Hardness distribution on the surface of a used High-Chrome work roll for HSM, Ø850 x 2300 mm, average hardness = 549.5 ± 46.2 HV

Only the average or the mean can, we hope, fall into the given range, but if this does indeed happen it may simply be good fortune.

To prove this, Illustration 34 shows the statistical distribution of many (more than 1000) rolls' average hardness readings on barrels of high chrome rolls and the next Illustration 35 demonstrates the same for neck hardness. It is very evident that standard deviations are beyond all specifications. If the specifications would follow the σ - idea, then we would need large tolerances, ranges of at least 20 Shore, but this would be realistic.

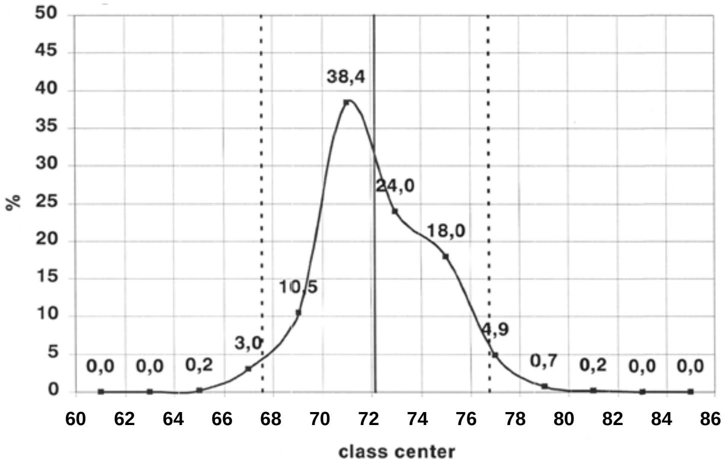


Illustration 34: Barrel hardness of High Chrome work rolls for HSM,
average hardness = 72.2 ± 2.6 ShC, more than 1100 rolls

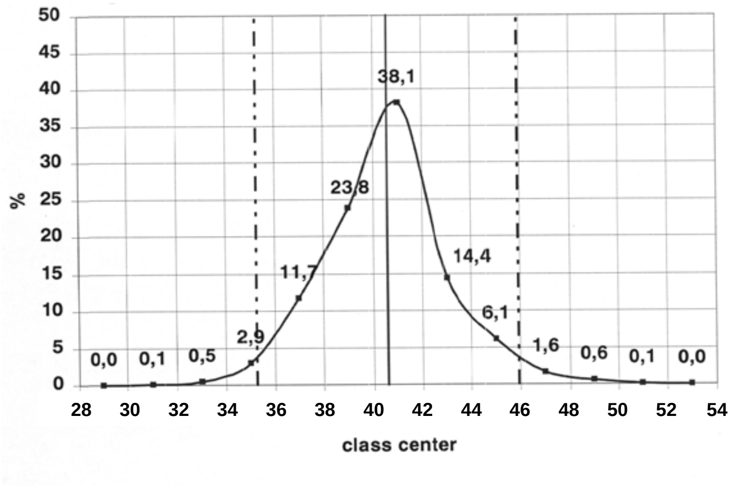


Illustration 35: Neck hardness of High Chrome work rolls for HSM,
average hardness = 40.7 ± 2.9 ShC, more than 1300 rolls

Besides dimensions and tolerances most prints / drawings of rolls and orders of rolls specify hardness (and sometimes mechanical properties for the rolls as well). This is a tradition - and some people representing *statistic process control* (SPC) recently tried to narrow the ranges because they believed that this would improve roll quality. However, they knew nothing about rolls and it was not really a serious proposition and thus created more problems than it solved.
Roll makers only face problems when someone - for instance, an inspector from a different firm - wants to see how hardness is measured on a roll. The consequence of false hardness readings on rolls is negligible because the influence on roll properties is only slight. (See chapter 4.8. and others).

One of these techniques to increase the hardness is frequently used on necks, namely work-hardening by cold rolling with certain tools. However - see chapter 3.2.5. - it is not very effective because the neck material is “soft” and sometimes it creates small surface cracks.

Hardness readings are necessary for roll makers and roll users (especially for back-up rolls for cold rolling to keep processes under control (chapter 3.1.4.). Hardness readings, however, are definitely useless for roll specifications (chapter 4.11.).

4.4. RESIDUAL STRESS

Residual stresses - acting as pre-stress - do have a high impact on the strength of components, in particular on rolls. Compression stresses increase fatigue strength (chapter 3.3.), reduce crack propagation (chapter 4.5.2.) and reduce shear stress at the roll barrel surface and work-hardening (chapter 3.2.5.). Tensile residual stresses may cause roll breakage, chapter 4.5.1.

Compression and tensile residual stresses in a roll compensate each other over the cross section of the roll. The right level of residual stresses - high compression versus low tensile - has to be controlled.

Rolls normally do have residual stresses, two-dimensional at the surface, three-dimensional in the volume. At the surface the radial stress is zero and the longitudinal (axial) stress is also zero at the barrel edge - but, at the main part of the barrel (starting for work rolls for hot strip mills or similar dimensions about 100 mm from the barrel edge) axial and circumferential (tangential) stress are equal in size and sign. At the centre-line, close to axial area of the roll, tangential and radial stresses are equal in size and sign. Here the relation of longitudinal to tangential / radial stress is given by the relation of roll diameter to length. Which stress exceeds at the centre-line the material strength first creates a spontaneous breakage of the roll. The fracture may be perpendicular to the axial direction in case the longitudinal stress is too high first, or the fracture may happen in axial direction (in most of these cases like a "Mercedes Star") when the tangential / radial stress is too high first.

If the residual stresses are measured at the most useful spot, in the middle of the barrel (and barrel length greater than two times the diameter), then circumferential und axial residual stresses have to be equal in size and sign (see above). The mean or the average of both main stresses is the true result for both (all) directions. The measured difference of the main stresses is an indication of the reliability of the measurement. In case one stress is more than 50% higher than the other, it is recommended to repeat the test.

There are formulae in use to calculate the compensating stress in the centre of the roll (but there is of course no method to test it non-destructively). In the past the results were sometimes proven experimentally. The assumption is always that the hard part of a roll, the working layer (the high alloyed working layer of compound cast rolls or hardened barrel area of forged rolls), takes the compression and the "core" the tensile stress.

It is highly fashionable to calculate residual stresses by computer-simulation methods. However, traditional roll makers rely on measurements. The simulation of residual stresses with the model of inverse shrinkage was done and the results correspond well to reality. However, this is no way to calculate the real value of residual stresses, it is helpful only to understand the principles of residual stress distribution.

There are two causes of residual stresses in rolls but both are connected with thermal gradients during cooling down from casting and forging or from high temperature heat treatment.

One influential factor on residual stress is built up by plastic deformations at and below the surface while the surface temperature continues to decrease and the inner part of the roll is still at a much higher temperature. The outside material shrinks but it is blocked by the interior: the outside, two-dimensional stress, easy for plastic deformation - the inside, even hot material with a low limit of elasticity but with three-dimensional stress of same sign (compression) cannot move and is unable to take plastic deformations. When the roll is completely cooled down the outer part is too big, the inner part too small. But there has to be compensation in the roll and this results in outside compression residual stress and inside tensile residual stress.

There are three risks for damage during roll manufacturing:

- In cases where shrinkage or outside plastic deformation is blocked by some mechanical hindrance (mould too strong, fire-cracks in the chill moulds) a hot tear may happen.
- In cases where high temperate quenching is too strong, too rapid so that one or the other surface stresses reaches or exceeds high temperature strength (normally it is the tangential stress - but this is a question of the proportion / dimension of the roll) then a hardening crack will occur.
- If after cooling down the internal tensile stress exceeds the material strength, then an internal crack is formed, which might break the roll into two (or more) pieces. These cracks are most frequently orientated perpendicular to the axis - but not necessarily!

Heat treatment of rolls is most critical for residual stresses but if well controlled, residual stresses are controlled as well. In any case it is highly recommended to check all rolls with ultrasonic methods for internal soundness.

In this case the risk of breakage increases when the surface of the roll (high internal tensile stress) is heated up; the thermal gradient - outside hot, inside still cool - increases the tensile stress and the roll may break up. This may happen during heat treatment "stress relief", in a roll makers plant - or in the mill (see next chapter).

The release of residual stresses that are too high is a problem of roll makers. The roll surface area has to perform plastic deformations during tempering which depends on the actual surface stress and on the temperature and time-related yield point. The centre of a roll - always under close-to hydrostatic stress conditions - does not help to reduce residual stresses. It is not a question of toughness, only in the case of internal cracks!

The second influential factor on residual stresses is caused by microstructure transformation (see TTT-curves!). An austenite - martensite transformation takes place at temperatures below 300° C and it increases the volume. So the outside part of the roll expands, causing more compression residual stress outside and consequently more tensile residual stress inside. This increases the risk of internal cracks.

Some roll grades have to be tempered after quenching from austenite temperature several times. This may help to reduce residual stresses, but as long as retained austenite is transformed to martensite - with a higher volume than austenite - residual stresses increase. But whatever the level of residual stresses might be, the worst for the life of a roll is non-tempered martensite because this material is very brittle and of very low ductility so that cracks are often formed and propagate even under high residual compression stresses. Residual austenite is less critical for roll life than non-tempered martensite.

Residual stresses - comprising a compression stress on the outside and a tensile stress internally - are most essential for roll life. Residual stresses act as a pre-stress forming a component which is extremely important for fatigue of all notched parts (see chapter 3.3.2 - fatigue strength, Smith diagram).

Rolls are “notched high stressed rotating tools” that operate under alternating loads. In addition we have cracks, mainly fire-cracks, in section mill rolls or on work rolls for hot rolling of flat products, and cracks are "very sharp notches".

Only with ("high") residual compression stress crack propagation is slow or even stopped. Therefore for some rolls it becomes possible to accept cracks without breakage and spalls. However, the “right” level of residual stresses is dependent on the roll grade and this precondition has a high impact on fatigue level and roll life.

One example: High Chrome iron rolls have "by nature" a much higher level of residual stress than ICDP and consequently High Chrome Iron is very forgiving of any fire-crack maltreatment. However, in the same application ICDP is very sensitive to fire-cracks and frequently shows bad spalls related to fire-cracks. Whether fracture toughness might have some impact on crack propagation or not is hard to decide – the value of fracture toughness of these materials is in any case low and variation high – an speculation, which can not be proved.

The fillet of back-up rolls should never have tensile residual stress (or simply no compressive residual stress), otherwise there will be a problem.

Measuring residual stresses is a complicated and a time-consuming procedure - but roll makers are capable of doing so mainly for research purposes or for very special reasons. Normally only single, carefully chosen spots are measured. Non-destructive methods are available, however the ultrasonic measurement method has not yet been developed for rolls today (there is a chance theoretically) and the X-ray-diffraction method is not reliable because the depth of investigation covers only a small part of a millimetre. Therefore everything relies on the surface preparation (even more so than hardness readings). A state-of-the-art method is to drill a hole or a ring up to 5 mm deep into the surface and to measure the release of stress with strain-gauges close to the hole or in the inner part of the ring groove.

Some remarks on frequently discussed issues of residual stress:

- For the same roll grade there is definitely not a strong relation between barrel hardness and the level of residual stresses - this would make everything really easy! Both parameters are certainly influenced by heat treatment. Heat treatment can, however, be executed in different ways with the same final hardness but with quite different residual stresses!
- Rolls with very low levels of residual stress were tested for different reasons but these rolls failed due to excessive crack growth from fire-cracks and other cracks, initiated early in roll life.
- Secondary residual stresses, induced in the roll surface by machining, whether by cutting on a lathe or during grinding, were discussed, but these stresses do not have any influence on the life of a roll.

4.5. ROLL DAMAGE CAUSED BY ONE SINGLE LOAD

4.5.1. THERMAL BREAKAGE

Whenever a roll is put into service and starts to work, the surface heats up - this is true for both hot and cold rolling - to a mean temperature, which stabilises after some rolling time. During this period there is a temperature gradient in the roll, hotter outside, cooler inside.

Consequently the outer part shows more thermal expansion than the inner part of the roll. This is what creates thermal stress, compression stress outside - tensile stress inside.

The thermal tensile stress adds to the residual tensile stress and in case total tensile stress reaches the strength of the inner material - (which is sometimes not as good as expected) - then a crack is created and usually the roll falls disintegrates.

The lower the initial temperature of the roll is when it is put into the mill, the higher the risk of thermal breakage. Failures of this kind occur much more frequently in winter (low outside temperatures) than in summer.

Actually three factors are important for thermal breakage:

- Thermal gradient
- Strength and integrity of core material
- Residual stresses

Formerly, about fifty or sixty years ago, thermal breakage happened quite frequently, work rolls of plate mills were especially prone to this failure. At that time clear chill grades and later ICDP-grades with lamellar grey iron core material were in service and the strength of core material was very low (≤ 200 N/mm^2). To reduce the number of failures it was state-of-the-art to preheat these rolls, which bore some risk in itself, but methods of controlling this were soon developed. Anyway it is still highly recommended not to start rolling with a roll temperature below room temperature (≈ 20° C).

The strength of the core material today is so much higher than before, especially since ductile iron is used (for other reasons as well). However, in the area close to the centre-line of a roll, where the highest tensile stress builds up, the material strength is always at a minimum due to casting segregations, shrinkage, porosity, etc.

Residual stress has a high impact on thermal breakage as well and for all compound rolls roll-grades shell thickness is important. With the assumption of constant compression residual stress σ_{shell} in shell material and constant tensile stress σ_{core} in core material, it is easy to calculate the tensile residual stress when we call the size of shell area F_{shell}, and that of corematerial F_{core}.

$$\sigma_{shell} \cdot F_{shell} + \sigma_{core} \cdot F_{core} = 0$$

$$\sigma_{core} = -\frac{\sigma_{shell} \cdot F_{shell}}{F_{core}}$$

This shows directly that the stress in core material is proportional to the ratio of the area of both materials (high shell thickness, large area of shell, small area of core-material) and the risk is always increasing, as well as the level of (desired) compression stress, which is related to the shell material. These criteria have to correspond well:

- Shell thickness - large enough to reach designed scrap size, but not too high.
- Residual compression stress - high, however not too high.
- Low thermal gradient in the roll during start up period (for each campaign!)

A strange example of thermal breakage should be discussed because of the peculiarity of the situation. This used to happen with billet mill rolls of ductile iron (without any heat treatment of the roll).

These rolls tended to break during rolling at the largest cross section between the grooves, Illustration 36. The explanation for this failure - which seems to contradict all experience from mechanical engineering - was given in relevant literature. The residual stresses (always compression stress outside, tensile stress in the inner part of the roll) are reduced in all areas where grooves are machined into the roll but remain high in the areas between the grooves. When these rolls are heated up during the rolling process thermal stress is added to residual stress and when the total tensile stress - at a maximum between the grooves - reaches the strength limits of the material, thermal breakage occurs between the grooves; thermal breakage, no bending fatigue or anything else. This is strange, isn't it?

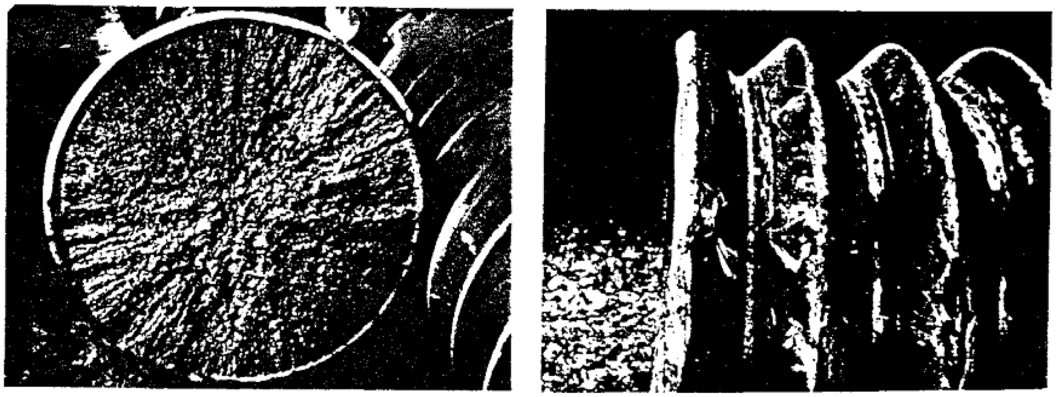


Illustration 36: Broken grooved roll with fracture in largest cross section

4.5.2. TORSIONAL BREAKAGE OF DRIVEN ROLL NECKS

Fatigue-torsional failure of necks is observed very rarely. Today, as in the past, in most cases when necks break they show the typical topography of a fast, brittle burst, with fraction areas inclined at 45° to the axial direction (see Illustration 37).

Illustration 37: Neck failure from drive end torque

Whenever there is a severe rolling accident - e.g. the rolling gap is too narrow - driving motors build up a huge torque moment and because these motors are so strong and powerful one part of the total system is supposed to break down:

- The motor may burn
- The spindle may deform,
- The roll neck may break.

It is to be hoped that the roll neck breaks because this is by far the lowest price version and easiest to repair - just change the rolls! If the roll neck does not break severe damage may happen to the spindle and/or the motor. It has sometimes been experienced that the spindle removed the motor from its foundations …

For roll design and for establishing roll specifications, questions often arise about the torsional strength of roll material. Then everybody starts to calculate the motor torque moment, speed etc. - but there are no figures for torque strength available anyway! After many years of experience with rolls I can state the following:

- Torque fatigue failures have hardly ever been experienced (reasons: the notch factor is always small; the number of real cycles is always very low - contrary to roll bending, surface load etc. - because only one cycle per coil) so torque can be considered as a static load;
- Neck breakage/failures were never experienced besides mill accidents - luckily necks are safe for normal rolling conditions;
- For calculations of static torque strength it is allowed (and usual) to take 90% of tensile strength as a fact.

4.5.3. "FIRE-CRACKS"

A fire-crack pattern on the surface of rolls used for hot rolling with water cooling of the rolls is most common.

Fire-cracks might be initial cracks which could develop into deeper cracks and spalls. Certain procedures have been established on how to handle, how to regrind these rolls, depending on the mill stand and the roll quality.

A fire-crack pattern increases friction, chapter 3.6., which helps to increase roll bite. In a critical stand in terms of roll bite, see chapter 4.8.3., sometimes a “bigger” fire-crack pattern is intentionally “operator made” with very special rolling conditions to overcome a bite problem.

Fire-cracks have of course been known for a long time and various strange theories have been published which neglect all basic knowledge of the material sciences, therefore we will not deal with the relevant literature in this respect.
Results from practical experience are:

- The higher strength of roll material is, the wider the network of fire-cracks appears and the deeper the cracks are - in cases when fire-cracks occur.
- During rolling the fire-crack pattern builds up in the very first rotations of a roll.
- In hot strip mills the fire-crack pattern becomes finer from F1 to F2 to etc.; in the last stands it disappears. Sometimes it is not detected until the rolls are pulled from the mill, often the fire-cracks can be seen from the operator console.
- The worst fire-cracks are found after mill stops with a slab/strip in the mill, and are most severe in the early passes (rougher!).

During rolling heat from hot material plus deformation heat transfers to the rolls and penetrates the roll. The contact temperature between roll and rolled material is easy to estimate and the transferred volume of heat depends on contact time, heat conductivity of both materials and of the transmission coefficient, depending on isolating layers of oxides on the surface of rolls and / or rolled material.

When the heated roll surface with a thermal gradient perpendicular to roll surface during revolution of the roll is quenched by cooling water, surface tensile stress builds up. In case tensile stress reaches tensile strength of shell material cracks are initiated – fire-cracks. Surface cracks (this is what fire cracks are) only form under tensile stress. Actually fire-cracks are thermo-shock cracks which form under a very sharp cooling rate on the roll surface; it takes only a fraction of a second until the roll surface at a temperature higher than 500°C (for hot rolling steel) is hit by cooling water. The crack will relieve stress in neighbouring areas and the next cracks will build up during roll revolution as soon as the surface stress level reaches strength again. So during one revolution the whole barrel surface is cracked and the pattern builds up.

This explains the different fire-crack pattern of, for example, High Chromium and HSS (with higher strength) in hot strip mills. It can also be shown that due to higher heat conductivity of aluminium with very thin oxide layers the roll surface temperature is higher than when rolling steel. The risk of fire-cracks for rolls is high when rolling aluminium even though the temperature of hot rolled aluminium is relatively low.

Following this explanation it is easy to find a strategy to avoid roll damage by fire-cracks after mill stops with hot material in stands. Quenching of heated up areas after mill stops should be avoided, slow heat dissipation does not harm rolls! This means:

- In roughing stands (long contact length / time, high heat transfer): immediately stop cooling water, open the roll gap, push out the slab and give the roll time - without any water cooling! - for heat dissipation. This reduces the temperature gradient at roll surface.
- In finishing stands: do not open the roll gap (to avoid water quench of rolls), keep cooling water running until strip has cooled down (black) and the roll has cooled down by strip and heat dissipating into the roll. Then shut down - cooling water, open roll gap etc.
- After a severe mill accident change rolls, check roll surface and regrind rolls. Cracks of any kind are not allowed for some grades (ICDP), for other grades (high chromium, HSS) cracks should be closed at least before putting rolls back to operation.

Cracks of all kind - thermal or mechanical overload - grow progressively.

4.5.4. LOCAL OVERLOAD

Local mechanical overloads are an everyday occurrence and some intrusions, impression, bruises are always found. Whatever enters the gauge has to exit on the other side. We have seen an impression of screwbolt M80 - luckily on plate - which had fallen out of the mill stand. Normally it is not as dramatic as this but tail-ends of strip like to flip over and perform like crazy; wire from brushes in alu-hot mills break and get between work- and back-up rolls. All remaining steel/oxide from burning slabs is not always cleaned off as it should be, and this is hard material that enters the mill etc. etc.

Under normal rolling conditions everything is under control: there is no local mechanical overload. However, in the case of mechanical overload one or the other partner has to be deformed or it will disintegrate (at best it would be pulverised - no high overload). Choosing the right grade / hardness for one application we have to bear the following in mind:

- Section mills: in case of an impression or bruise in the last pass there is no alternative but to redress the roll. In case it happens in an early stand this is fate and has to be accepted.

- Hot strip mill: in most cases local overload is caused by "hot" metal which can easily deform. No problem: W.R. and B.U.R. may have the same hardness more or less. No risk! (Contrary to old traditions with "soft" B.U.R. - but this is history because higher wear resistance is required, see chapter 4.8.1)

- Cold strip can only be rolled / deformed with high tension of strip plus compression of the rolls (see chapter Mohr's circle – chapter 3.2.2.) and after the first cold plastic deformation work-hardening is high so that in case rolling accidents occur strip under uni-directional load cannot take more plastic deformation. Work rolls should not take deformation (then they would need instant redressing), so B.U.R. have to accept the local overload by plastic deformation (hopefully without a crack). But to achieve this, hardness of B.U.R. should be significantly lower than hardness of the W.R. This is a traditional rule but still valid.

4.6. ROLL DAMAGE CAUSED BY FATIGUE

There is all kind of fatigue damage found with rolls. Involved are rolls for long products and rolls for flat products, work rolls and back up rolls. Fatigue damage may start at the surface or sub-surface. The reason for a fatigue problem may found in too high loads in a mill, but more often, we have situations that "better rolls" can improve.

In some cases of fatigue, we discuss "notched components / rolls", see chapter 3.2.2., particularly Illustration 20 to Illustration 24. The "notch factor" and residual stresses (as pre-stresses) are crucial. Typical examples for fatigue breakage are barrels of section mill rolls or the filets of two-high mill rolls or of back up rolls.

However, there are cases of fatigue breakage without influence of designed notches as well, namely so-called saddle-spalls in double poured work rolls with grey / lamellar graphite iron core material for flat product, barrel edge spallings in work or backup roils and spallings in general.

4.6.1. FATIGUE BREAKAGE UNDER THE INFLUENCE OF DESIGNED NOTCHES

4.6.1.1. FATIGUE BREAKAGE OF SECTION MILL ROLLS

Illustration 38 shows a fatigue fracture of a section mill roll. Fatigue failure / breakage of the barrel of a roll indeed is very rarely. Normally even sharp notches of the pass design do not create fatigue problems for a roll.

Illustration 38: :Fatigue failure/breakage of a section mill roll.

To understand "fatigue" of a barrel of a section mill roll we have to consider some points:

1) Section mill rolls operate between redressing in the range of low cycle fatigue that is with far less than 10^5 cycles, where the strength is higher than the fatigue strength (more than 10^7 cycles, see Illustration 19).
2) The "fatigue strength" of notched components decreases faster and more severe with increasing number of cycles than that of un-notched components (see Illustration 19). The "very low cycle fatigue" of notched parts is even higher than that of un-notched ones. In consequence of that, we have to expect that for low cycle fatigue of section mill rolls the notch have normally no high impact.
3) "Normally" rolls have compression residual stresses at the surface (and compensating tensile residual stresses in the roll centre) which reduce the influence of notches on fatigue (see Illustration 23 and Illustration 24).
4) In case of acicular nodular iron rolls, it may (should not) happen, that there are no compression residual stresses in the groove surface (maybe there are even tensile residual stresses in the worst case), fatigue cracks will develop and the roll breaks, see Illustration 38.

5) Section mill rolls, which were heat treated with plain barrel, often show after machining of very deep groves (see for example the pass design of piling rolls) too low residual stresses. Fatigue breakage of these rolls may occur. The technical solution is an adequate heat treatment of pre-grooved steel rolls, which should create the right residual stresses in the finished roll body.

Sometimes, after a cooling problem in the mill, rolls will show some circumferential fire-cracks, which with some depth really reduce the cross section of the roll, and due to high load the roll may break under the condition of low cycle fatigue.

4.6.1.2. FILLETS OF ROLLS

The filets of rolls should never break even the number of load cycles is very high, especially for back up rolls. The notch factor of filets of back up rolls is always around 2 and hard to improve, diameters for barrel and necks are given and the space for the greatest diameter in the filet is limited, but it is always worthwhile to reduce the notch factor. Because the design is given the residual stresses are crucial.

In case a crack develops, the risk of breakage can be kept under control by using the science of fracture mechanics. When the crack in a particular area is initiated, it is possible to follow crack propagation by non-destructive methods. Even though there is no information about the statistic levels of alternative loads, crack propagation should be slow and in no case accelerating – when this starts to happen, the further use of the roll should be terminated. It is possible to calculate the critical maximal depth of the crack before breakage and by including a safety factor it is possible to avoid breakage.

This means there are two criteria to watch to avoid a catastrophic neck breakage: no accelerating crack propagation and rolls with a certain depth of fillet cracks have to be taken out of service. This was done with a number of back-up rolls in the past without one fatal failure (in this case crack depths of 100 mm were allowed!).

The problem is that all kinds of repair in the fillet of a roll like welding of the cracked area or machining a greater radius in the cracked fillet would make the bad problem worse. For this reason any fillet repair is forbidden.

It is a question of chance and of course some risk as well when deciding to tolerate rolls with cracks in the fillet. Naturally everybody is more reassured when there are no cracks in the fillet of back-up rolls. “High compression residual stresses” are urgently needed in these areas and it is state-of-the-art to control these. The compression residual stresses with a small gradient for rolls are a long-term solution for fillet areas while all the other traditional work like polishing, cold work-hardening (with too high gradients) are more or less ineffective and useless.

Sometimes corrosion fatigue - especially in mills for hot rolling aluminium where they use terrible cleaning agents in the cooling water (but it also happens in hot strip mills for steel) - further increases the problem. A good solution is to seal the fillet from penetration of these horrible chemicals into the fillet, as well as reducing nominal stresses by optimising the roll design and high residual compression stress in the fillet. (After a few failures subsequent rolls survived 25 years without any initial crack.) The experience of these roll examples show how technical problems can be solved with the help of roll maker. One other fact should be mentioned: with corrosion fatigue there is no safe operation at all, there is no fatigue limit; corrosion fatigue breakage is a question of alternating stress and time, chapter 3.3.3.

All people involved in problems like this should look for technical solutions in advance! Illustration 39 shows the influence of corrosion and corrosion protection. These Wöhler curves were gained through using a high-frequency testing machine (to reduce test time 3000 rpm). In practical applications corrosion fatigue failure would happen with a lower number of revolutions because with a lower frequency there would be more time for corrosion and necessary diffusion.

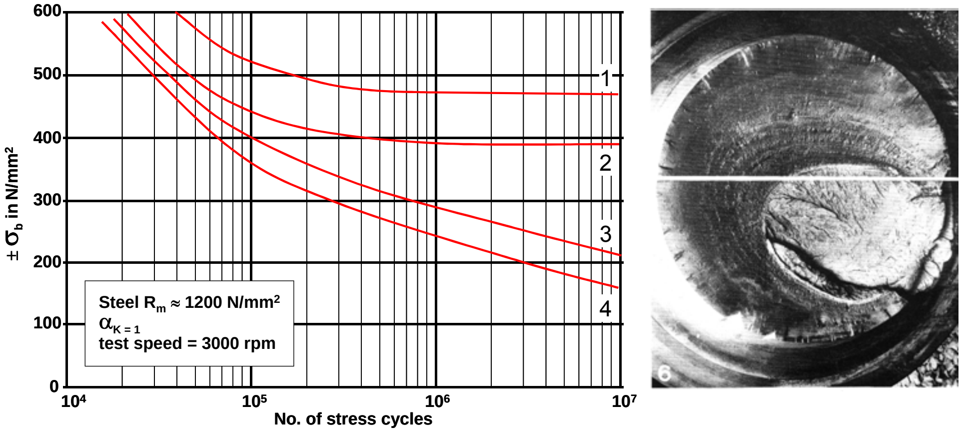


Illustration 39: Corrosion fatigue strength of steel (resolving bending test) – or neck breakage due to corrosion fatigue at low bending stress [10].

1) in air

in fresh water:

2) good corrosion protection, 3) bad corrosion protection (tectyle brown; zinc-chromate),

4) unprotected test piece

4.6.2. FATIGUE ON ROLLS WITHOUT INFLUENCE OF DESIGNED NOTCHES

4.6.2.1. SADDLE SPALLS IN WORK ROLLS

In the 1980s new rolling strategies were introduced in some mills and as a result many double poured work rolls made of High Chromium Iron with grey / lamellar graphite iron core and lamellar graphite failed due to heavy spalls (often called “saddle spalls”), which started definitely in the core material, something that had so far never happened before. It was proved that this fatigue problem was related to the strength of grey iron in combination with tensile residual stresses in the core material. Today in many high loaded mills nodular iron is used as core material. In the old days, when this problem became evident, it was also the practice to reduce the total level of residual stresses. This did indeed help to avoid spalls but these rolls became more critical concerning fire-cracks.

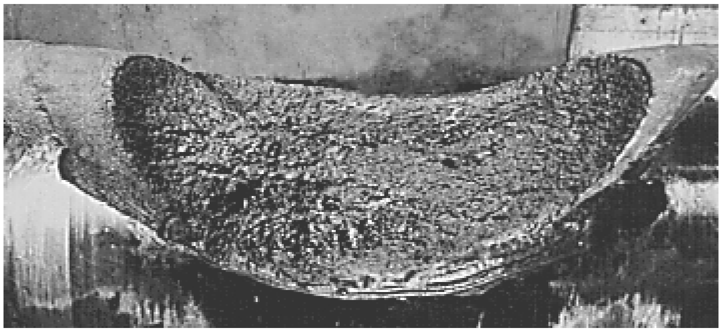


Illustration 40: saddle spall - “saddle” shaped fatigue spalls originating in the core material below the shell/core interface and breaking out to the barrel surface [11]

4.6.2.2. EDGE SPALLING

A very special fatigue problem is "edge-spalling", which in some mills happens frequently, in others very seldom. Edge-spalling may happen to work rolls or back-up rolls. Edge-spalling is a mill problem, not a direct roll problem, even though it may happen to rolls from one supplier more often than to others.

Edge-spalling is a fatigue problem due to permanent overstressing. This may have various reasons but they are easy to understand: a separating force is transferred through the bearings of the back- up rolls via bending to the barrel and by pressure to the barrel of the work-rolls and finally to strip (mill stack deflection). All kinds of deformations take place, nevertheless when everything has been taken into consideration, the strip should be flat after rolling. Due to bending of back-up rolls it is easy to see that the maximum pressures are at the edges (action - reaction), the same is true for work rolls and back-up rolls. The location of the maximum pressure points is influenced by the ground barrel shape and chamfering, roll wear during a rolling campaign and roll bending. Additionally because the edges are a singular point of the rolls ($\sigma_{ax} = 0$) the shear stress is higher than anywhere else in barrel (where $\sigma_{1, 2, 3} \neq 0$).

Roll bending increases the risk of overload. In case the mill operator starts to compensate roll wear by roll-bending - (this is possible and practised to some extent) - then catastrophic failures will occur rapidly! However, there are simulation programs available to calculate stress distribution along the barrel. They show stress peaks at the edges and these programs are good tools for simulating methods to avoid edge spalls, to establish

- the best shape for the barrel of rolls
- limits of maximum wear for rolls.
- the “right” roll barrel crown

Illustration 41 may demonstrate load distributions in mills and end spalling.

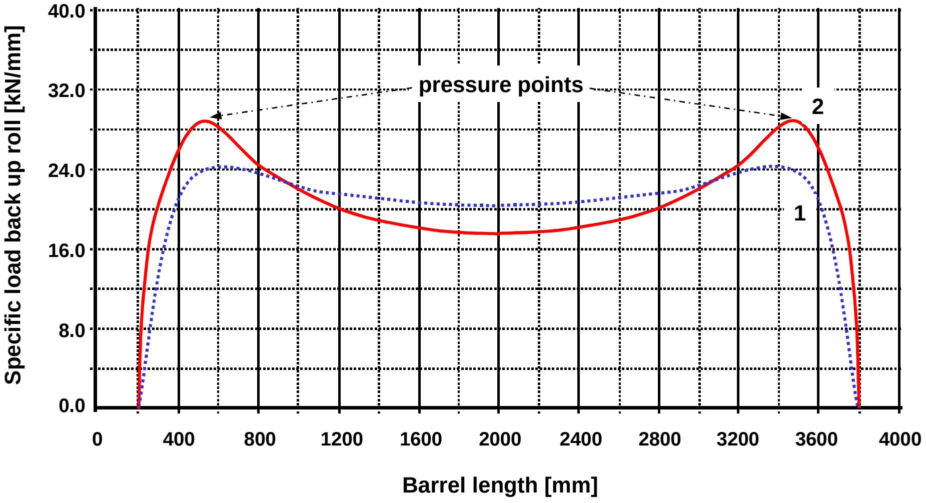


Illustration 41: Specific load distribution in contact zone between W.R. and B.U.R.
back-up roll – 3800 mm barrel length; work roll – 4000 mm barrel length
1) without work roll bending; 2) with work roll bending

4.6.2.3. SPALLS, SPALLING IN GENERAL

There are two different types of spalls, one starts at an initial surface crack and the other type starts sub-surface.

Surface cracks are normally caused by local overload, all kind of rolling accident, just abnormal rolling conditions. There are bruises, severe fire cracks, "strip on the roll", cobbles etc. etc.. In case, plastic deformation of the roll surface should be greater than the material (for instance after work hardening) allows, then a crack starts.

Spalls, these fatal roll damages always tend to happen with (relative) low numbers of revolutions -that means: crack initiation, crack propagation and final spall-failure may develop in one single rolling campaign.

Illustration 42 shows a frequently observed “tongue type spall” of an ICDP hot strip mill work-roll, starting from a bruise crack and circling the roll until it finally spalls. These spalls are very similar to those in forged work-rolls in cold strip mills and they are found some times in back-up rolls as well.

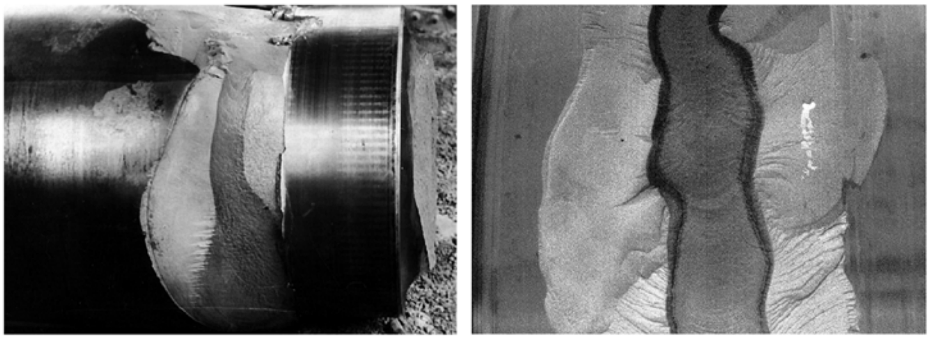


Illustration 42: Ribbon fatigue spall due to initiated pressure crack on the barrel surface (Cat’s tongue spall) [16]

Because nobody is sure that the rolls are not abused, the best and only way to avoid - or at least reduce the risk for - spalls is to redress the working surface of rolls regularly, basically because of wear, but at the same time damage to the surface should also be eliminated. This includes all initial cracks, work-hardened areas due to local mechanical overload. The roll surface is rebuilt to a pristine state concerning fatigue, hopefully! In cases where there are undetected remaining cracks then the next campaign might be the last for this roll because cracks grow rapidly (depending on roll grades, residual stresses, loads etc.).

To assure a perfect roll surface after re-machining, re-grinding it is highly recommended to use automatic non-destructive testing equipment (e.g. eddy current), especially in mills with high cobble rates, rolling light gauge and using "sensible" roll grades like ICDP, HSS. It is worthwhile to use this equipment everywhere, always.

The sub-surface starting spalls are very typical for flat cold rolling, back up rolls are involved, but sub-surface starting spalls are observed elsewhere too.

I found the best literature to this subject in *FORGED HARDENED STEEL ROLLS SERVICE PROBLEMS CAUSES AND PRVENTION by Union Electric Steel Co, 1999* (and the results and conclusions are not limited to forged rolls but valid for any kind of material) Union Electric (UE) presents many examples and gives useful help and theoretical back ground information. Sub-surface spalls start at the point of highest shear stress in the contact zone of back-up- and work-roll (Hertzian pressure). However even with equally distributed stresses/loads it is evident, that the "crumbly" (expression from UE)high cycle fatigue spalling is not equally distributed. The main reason for this fact is, that sub-surface spalls always start at definite "material defects", which might be a non-metallic inclusions or micro porosities - and material defects are not equally distributed.

The solution for this problem is material with better particle cleanliness (see chapter 3.2.4.). People from forges bet on ESR (electro slag re-melted) material instead of EAF (electro arc furnace) and have proved the success of this method. Foundries tried to use ESR blocks instead of cast rolls - and they failed. However, even the cleanliness of cast materials for back-up rolls was improved.

Every year some people publish "new scientific results" about research on this field of "crumbly spalls", results of various contact stress fatigue tests under various conditions and finding new stress limits etc, but it is evident, that "good rolls" are doing fine under normal rolling conditions - and "not-good rolls" are doing worse. The task is to improve roll material, especially the particle cleanliness. This development took place in bearing materials some 20 years ago with great success at the end.

As long as mill builder stay with the design limits for rolls - see chapter 4.10. -and they do, rolls should do their job under normal rolling conditions without any severe failures (crumbly spalls included).

4.7. DAMAGE OF STEEL ROLLS DUE TO HYDROGEN

Hydrogen in rolls never was discussed openly, this is one of the best kept secrets. Luckily problems with hydrogen do not occur every day, but in some cases they do, then normally big steel rolls - forged or cast - are involved.

One of the problems is that it is not easy to measure hydrogen in liquid steel - it is much easier today than 20 years ago - and it is almost impossible to measure hydrogen in solid steel. Steel makers certainly know that during steel processing, after blowing oxygen into the melt to clean it, the hydrogen content will be zero. However, more processing steps are still to come like alloying, tapping, casting etc. and the hydrogen content will always increase. The open question is how much and what is the limit. And what should be done in case the hydrogen content exceeds a certain limit and by how much? Who can estimate the risk? Is there a chance to get rid of the hydrogen in steel by diffusion, how long will it take, at what temperature. There are many different questions but also possibilities.

Hydrogen does and did not cause problems in steel of high carbon content or iron.

Plate manufactured from steel which was not treated by vacuum degassing (secondary treatment) frequently used to have hydrogen problems. Internal hydrogen defects caused bad ultrasonic test results and low transverse strength. Plate mill people learned to overcome this problem by piling plate after rolling so that it cools down very slowly especially at the temperature of the austenite to ferrite transition where the diffusion rate of hydrogen is at its maximum.

Is there a chance that by learning from their experiences roll makers can dispense with hydrogen? It is not so easy but of course we can learn from every experience, and undoubtedly there are opportunities to reduce the hydrogen content in large rolls.

What are the problems caused with hydrogen? There are two:

1. Special fatigue - starting at one or more round cracks perpendicular to the longitudinal direction of the roll and growing conically into both directions, Illustration 43 of a forged back-up roll, Illustration 44 of a broken cast-steel roll.

Illustration 43: Hydrogen initiated breakage of a forged back-up roll

Illustration 44: Hydrogen initiated breakage of a cast back-up roll

Illustrations of this phenomenon are published in relevant literature but without a suitable explanation.

It takes a long time until this fatigue becomes evident. The cracks do not really work as stress raisers through bending, they are situated more or less in the stress-free centre area and it is only thermal stress that really alternates from campaign to campaign. These rolls are in service for many years until the problem becomes evident. The mechanism is explained nowhere in detail, however it was observed that these phenomena always start in the upper barrel end, upper neck, where hydrogen concentrates during solidification and where during primary cooling in that volume and where the austenite – ferrite transition takes place last. It is really a progressive fatigue situation, however the only stresses in this area are related to residual and thermal stress and the number of alternations of loads is very small. But ultimately hydrogen was found to be active.

2. Hydrogen-related delayed brittle fraction happens unexpectedly, even without any rolling load on the roll, sometimes when rolls are still on stock, even years after delivery. This phenomenon is well known in material science and there are special tests available to examine the sensitivity of materials for this. The material is made brittle by hydrogen and when subjected to a load, sooner or later (depending on the content of hydrogen and the stress) the sample / or roll begins to disintegrate without any sign of deformation, not even anywhere in the area of fracture topography which shows only cleavage face.

Hydrogen is critical for steel only as long as the atoms of hydrogen are dissolved in the microstructure and can move by free diffusion. As soon as two atoms have combined to H_2-gas sitting in a cavity, porosity, ... they can no longer do any harm. Shrinkage cavities are the best traps for catching hydrogen!!

A hydrogen-related failure has never been found in rolls with large shrinkage cavities. And because cast rolls always have at least micro cavities, the tolerable content of hydrogen is much higher than for forged rolls (factor of 2).

4.8. WEAR AND FRICTION OF ROLLS

4.8.1. WEAR AND ROLL PERFORMANCE

Whenever materials move and slide relatively to each other then friction and wear occur. Simple models were used to build machines to test wear, one sample slides on the other under load, pin-disc-machine, or 2- cylinder machines or others and always the loss of weight indicates the amount of wear. Wear is a function of the tested materials, of running time or wear-length (in terms of metres, kilometres...). However, the figures achieved are not really helpful for practical use because they are influenced by too many parameters. For rolls the best testing equipment is a rolling mill.

In rolling mills wear takes place mainly at the areas of highest friction, that is between a roll and the rolled material (there is of course also wear in mills on other parts without almost no friction, for example, the barrel of back-up rolls in four high mills is subject to wear as well, but the amount is not as high). Wear normally is not equally distributed on the barrel from one end to the other because strip conditions are not the same over the strip width and the edges of rolls are never in contact with rolled material at all.

In hot rolling mills the roll surface is influenced by changing temperatures during each rotation, which may create fire-cracks (chapter 3.5) and these influence friction and wear.

A third factor of impact on wear is roll/strip cooling. Cooling agent water or water emulsion/mixture may be clean or not and may contain lubricants and chemical additives, which are sometimes very aggressive (for example when hot rolling aluminium)

Wear and fire-cracks increase progressively during the rolling campaign.

After each campaign rolls are redressed, reground to re-establish the correct original shape. This means the diameter of a roll is reduced by grinding until all visible signs of wear and the necessary part of fire-cracks (chapter 4.5) have been removed - today often under the control of eddy current testing equipment, which is highly recommended. Additionally some amount of stock is removed for safety reasons to reduce the risk of problems due to undetected surface damage.

In case the roll surface shows damage from a mill accident - local intrusion or fire-cracks -then these have to be eliminated by further grinding, of course.

At the end of roll life the total rolled material - in terms of tons or length of product (kilometres) - is related to total stock-removal for normal rolling, excluding stock-removal for accidents. This results in a figure for *productive or effective roll performance.* If stock-removal for accidents is included, then this figure is called *total roll performance.* These figures are the most important ones for evaluating the roll, comparing it with others, other grades and in making a distinction between various roll suppliers.

Roll wear depends on the used roll grade, chemical composition and microstructure. Roll wear decreases with an increased content of extremely hard carbides, chapter 3.5 (or other very hard particles - ceramics - maybe in future). During the last 50 years different roll grades were used for W.R. of hot strip mills and for some time up to 4 different grades were used simultaneously in different stands. All these grades were manufactured in basically the same range of hardness, Illustration 45. However wear performance differs widely.

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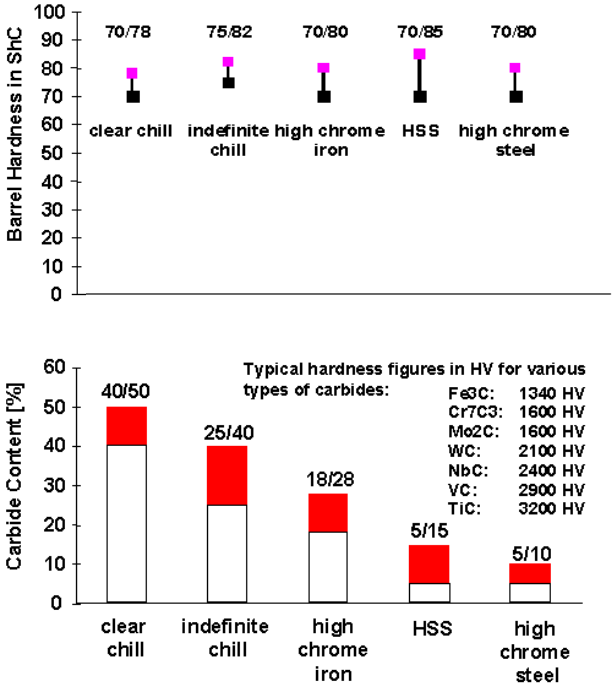

Illustration 45: Range of barrel hardness and content of carbides of different roll grades [17]

Carbide content may be of importance only for one grade (ICDP). Comparing different grades the type of carbides is more important for wear resistance than the total content. No doubt, HSS (5-15 % carbides) does not show any wear compared to ICDP (25-40 % carbides).

The development of carbide enhanced ICDP rolls followed this strategy - less carbides, however carbides of higher hardness in a strong martensitic structure to keep the hard carbides strong. The performance of these ICDP rolls was improved in many mills, by a minimum 20 %, maximum beyond 100 %. And other grades will follow the same direction - always bearing in mind that wear resistance is just one required property.

For the same roll grade the hardness is of no importance at all, see Illustration 46. The little increase in wear resistance that might theoretically exist is often over-compensated by the risk of unproductive loss of roll life following rolling accidents. Never to forget: with increasing hardness the ductility of the material is reduced and for all materials there is an optimum, maximum of useful hardness, chapter 3.2.4.

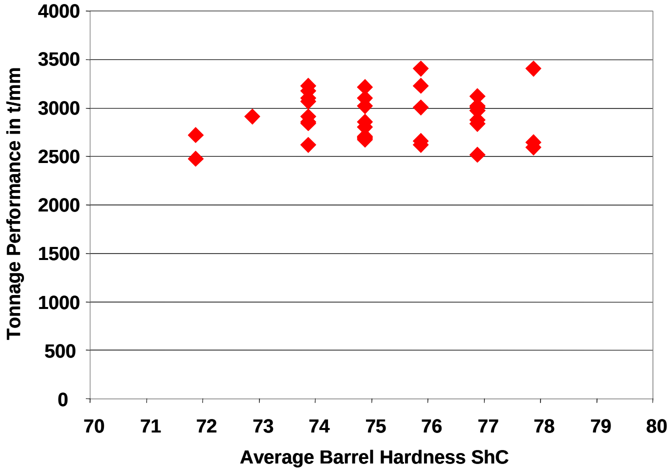

Illustration 46: Tonnage performance of ICDP work rolls Ø680 x 1900 mm, excluding mill accidents

Unfortunately it is not easy to find general rules for best wear resistant materials for all applications because the wear conditions vary too widely.

For curiosity's sake here is one example of demonstrating the importance of roll/strip cooling in wear. In the 1980s high chromium iron was tried in back-up rolls for cold rolling. There was almost no wear but the rolls failed because local mechanical overloads created cracks and spalls and there was not enough ductility to take any deformation. So the same type of roll was used as a back-up roll in hot strip mills with less risk for local deformation and spalls, and none of these rolls spalled. However, these rolls supported 3 to 5 times more wear than with normal steel back-up rolls. Only the cooling media - clean emulsion instead of dirty water - was different in cold versus hot strip mills but evidently the "aggressive" water in hot strip mills and the heterogeneous microstructure did not match. Consequently the more homogeneous 5% chromium back-up roll for hot rolling was developed.

4.8.2. WEAR ON ROLL NECKS

Formerly sliding bearings (made of wood and later of plastics) were used for rolls, but modern mills only use roller- (and ball-) bearings or hydro-static/ hydro-dynamic bearings. Normally necks are not used as an inner part of these bearings but inner rings are made of steel and mounted on to the necks by shrink fitting - no friction, loose and fixed to the right position by keys - almost no friction, or loose with permanent relative motion to the neck (typical for work rolls in hot strip mills).

Roll bearings always use lubricants, grease or oil, to achieve lubricant friction, which is far less than any sliding friction.

In the case of perfect fluid friction there is no wear on necks whatever the neck material and its hardness might be.

However, in recent years two developments have taken place which created severe problems with neck wear:

- For many reasons (one of these was more wear-resistant barrels of new roll grades) the campaigns in the mills became longer but the grease lubrication was insufficient for these extended periods because it was washed out of the bearings by the cooling water etc. This problem was solved by better seals on the bearings and/or by re-greasing during one long campaign.
- Intelligent people tried to improve strip tolerances by narrowing the bearing slackness / clearance. This was contra-productive because the volume of grease in the bearing was reduced and the risk of metal to metal sliding friction increased, both with a negative effect on neck wear. It is strongly recommended to adhere to the instructions of bearing suppliers, see Table 2.

nominal size of borehole		**tolerance of new roll**	**max. operating tolerance**
over [mm]	**till [mm]**	**[mm]**	**[mm]**
101.6	127.0	-0.100 / -0.125	-0.460
127.0	152.4	-0.130 / -0.155	-0.530
152.4	203.2	-0.150 / -0.175	-0.610
203.2	304.8	-0.180 / -0.205	-0.690
304.8	609.6	-0.200 / -0.250	-0.910
609.6	914.4	-0.250 / -0.330	-1.220
914.4		-0.300 / -0.400	-1.520

Table 2: Measure tolerances of roll necks; taken from a maintenance manual of a roll bearing manufacturer

Neck surface repair for wear by welding or flame spraying of metals or oxide layers so far has not really been successfully applied.

The best and only solution to minimise wear on roll necks is to ensure good lubrication and necessarily the “gap” should be wide enough.

4.8.3. BITE ANGLE AND COEFFICIENT OF FRICTION

Hot rolling with no or only minimum tension on strip needs “high” friction between roll and rolled material to push the material through the stand. In case friction is too low, slippage occurs, causing different problems in the mill. The critical parameters of rolling conditions to avoid slippage is the bite angle and rolling speed, the higher the speed, the smaller the bite angle (if there is static friction it is all right; sliding friction results in slippage). Illustration 47 shows the critical dependence of bite angle and speed which was developed experimentally for conditions with freshly ground rolls.

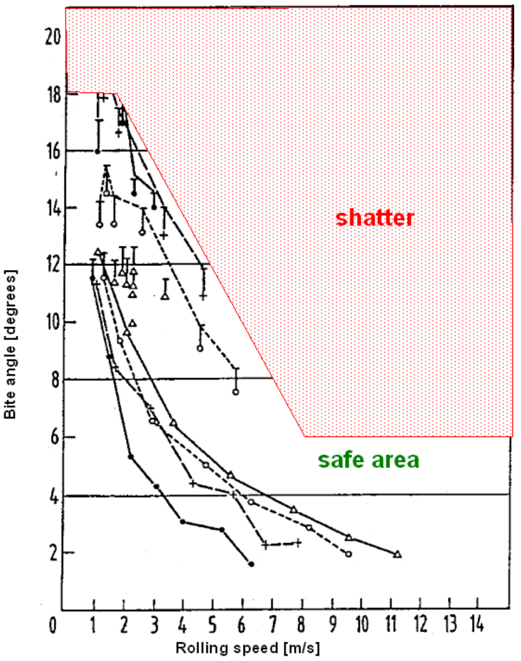

Illustration 47: Bite angle vs. rolling speed relationship for various hot strip mills [18]

In case the rolling schedule shows too high a bite angle for the desired speed, then the rolling speed has to be reduced or the roll surface needs help to increase friction. For example, a good, open fire-crack pattern is useful or ragging of the roll surface or something similar.

Often slippage is only experienced with freshly ground rolls after roll change so mills developed special rolling schedules for the first number of slabs to build up a “nice” fire-crack pattern before changing back to normal.

Sliding friction between metals, chapter 3.6., depends on the combination of materials but it was found that there is no major difference between hot steel and the various materials used for rolls for hot rolling, including Indefinite and HSS materials.

However, the coefficient of friction in a mill, Illustration 48, calculated from measured and calculated separation force shows a very different result. In the mill the coefficient of friction is much higher than measured in the laboratory and it changes from slab to slab (of course the roll material is the same, only the surface varies) and it increases and differs for various materials.

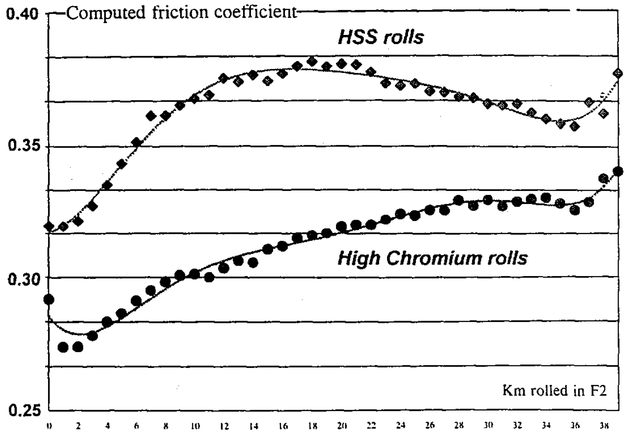

Illustration 48: Increase in the coefficient of barrel surface friction during a rolling campaign [19]

It was shown before that friction is a function of materials and of the surface condition. It is evident that the surface conditions, the fire-crack pattern and oxide layers are more important than the roll material itself, and the surface conditions are highly influenced by the rolling conditions. Illustration 49 show the fire-crack pattern of different materials and this can explain the difference in the coefficient of friction in the mill easily.

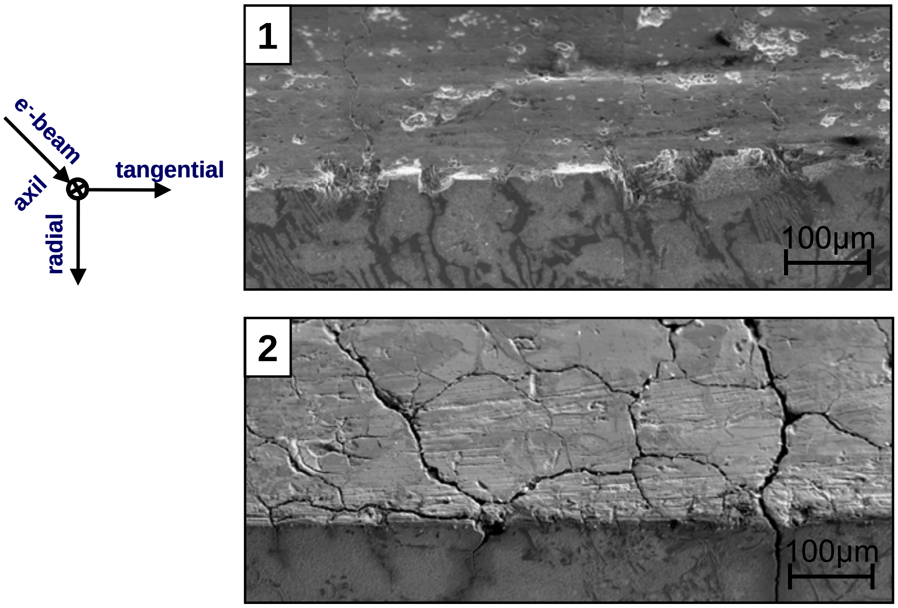

Illustration 49: Surfaces of worn work rolls;

1) High Chrome Iron

2) HSS

SEM-images, Angle of incidence of the electron beam is 135° to roll surface and cross cut to rolling direction. The cross cut has been etched with HNO_3 for 12 sec.

4.9. ROLL REPAIR

4.9.1. ROLL INSPECTION AND REDRESSING OF BARREL SURFACE

Rolls are non-destructively and carefully inspected by ultrasonic methods during the roll manufacturing process to ensure that there are no hidden defects in the roll like internal cracks due to casting or heat treatment or at the interface between shell and core of double poured rolls. Ultrasound is also used to measure Young’s modulus of compound rolls of different materials.

During rolling rolls lose their initial shape and surface conditions. As soon as set up levels are reached, rolls are taken out of service and are reground to initial conditions.

During hot rolling of flat steel or long product work rolls wear and fire-cracks are created, related to heat transfer from rolled steel to rolls and cooling conditions.

Work rolls for aluminium-hot-rolling or cold rolling of steel show less wear but the roll surfaces lose roughness and this influences the finished product as well. Chrome plating is used to prolong rolling campaigns but no surface lasts for ever and all strips and bars have a head and a tail end which stress rolls differently from the rest of the strip/bar. These ends are different in shape and temperature from the other part, the tail ends are often somehow out of control with all kinds of abnormal rolling conditions.

Back-up rolls show wear (easily measurable) and surface fatigue (only controllable with high- tech equipment) so there are some reasons to redress and rebuild a new, fresh surface. Through trial and error all mills have established their own system of redressing based on rolling time, tonnage or length of rolled material. Back-up rolls, especially those of cold strip mills have to be checked for areas of work-hardening by hardness readings (chapter 3.2.5.) because in the case of work-hardening the ductility is reduced and the next local overload may start a crack, which eventually may cause a spall. Measured work-hardening has to be eliminated by stock removal on the grinder.

Under normal rolling conditions everything is relatively simple. However no mill experiences normal rolling conditions all the time. There are cobbles (rolling stops due to power failure), troubles with the cooling system, wrong bar temperatures, incorrect adjustments of roll gaps and many other reasons which lead to abnormal rolling conditions. Rolling problems may create all kinds of overloads to roll surfaces, which may or may not be easy to detect. To make sure that there is no severe damage anywhere, it is highly recommended to check roll surfaces with methods of non-destructive testing (all kinds of equipment is available). Today it is state-of- the-art to check the roll surface after each run on the grinder with some eddy current device for all kinds of cracks and defects. The rolls are ground until the threshold of the instrument reaches a certain level, which depends on the roll grade.

Undetected initial surface damage may create real problems like small - or big spalls, which always start at cracked or overloaded areas.

Some grades (ICDP, HSS) are very sensitive to minor cracks; some grades (High Chromium Iron or Steel) are less sensitive, so remaining fire-cracks are tolerated - if the cracks are closed after regrinding.

Whenever a surface crack is detected it is very useful to measure crack depth and size with ultrasonic methods. Then it can be decided whether roll repair is feasible or the crack size is fatal. Mill people may request support from roll makers, who can offer great experience in ultrasonic inspection.

Residual stress - compression stress in the working area - is one component to reduce the risk of roll failures due to initial cracks, however this has to be controlled - as far as possible - during manufacturing of rolls.

4.9.2. SPALLS

Spalls are often catastrophic with no chance of repair. However, there are some typical spalls, which do not necessarily lead to loss of roll-life and repair is possible. This is of some importance especially for “heavy” rolls, like plate mill work rolls or back-up rolls for hot or cold rolling.

4.9.2.1. SPALLS IN WORK ROLLS

Minor spalls are often not really fatal and in plate mill work rolls can be repaired by plugs. Some mills regularly order plug material with each new roll, especially plate mills with severe rolling conditions, rolling stainless steel or which have frequent mill problems. If it is done correctly a roll life can be saved. Many of these repaired rolls reach normal scrap size without any further problems.

The same procedure was used successfully with roughing rolls in hot strip mills but never to my knowledge in finishing stands of hot strip mills.

4.9.2.2. SPALLS IN BACK-UP ROLLS

Small spalls in back-up rolls (in cold strip- hot strip - or plate mills) can be repaired simply by cleaning the spall out carefully by hand-grinding. It is important that all cracks are thoroughly eliminated, or at least no crack should remain in the loaded area. And the transition from the cleaned area to the loaded part of the barrel should of course be very smooth and soft. Often a minor spall cleaned and ground in this way disappears completely after some normal campaigns, after some millimetres of normal stock removal.

Typical for some mills (hot strip mills and plate mills) is barrel-edge spalling of back-up and/or work rolls. This is caused by mechanical overload at the edges resulting from geometric design problems or too high wear on work- and/or back-up rolls, and edges are always the weakest part of rolls.

But even edge spalling of a back-up roll does not necessarily mean a complete loss of that roll. Successful repair is possible!

It is frequently proven that repair by shrink fitted rings is possible and these repaired rolls normally reach designed scrap diameter without further problems. But shrink dimensions and ring quality have to be adjusted correctly, otherwise the ring may split, or it may widen and fall from the roll. There are a few more points to observe, especially for the gap between ring and barrel. However, if everything is done correctly, the repaired roll will return to safe operation and help to save money.

4.9.3. WEAR ON NECKS

4.9.3.1. WEAR ON NECKS AT THE BEARING AREA

This is normally a problem of insufficient lubrication which occurs for many reasons. Sometimes the gap between roll and bearing inner ring is designed too small and this always leads to catastrophic wear. All kinds of repair - surface welding, spray coating - fail to a high percentage.

Sometimes, especially in the case of better roll qualities and longer campaign length, there is a lack of lubricant and so intermediate grease refilling is recommended.

With oil circulation lubrication in bearings and good sealing no problems are to be expected apart from maintenance mistakes.

With grease lubricants the best results are achieved by adhering to bearing manufacturers' recommendations concerning dimensions. Neck hardness - with good lubrication - does not have any influence on wear.

4.9.3.2. WEAR ON THE DRIVING ELEMENT

Flat drive ends and clover-leaf sleeve sometimes show significant wear which might create problems in reversing (mainly in roughers) stands. This is a new challenge because the performance of rolls is increasing so much. However, this is a maintenance problem and it always starts with worn end parts of the spindle nose.
Weld repairs of the shoulders of flat ends can be done successfully - and in case it happens

frequently in a mill it is recommended to start new rolls already with weld on hard faces at the shoulders of driving elements.

4.9.4. CRACKS IN NECKS

4.9.4.1. CRACKS AT THE FILLET BETWEEN THE BARREL AND NECK OF BACK-UP ROLLS

These sometimes occur due to fatigue and especially in aluminium hot mills because of corrosion fatigue. No repair method has so far been successfully applied but it is possible to run rolls with cracks using fracture mechanics and by monitoring crack growth in order to avoid total breakage.

Roll makers have good chances of reducing the risk of fatigue neck problems by the right manufacturing process control.

In case corrosion fatigue is a specific problem in a mill (for example: back-up rolls in aluminium mills, which are in use for much longer campaigns than in steel mills because in aluminium hot mills there is almost no wear at all) then these rolls do need a safer fillet design, which does not allow any access of cooling water (including all chemical cleaning additives) to the fillet thanks to an excellent sealing.

4.9.4.2. CRACKS STARTING AT THE KEY GROOVE ON TAPERED NECKS OF BACK-UP ROLLS

Even keys should not really take any high loads - sometimes they do and spoil a neck. Repairs are possible and in some cases heavy (valuable) back-up rolls are cracked so it is worthwhile to attempt repair. However, welding in this area is not tolerable.

4.9.5. BROKEN DRIVE END OF ROLLS

If terrible mill accidents occur, stoppage of the roll for whatever reason - one element of the driving chain motor-(gear-) spindle - roll breaks down - the roll is the cheapest part of the chain. Hopefully the breakage is perpendicular to the axle so there is not too high a thrust onto the spindle and motor but normally breakage does not occur in this way but somehow at 45° and the spindle and/or roll have to be turned of.

If roll necks do not break, huge damage can occur to the stand.

Roll necks should have a breaking point incorporated into their design or the mill should use “fuses”, torque limiters and special safety breaking devices.

In the case of a broken drive end of a roll, repair is possible by various methods and experienced roll makers know how to handle this repair. There are some restrictions as regards the position of the damage. The repair is costly but in general not a problem.

4.10. DESIGN LIMITS FOR ROLLS

Mill builders and their customers are always in conflict: mills should be capable of rolling all kinds of products in every dimension etc. and at the same time investment and operation costs of mills should be low. This means high separation forces, a minimum number of roll passes, small neck and bearings, high rolling speed and so on.

However, there are technical limits, which have to be respected, and sooner or later some solutions are found and decisions taken. Design limits are not (really) based on science, most of these were found in long-term experience (trial and error). To stay with these limits is safe for everybody: mill designer, mill operator and roll supplier.

Sometimes design goes beyond these limits but then everybody should be aware of this and make efforts to minimise risks.

Initially (all) mills do not use maximum loads all the time, but sooner or later mill people will do so!

4.10.1. BENDING STRESS

The easiest way to handle this is to calculate nominal stress (bending momentum divided by section modulus), taking into account that the fillet design (notch factor) is typically the same for normal rolls ($1.8 \leq \alpha_K \leq 2.2$).

Rolls are safe if bending stress is
- less than 60 N/mm^2 for grey iron
- less than 90 N/mm^2 for nodular iron
- less than 120 N/mm^2 for cast steel
- less than 150 N/mm^2 for forged steel

4.10.1.1. TORQUE

Fatigue torque failures are real exceptions, so static torque strength (90% of tensile strength) can be used for roll design. See 4.9.5.

4.10.1.2. LINEAR LOAD FOR HOT ROLLING STRIP

The highest linear load is between strip and work roll. Traditionally this load was below 1500 t/m of strip width. This was safe for work rolls with grey (lamellar) core material. But mill people discovered that it is helpful to use maximal separation force for all dimensions of strip and the old limits were exceeded in many applications. However, the old type of work rolls failed.

If 1500 t/m strip widths are frequently exceeded only work rolls with (good) nodular core material can take that load for long terms.

4.10.2. LOCAL PRESSURE

4.10.2.1. FATIGUE (SPALLS) PREVENTION

The highest local pressure is between work and back-up rolls, the Hertzian stress. The safe limit is 2100 N/mm^2.

However, this cannot be easily calculated because Hertzian stress is not equally distributed from one end of the roll to the other. Due to back-up roll bending the maximum stress is always relatively close to the edges of rolls. To avoid the maximum stress occurring at the very end of barrels, back-up roll chamfer is always required (some relevant literature is available).

Nevertheless stress distribution is also related to grinded roll shape (crown), wear of work roll and back-up roll and roll bending as well. (The worst in my experience was when a mill tried to compensate roll wear by roll bending to achieve plate within given tolerances: many rolls failed by end spalling!)

A good simulation program helps to distinguish real load distribution.

The limit of 2100 N/mm^2 is beyond all strength properties of work rolls and back-up rolls material, but anyway this is a safe limit for standard rolling practice. However, it is necessary to regrind back-up rolls regularly on a fixed level to eliminate all fatigued surface material; the depth of highest stressed material is given by Hertzian calculation.

4.10.2.2. LOCAL SINGLE OVERLOAD DUE TO MILL ACCIDENTS

A typical critical accident is “strip on roll”, a little part of strip sticks to the roll surface and comes between work roll and back-up roll. This may happen only for a few revolutions but the local overload - never calculated - is far beyond any limit! These local stresses on both rolls and the little piece of strip are tremendously high and result in plastic deformation. In hot rolling the hot rolled material is most capable of taking plastic deformations - unlike cold rolling where the rolled material has the highest yield strength. Therefore in cold rolling the back-up roll should be the softest material to absorb plastic deformation, cold mill back-up rolls should be much softer with a lower yield strength than work rolls. This is not necessary for hot rolling. However, areas with plastic deformation / work hardening should be removed by redressing after each campaign.

4.11. SPECIFICATIONS FOR ACCEPTANCE OF ROLLS AND PERFORMANCE GUARANTEES

Rolls, as mentioned frequently, are functional tools in a mill and should perform under normal rolling conditions at least as well as guaranteed, and be able to withstand mill accidents.

“Normal rolling conditions” mean that the rolled material is in the right condition (temperature, de-scaled...) and the mill operates without problems: no power failures, good cooling, rolling speed, rolling schedules well set-up. It also means that that roll wear is under control and that rolls are correctly re-machined after each campaign (the surface is checked for bruises and cracks).

Mill people should (and normally do) keep track of all information concerning roll life: the rolled tonnage for each campaign, rolled finish length, stock removal for wear, and total and unproductive stock removal due to rolling or roll problems.

To meet these requirements including total performance and specific performance in t/mm or km/mm, there is no need to specify

- chemical composition
- surface hardness
- neck hardness
- material strength (of any kind - because nobody can measure it anyway)
- physical properties (thermal expansion, heat conductivity or others)

The “quality” of a roll is manufactured - not induced by inspection people - and roll users can easily find out which rolls are good and reliable. They may listen to all arguments of roll suppliers but the truth is shown in the mill.

Acceptance specifications are documented in roll drawings and order requirements but beyond material properties - see above - only dimensions and tolerances have to be met.

It is most important that rolls, bearings and accessories fit together properly, this is essential. And the accuracy of rolls (T.I.R.) has to be one degree better than the tolerance of the rolled product! There is a wide difference in tolerances for tin plate or heavy plate.

A T.I.R. ≤ 0,003 mm is acceptable for tin plate rolls but for a heavy plate mill roll (5m barrel length) the same T.I.R. is useless and also very hard to measure! In any case the tolerance for rolls is frequently much narrower than for any part of high-tech automotive parts.

It is so easy for any technical designer of mills and rolls to specify narrow tolerances but it is often very difficult to achieve these. And if there is no technical justification for them, it is just a waste of time, technology and money.

There have been long discussions between roll designers (mill builder) and roll makers resulting in a good understanding and full agreement but without any changes being made. The rest is left for negotiations between roll makers and inspectors. I know from many roll makers that there have been many useless discussions between their staff who are concerned with quality and inspectors (and sometimes roll users) but claims based on insufficient dimensions or exceeded tolerances have never occurred or at least only as a very rare exception due to machining errors, mistakes (such as a forgotten bore hole etc.).

Some examples of tolerance and reality in everyday life with rolls:

- The tolerances for the diameter of bearing areas of work roll necks for hot strip mills are usually in the range of ± 0.0125 mm to 0.025 mm.
  However: the bearing suppliers manual allows roll neck diameters which after wear may be between –0.3 to – 0.7 mm below the original minimum diameter (something that normally never happens to this extent), depending on the size of roll neck diameter.

- The turned groove for the split (divided segmented) bearing ring is almost the same as for the other parts of necks. However, this tolerance (as long as it limits the maximum diameter) is of no importance at all.

- It is often very difficult to measure tolerances - everything is so easy on paper! And many tolerances are too tight.

- Every dimension needs a tolerance, even the area of steady rest of roll necks for the grinder.
  Once we had an almost never-ending discussion with a roll user (of course an aluminium mill, hot rolling): a tolerance of one side is acceptable but the other side should have exactly the same diameter (difference in diameter zero!) so that there are no necessary adjustments on the grinder! A fine idea but impossible.

It is well understood that even very small defects - porosities, hard or soft spots - at the working area of a barrel are not allowed but what about the edges of the barrel or on necks and fillets? “Cosmetic” corrections are state-of-the-art; all roll makers have developed their own technology to perform and hide defects. Roll makers are responsible for their rolls, for ensuring that they work without problems in rolling mills and at the end can present good performance figures. Rolls are not made to win beauty awards and there is no extra money for a nice appearance (roll makers take care of that in marketing and publicity etc. anyway!).

And NDT - a hobby in the Far East - is good for endless discussions but is absolutely useless.

Once again: roll makers are responsible for the quality of rolls delivered and if a manufacturing problem occurs, they are liable.

Wear on necks at bearing areas is basically a question of lubrication, never of neck hardness. High hardness with, for example, nodular iron core material is absolutely counter-productive and results in high residual stress, many carbides and lack of strength, leading to breakage problems. And who takes the responsibility in case a problem occurs: roll maker or roll user - or the person who established the wrong specification? If it could be proved that high hardness on the necks in the bearing area would increase roll life (so far it never has been) then roll makers would come up with new technologies (they are available) but not for 3 or 5 or 8 ShC - but for 20 to 30 ShC - and someone would have to pay for this high-tech procedure!

To make a very long story short: for well established roll makers there should not be any discussion about acceptance inspections, the rolls have to fit into the mill and deliver a good performance. That’s all there is to it!

(Incidentally: the less people know about rolls, the more innocent they are and the higher are the problems with acceptance inspection! And vice versa: well experienced mill people never create inspection problems but they do know precisely how to handle roll failures, whether it is a problem of the mill or the roll makers!)

How can performance be rated? Roll performance is not given by the mill designer - he can only estimate some figures following his experience in other mills - nor is it determined by negotiations with mill purchasing people, even though they sometimes try to do so. Roll performance is “made” in the mill and influenced by rolling schedules, product mix, mill problem occurrence (cobble rate, for example) etc. Only the comparison of rolls in service over the same period (half a year) is adequate and acceptable. Otherwise the results are irregular and only useful for criticising roll suppliers. In times of bad business when there is no chance of optimising rolling schedules, “everything” is rolled (small, light gauge, small number of coils etc.) the roll performance (of every supplier) declines, and in a boom period the roll performance of each supplier improves.

It is useful to follow up performance figures stand by stand and often what is turned out appears to be miraculous. It is highly recommended to evaluate the performance figures stand by stand for each roll service.

It is very difficult to rate performance figures for rolls in section mills, especially when orders to roll are short and the rolls are turned anyway, whether they are worn out or not, so as to be prepared for the next (hopefully) big order.

However, it is always recommended to measure wear, wear profile and adjust total stock removal, to differentiate between different rolls.

In case all rolls are dressed the same, whatever the wear is, then there will be no difference between different roll grades, roll suppliers or anything else and as we are talking of “commodities”, only the price counts. However, roll users should try to work hard to reduce the costs of rolls (including dressing costs), and if they do, then they have to watch stock removal carefully. If stock removal is too low - merely from measuring near profiles - there might be a risk of spalls. This is evident for all kinds of back-up rolls but each mill has to find out the optimum/minimum of stock removal (with a limited number of rolls for a certain time - for instance 15 campaigns) otherwise there will be no progress, whatever the roll grade may offer!

4.12. CONCLUSION OF THE TECHNICAL DISCUSSION

In previous chapters many points concerning the mechanics of rolls were covered. Of course many issues were merely discussed briefly and the scientific background may still be unclear. The idea was to give guidelines for everyday work, clear statements about what is important and what is right and what is wrong.

There are fundamental laws of material science and nature which are valid for everything and everybody, nevertheless it is evident that for a brochure like this it is impossible to deal with every aspect in detail. In many cases where questions occur as regards roll and rolling mills the first task is to identify the various parameters of influence.

Variation between rolling conditions and roll properties is very wide. Mill people have experience in rolling, roll makers have experience with rolls in different mills. It is essential to bring these experiences together, open and very frankly.

Sometimes it seems difficult to talk (especially when money is involved) but people are available who have been in the roll business for a long time and they have seen very many different problems. Do not hesitate to ask questions and share experiences - this can be helpful for roll makers and roll users.

5. REMARKS ON THE ROLL MARKET

5.1. GENERAL OVERVIEW

The steel industry is - in long terms - a slow-growing business. Measured in t/year, lets say + 3 % per year. New capacities are being built up outside the old industrialised countries. Steel prices have been falling for a long time.

Roll productivity is growing for many reasons, perhaps we can talk about a 5% increase. (Roll consumption today for long products is down from 10 - 15 kg/t to 1 - 4 kg/t; for flat products from 4 - 6 kg/t to 1 - 2 kg/t; with strip casting roll consumption is far less).

Based on 600 million tonnes of steel a year and roll consumption of 1 kg/t, a roll volume of 600 000 t of rolls a year is given (- 2 % ≙ 12,000 t per year).

Now we have to distinguish between forged and cast rolls.

- Forged rolls, at least the blanks, can only be made by large, capital-intensive companies (steel plant, heavy forge, heat treatment etc.) which at the same time produce other forgings as well, not many forges only produce rolls.
- Cast rolls can be produced by any small foundry, equipment is cheap and available everywhere. But most rolls are cast. For the following remarks I will concentrate on cast rolls.

5.2. CAST ROLLS

Worldwide there are roughly 50 international roll foundries (not all globally active) and an unknown number of national roll makers, for example, in China (maybe 100 or even 400 in the People's Republic of China alone) and the former Soviet Union.

There is only one big roll foundry company (more than 50,000 t/year) a limited number of mid-size companies (20 - 50,000 t/year) and many small and "also" roll foundries.

And the main problem is that capacities have to be eliminated every year even though the production of rolled steel is growing!

The success of roll foundries is based on:

- roll quality, performance
- service
- innovation
- sales margins

The margin is the difference between the sales price and manufacturing cost. In Europe labour casts are - even for highly productive foundries - between 30% and 50% of the sales price. The percentage of labour costs increases with a decreasing weight of rolls. In some “cheap labour” countries labour costs are less than 10% of (the same) sales prices. To reduce the percentage of labour costs, technical improvements, new technologies and high investments are often necessary.

5.3. LOW TECH ROLLS, “COMMODITIES”

There are some roll grades, sizes “everybody” can produce, called “commodities”. This is valid for nodular iron and hyper-eutectic steels for (small) section mills and rings of these roll grades and clear chill for wire and rod mills.

Commodities never can be made and sold from countries with high labour costs, not even with superb equipment, if the intention is to achieve a profit.

5.4. SUPER HIGH TECH ROLLS

At the other end of qualities - contrary to commodities - are products with very special properties, resulting from successful research and development, and creating new ideas and manufacturing installations, often protected by patents. A typical example for this type of rolls are HSS produced by the “cladding process” or “HIP”-process.

These developments are often very costly and great amounts of money are invested into new equipment without knowing whether it will be successful or not, and sometimes money is wasted.

Developments of this kind are enforced by large companies only - and Japan is the only remaining country where big steel companies still run roll foundries.

Most steel companies (besides Japan and China) sold or shut down their own roll foundries because of the small volume of roll business.

However, even in Japan it would be much more effective to sponsor new ideas and pay for research and development instead of running “many” roll foundries which have difficulties in making money.

5.5. MID-LEVEL TECH ROLLS

Rolls for rolling flat products are not “low tech” but they may be state-of-the-art worldwide, even compound, double-poured work rolls.

Roughing work rolls and back-up rolls are certainly not commodities today - possibly in the future.

There is very strong competition in the market of “mid-level technologies”, as far as price is concerned, and with improved roll grades, carbide-enhanced ICDP, carbide-enhanced high chromiums, semi tool steel, HSS, higher alloyed (5% Cr) back-ups.

Roll performance is improving. Roll users want to speed up the technology of the best roll supplier to heat up competition and achieve a low price - high-tech products and all this against the background of a shrinking market volume.

5.6. CONCLUSION

The market volume is decreasing nowadays and will undoubtedly continue to do so in future.
There may be good products with less competition and special expertise (rolls for paper mills, crushing mills etc.) but competition in the roll market for steel industries will indeed remain strong. Over-capacities of roll making have to be eliminated but sometimes it takes a long time to do so. And until weak companies disappear, they spoil the market for long periods with low prices, making it difficult for good companies to finance necessary research and development.

Roll users operate counter-productively if they keep weak roll makers in business longer and buy according to the lowest price. They should pay better prices for better products - in their own interest.

All roll makers have to make their own decision on investing money in productivity and/or research and development. To stay in business is also of extreme importance.

For the near future rolling mills will use rolls but the volume will continue to shrink and so the next question will be: how long will we need so many rolling mills?

We can certainly assume that nobody will need about 50 international (but not globally operative) roll foundries. My guess is that no more than ten real roll foundry companies will survive the next 50 years and these companies will of course be the most innovative in every respect.

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