Development of Mechanical Surface Strengthening Processes from the Beginning until Today

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1. Introduction

It is well established that in ancient times already mechanical treatments have been applied in many manufacturing processes concerning metallic materials /1, 2/. Hammering evidently was the first mechanical method to bring particular goods to final shape and strength. In the historical development, individual craftmanship and experiences influenced the application of mechanical hardening effects, whereby secrecy played an important role for the preservation of competitive advantages. However, not before the middle of the nineteenth century - running parallel to the development of the railroad technique - the first single-minded applications of mechanical surface strengthening methods became known in the engineering science. Already in 1848, "roll burnishing" was used for railway axles and journals. Around 1880, cold-rolled shafts with improved strength and finish were successfully applied. In these formative years of modern technology it became quite obvious that in service, much more components and structures failed by cyclic than by static loading. Consequently, since the classical work of A. Wöhler /3/, strong efforts were made to measure the resistance of materials to fatigue under controlled conditions and to understand the processes responsible for the fatigue behaviour. In the course of time, it was realized that failure by fatigue depends on a large number of parameters, and very often develops from particular surface areas of engineering parts. Therefore, it seemed possible to improve the fatigue strength of fatigued parts by the application of suitable surface treatments, of which the mechanical surface strengthening processes represented an important group. Nowadays, we are very familiar with several mechanical surface treatments which alone or combined with other hardening processes can lead to significant improvements of the fatigue strength of materials under constant as well as random-like amplitude loading conditions. Also, the corrosion fatigue resistance of materials and the fretting corrosion behaviour of contacting surfaces can positively be influenced by mechanical means. The scientific fundamentals of these facts were developed in this century at the end of the 1920's and at the beginning of the 1930's.

In this paper, the scientific and technological efforts will be outlined, which were made during the development of mechanical surface strengthening procedures to improve the fatigue strength of materials. Excluding particular straining methods, e.g. coining or inhomogeneous plastic deforming, which can also be restricted to well-defined surface and subsurface areas, three different ways exist in which the fatigue strength can mechanically be effected: Firstly, by machining, secondly, by rolling and thirdly, by shot peening. These processes are applicable to brittle as well as to ductile materials. Furthermore, they are not restricted to materials with particular chemical composition or to distinct material states. Moreover, they can be applied to smooth and notched surfaces. In the following, the historical marks in the development of these three surface strengthening methods will be discussed in more detail up to the end of the 1950's. All data presented were carefully gathered and are well documented. However, the authors are not quite sure whether or not they overlooked some important documents. In the final chapter of the paper, it will be commented on some newer contributions to mechanical surface strengthening. Thereby, from the large amount of excellent work achieved by many scientists in the last three decades, for reasons of space only a few examples can be selected, of course individually. This has been done with full respect to the entirety of investigations which determine the scientific and technological progress reached in this important field.

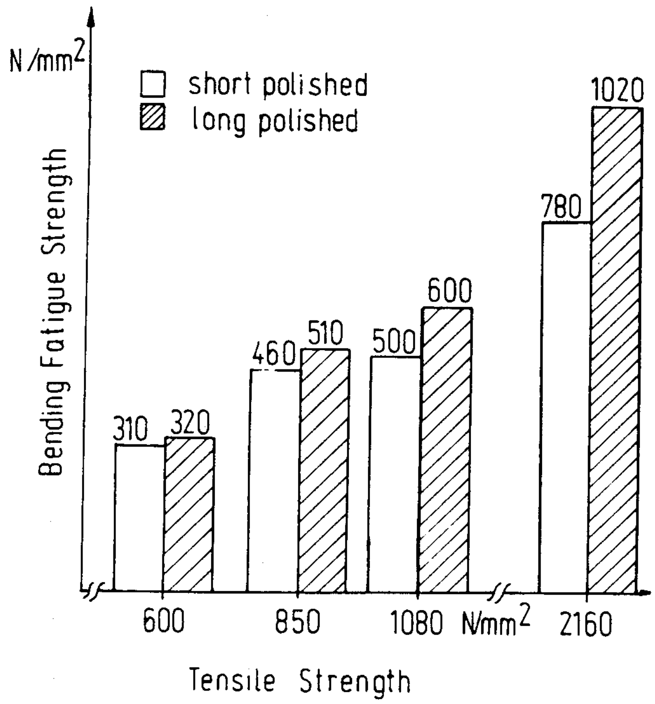
2. Surface Strengthening by Machining

Most engineering parts are machined by processes like grinding, milling, turning, planing, honing and polishing. In the surface areas of the machined parts, all these treatments produce work-hardening effects, residual stress states and a characteristic surface topography. Tab. 1 gives a review of the first scientific investigations, which clearly pointed out the importance of the surface state for the fatigue behaviour and the particular features of machined surfaces. Already in 1928, R. Mailänder /4/ showed that differently polished surfaces led to differences in the fatigue behaviour of steels. As can be seen from Fig. 1, the fatigue strengths of specimens polished strongly were higher

Table 1: Development of surface strengthening by machining.

Author(s)	Year	Statements/Proposals	Ref.
R. Mailänder	1928	Bending fatigue strength depends on severity of polishing	4
E. Houdremont R. Mailänder	1929	Differences in the endurance limit of polished and turned steels increase with increasing tensile strength	5
G.A. Hankins M.L. Becker	1932	Differences in the rotating bending bending fatigue strength of polished and unmachined forged spring steels	6
W. Ruttmann	1936	Workhardening and compressive residual stresses due to turning, grinding and polishing enhance the fatigue strength	7
E. Siebel M. Gaier	1956	Quantitative correlation between fatigue strength and surface roughness for steels and non-ferrous alloys	8

than of those polished slightly. At that time, it was also recognized that the surface roughness appreciably effects the fatigue strength. One of the first results, which documented that the effect of surface roughness on the fatigue strength in rotating bending increases with increasing tensile strength, is shown in Fig. 2. E. Houdremont and R. Mailänder /5/ obtained these results from fatigue tests performed on polished and rough-turned specimens. In each case, the rough-turned specimens held the lower quantities of fatigue strength. However, since machining also workhardened the surface area and produced residual stresses, it was not possible to evaluate clearly the roughness effect.



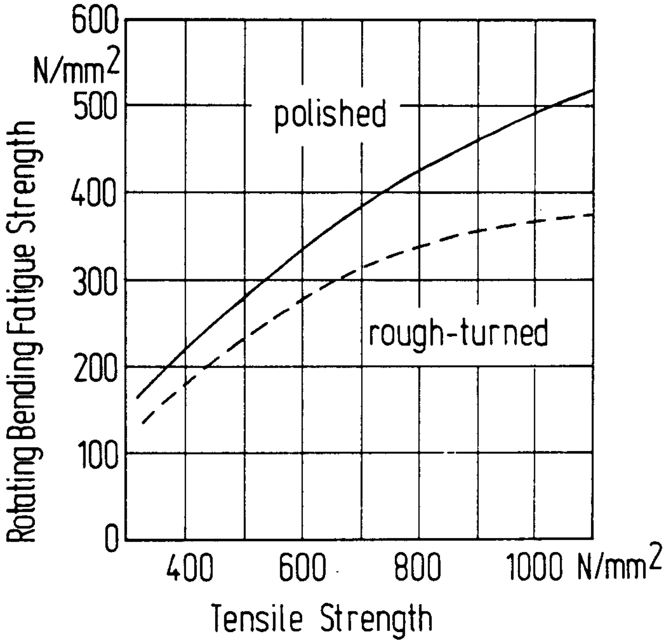


Fig. 1: Endurance limit of slightly and strongly Polished steel specimens with different tensile strengths

Fig. 2: Influence of polishing and rough-turning on the fatigue strengths of steels with different tensile strengths

In 1932 G. A. Hankins and M. L. Becker /6/ observed a marked reduction in the fatigue strength of spring steels due to decarburation effects. When the decarburized surface layers of the forged specimens was taken off by machining, the fatigue strength increased. As can be seen from Fig. 3, in the case of very high-strength steels, the fatigue strength of the as-forged specimens was only about 20 % of that of the machined ones. This is one of the earliest documents showing in which dramatic way surface machining can influence the fatigue behaviour of materials with imperfect surface layers.

Not before 1936, it was shown by W. Ruttmann /7/ that due to turning, grinding and polishing, surface residual stress states occur, which penetrate to a certain depth into the machined material. After polishing, compressive residual stresses up to 600 N/mm² were determined in high-strength steels.

The first thorough investigation of the quantitative consequences of the surface roughness on the fatigue strength was performed by E. Siebel and M. Gaier /8/. For several steels and non-ferrous alloys, the surface roughnesses after performing various machining methods were measured and characterized by the maximum depth of surface grooves R. Different correlations were found between the fatigue strength and R for differently heat-treated steels. However, no change in the fatigue strength was observed, provided that R was smaller than a critical value R_0. Fig. 4 shows a typical result of this work. The so-called surface fatigue factor

$$m = \frac{\text{fatigue strength for surface roughness } R_t}{\text{fatigue strength of smooth specimens}}$$

is drawn versus the logarithm of R_t. The results are valid for push-pull and rotating bending tests.

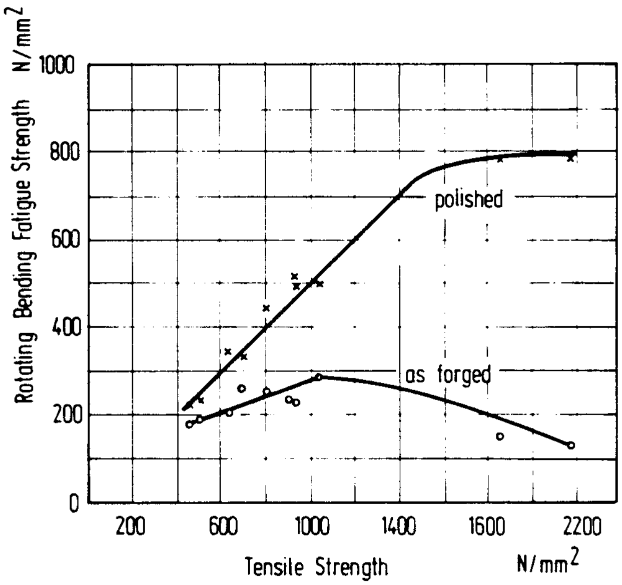


Fig. 3: Fatigue strengths of decarburized and of decarburized and machined spring steels

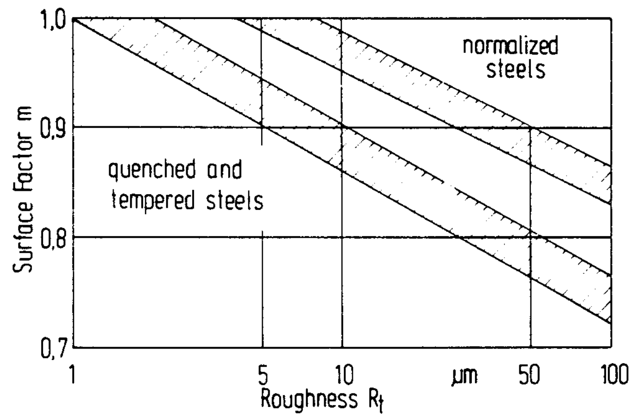


Fig. 4: Relation between surface fatigue factor and surface roughness for normalized and quenched and tempered steels

3. Surface Strengthening by Rolling or Pressing

Tab. 2 summarizes some important contributions to the field of surface strengthening by rolling or pressing, which are documented in the freely accessible literature. Hints to earlier applications of rolling as a finishing process /1/, as mentioned in the introduction to this paper, were not included.

The first experiments making evident that rolling effects the fatigue behaviour of metallic materials were performed by O. Foeppl /9/. Fig. 5 shows the apparatus applied for the surface treatment of smooth cylindrical bars. The rolling pressure of the three rollers was simply adjusted by screws. In the middle part of the picture, the general results of reversed torsion fatigue tests performed with cold-rolled steel specimens (Foeppl said: "surface compressed ones") are compared with those performed with polished specimens. It can be concluded that the rolling treatment improves the fatigue behaviour of the materials investigated.

Table 2: Development of surface strengthening by rolling or pressing

Author(s)	Year	Statements/Proposals	Ref.
O. Föppl	1929	Increase of numbers of cycles to failure due to surface rolling	9
G. S. V. Heydekampf	1930	Cold rolling raises fatigue or endurance limits of steels	10
W. Fahrenhorst G. Sachs	1931	Evidence of a three-axial residual stress state due to a rolling surface finish on drawn rods	12
H. Isemer	1931	Cold-rolled screw threads exhibit improved fatigue behaviour	14
A. Thum H. Wiegand	1932	Bolted joints of high-strength steels with surface rolled threads show increased fatigue strength	15
E. Hottenrott	1932	Enhancement of corrosion fatigue strength of steels due to surface rolling	21
A. Thum H. Ochs	1932	Surface rolling of smooth and notched parts improves corrosion fatigue behaviour	22
A. Thum F. Wunderlich	1933	Improvement of press-fitted axle assemblies due to cold-rolled partners	23
H. Bühler	1935	Residual stress analysis on rods after surface finish rolling	13
O. J. Horger	1935	Increase in fatigue strength of cold-rolled steel parts.	24
US-Patents Nr. 21 14 978/9	1938	Cold-rolling manufacturing equipment	25
A. Thum E. Bruder	1938	Cold-rolling improves the fatigue strength of filleted shafts	16
G. Sachs	1939	Improving aircraft propellers by surface-rolling	27
O.J. Horger T.V. Buckwalter H.R. Neifert	1944	Fatigue improvement of filleted parts with large diameters	26
G.N.J. Gilbert K.B. Palmer	1953/54	Improvement of fatigue strength of cast iron by surface rolling	28

These and other findings were summarized by G. S. V. Heydekampf and published 1930 in the September issue of "The Iron Age" /10/. In this publication, also a remarkable observation concerning crack initiation was described, which is shown in the lower part of Fig. 5. In rotating bending fatigue experiments, it was observed that the fatigue failure started from small slag inclusions beneath the surface. The crack initiation site was in the centre of a small elliptical area. Crack propagation occurred towards the cold-rolled part of the cross-section, although the loading stress was higher there. The influence of surface notches seemed to have been eliminated by the rolling process. In polished but not rolled specimens, cracks initiated at the very surface, probably at small slag inclusions.

Using the boring-out method /11/, W. Fahrenhorst and G. Sachs /12/ investigated in 1931 that the triaxial residual stress state of a drawn shaft was changed markedly by surface rolling and polishing. Typical results are shown in Fig. 6. As can be seen, rolling converts the axial and tangential surface tensile residual stresses into compressive ones. Later on, H. Buehler /13/ determined the complete residual stress state of steel rods which were stress relief annealed before applying smooth surface finish rolling (in German: "Prägepolieren").

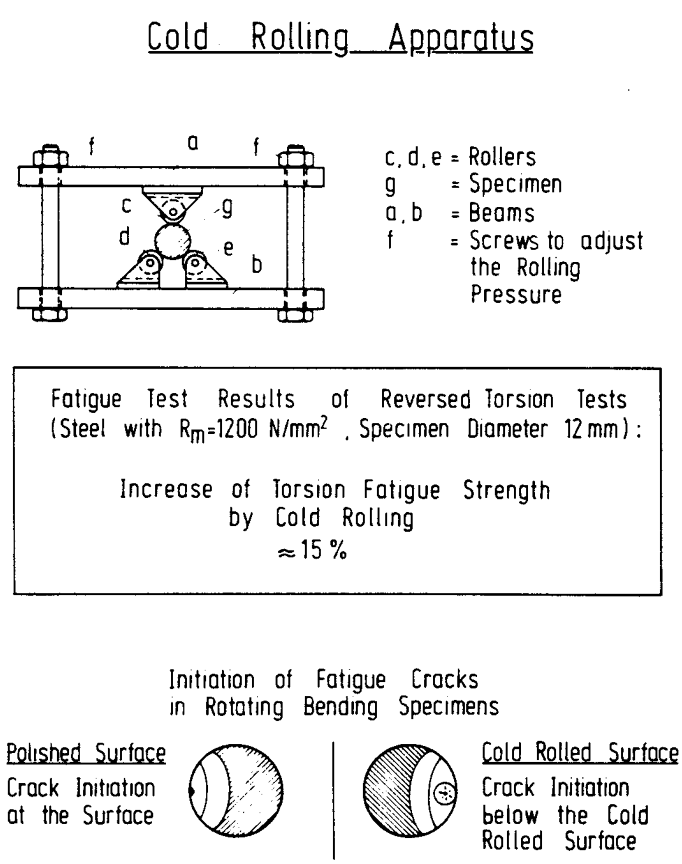


Fig. 5: Cold-pressing apparatus used by O. Foeppl and some fatigue data obtained with cylindrical specimens

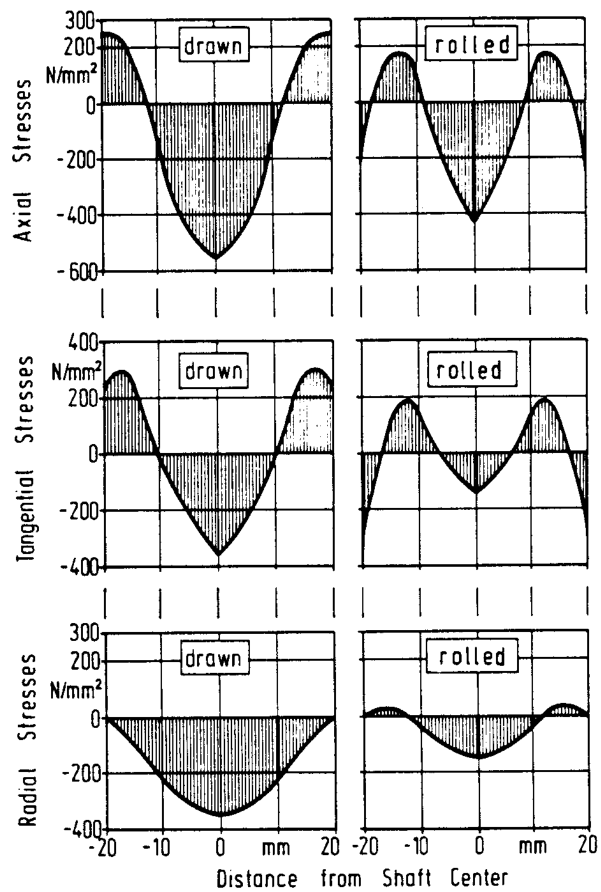
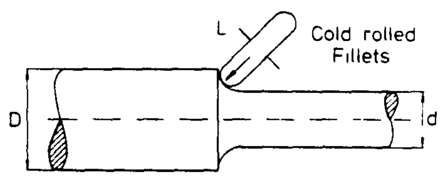


Fig. 6: Triaxial residual stress state of a drawn (left) and a drawn and cold-rolled shaft (right)

In the early 1930's, O. Foeppl extended his surface rolling experiments to notched parts. One of his co-workers, H. Isemer /14/, investigated enhancements by 20 % up to 65 % of the rotating bending fatigue strengths of screw threads. At the same time, also A. Thum and co-workers /15 - 17/ started to work in this particular field. Numerous fatigue experiments were carried out with the aim to evaluate quantitatively the influence of surface rolling on the fatigue resistance of notched specimens and components.

Also in the case of steel shafts with fillets of different stress concentration factors, relatively strong improvements of the appertaining fatigue strengths due to rolling were observed. Typical results are summarized in the left-hand part of Fig. 7. Fatigue strength increases between 30 and 68 % were reported.



	Specimens similar to Components				Original Shaft with Fillets
Diameter D [mm]	24.2	22	22	21.6	168
Diameter d [mm]	15	17	17	18	133
Stress Concentration Factor K_t	2.9	2.2	2.2	2.2	2.2
Tensile Strength [N/mm^2]	835	910	600	400	700
Rolling Load L [kN]	3.4	6.8	5.05	2.45	6.7
Increase of Fatigue Limit [%]	30	68	56	57	30
Reference	Thum, Bruder	Thum, Bruder	Thum, Bruder	Thum, Bautz	Horger, et al
Year	1938	1938	1938	1936	1944

Fig. 7: Improvement of rotating bending fatigue strengths of filleted shafts by cold-rolling

To explain the large improvements of the fatigue resistance due to cold-rolling (pressing), two courses of thoughts were applied in Germany in the early 1930's which are schematically illustrated in Fig. 8. According to O. Foeppl /9, 18/, the compression of the material near the surface should be the main reason for the gain of fatigue resistance. A. Thum /20/ strongly opposed to this, since he believed that the existence of compressive residual stresses in and beyond the cold-rolled surface was responsible for the enhanced fatigue properties. He argued that the superposition of loading and residual stresses determines the effective stress distribution of a bending specimen with reduced stress values in the tensile-loaded part. Fig. 9 illustrates the situation assumed for both smooth and notched specimens according to the work of H. Oschatz /20/.

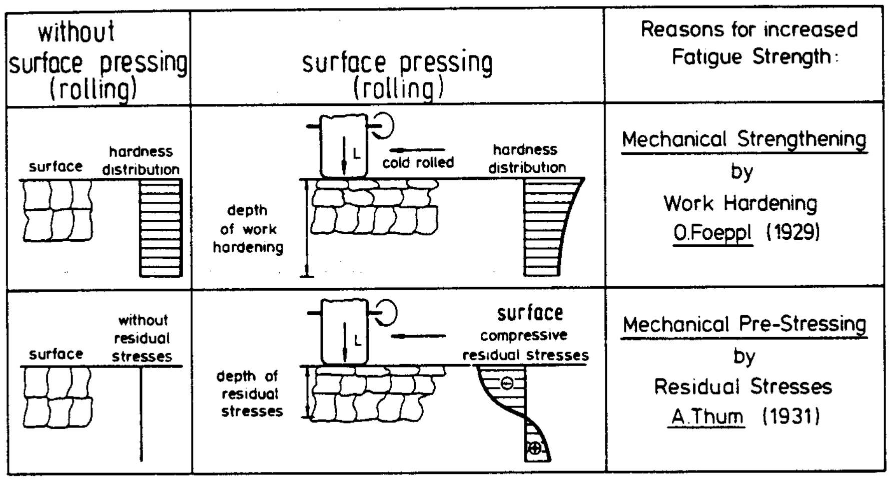


Fig. 8: Interpretation of surface pressing (rolling) effects according to O. Foeppl and A. Thum

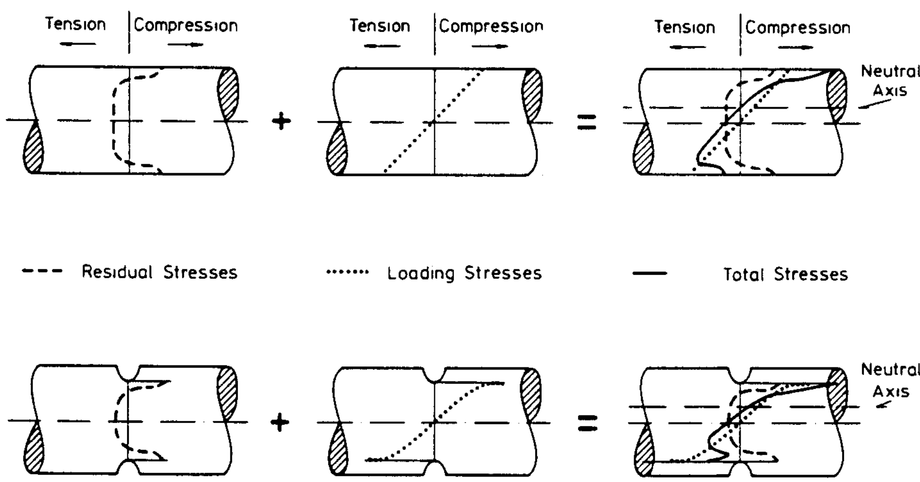


Fig. 9: Superposition of residual and loading stresses of smooth and notched specimens according to A. Thum and H. Oschatz

In 1932, two further very important publications appeared which clearly illustrated that rolling improves the corrosion fatigue behaviour of smooth and notched steels. E. Hottenrott /21/ performed fatigue tests with various plain carbon steels up to $2 \cdot 10^6$ cycles in tap water and showed that decreases in the corrosion fatigue strength could be compensated by surface rolling. A. Thum and O. Ochs tested /22/ cylindrical specimens with and without a pre-stressed cross-hole under rotating bending conditions in different atmospheres. Typical results of these investigations are shown in Fig. 10. In laboratory air as well as in tap water from Darmstadt, the locally pressed specimens exhibit a better fatigue behaviour than the unpressed ones. It was clearly demonstrated that the constructional steel of the German grade St 37 does not have a fatigue limit under corrosion fatigue conditions.

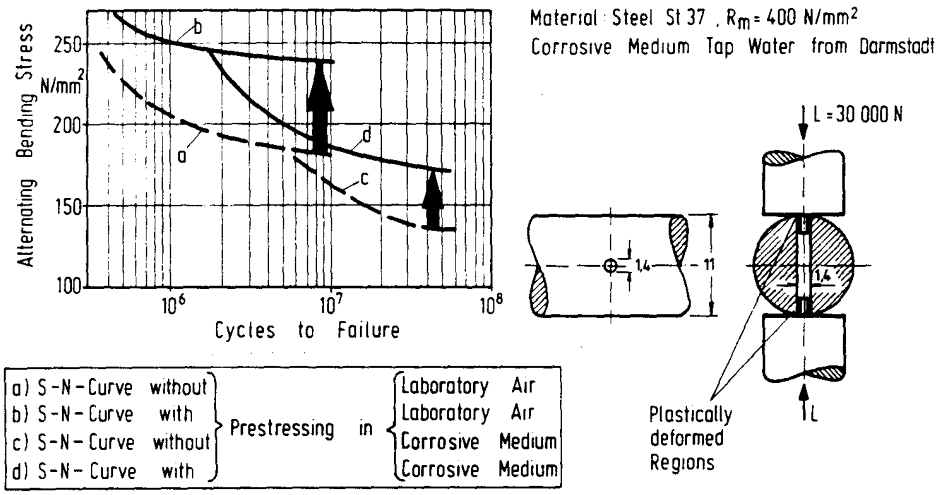


Fig. 10: Improvement of corrosion fatigue behaviour of notched and cold-pressed steel specimens

One year later, in 1933, A. Thum and F. Wunderlich /23/ observed for the first time that the fretting fatigue properties of cyclically loaded component pairings like press-fits can markedly be improved by surface rolling. Surface strengthening was stated to be a useful means to reduce in the slip zone of friction pairings the effective oscillating shear stresses so that adhesive-abrasive wear leading to surface cracking was reduced. As an example, Fig. 11 shows the fatigue behaviour of different shrink connections which were tested in rotating bending. Comparing the rotating bending fatigue strength of these parts with that of smooth samples, it becomes evident that the fatigue strength of the former can be influenced positively by a combination of cold-rolling the shaft surface and constructive measures concerning the load transmission geometry. Since the crack formation is suppressed extensively by the compressive residual stresses in the friction zone of the shaft surface, no fatigue limit will be observed.

Design of Axles Tested	Rotating Bending Fatigue Strength [N/mm²]	Related Fatigue Strength $\frac{\sigma_{bW\ Axle}}{\sigma_{bW\ Press\ Fits}} \cdot 100$ [%]
14 mm Ø	290	100
14 mm Ø	155	55
cold rolled Axle	270	93
	180	62
	210	72
cold rolled Axle	300	104

Material Ck 60, Tensile Strength = 670 N/mm²

Fig. 11: Improvement of fatigue properties of press-fits by cold-rolling and designing

Parallel to the German investigations just described, O. J. Horger /24/ applied the surface rolling concept in the United States to improve the fatigue strength of steels. He published his work in 1935. An equipment for rolling larger dimensioned shafts /25/, USA-patented in 1938, is shown in Fig. 12. This three-roller device "provides a satisfactory mechanical arrangement for applying a known pressure on cylindrical members". It was "designed to roll 6- through 15-inch diameter shafts by reversing". "Two rollers have a relatively sharp contour radius of 1 1/2 inch while a third roller has a 5-inch contour radius. The former gives depth of workhardening and the latter a smooth finish". Also larger dimensioned shafts with fillets (d = 133 mm and D = 168 mm) have successfully been surface-rolled /26/. Characteristic data are inserted in the right part of Fig. 7. The observed increase in the fatigue limit was 30 %.

Worthwhile to mention in this connection is also the work of G. Sachs /27/, who documented in 1939 that aircraft propellers manufactured from a magnesium alloy can gain a marked improvement of their fatigue behaviour, if they are cold-rolled. Finally, it should be pointed to the work of G. N. J. Gilbert and K. B. Palmer /28/ who gave evidence that surface rolling enhances the fatigue properties also in the case of cast iron.

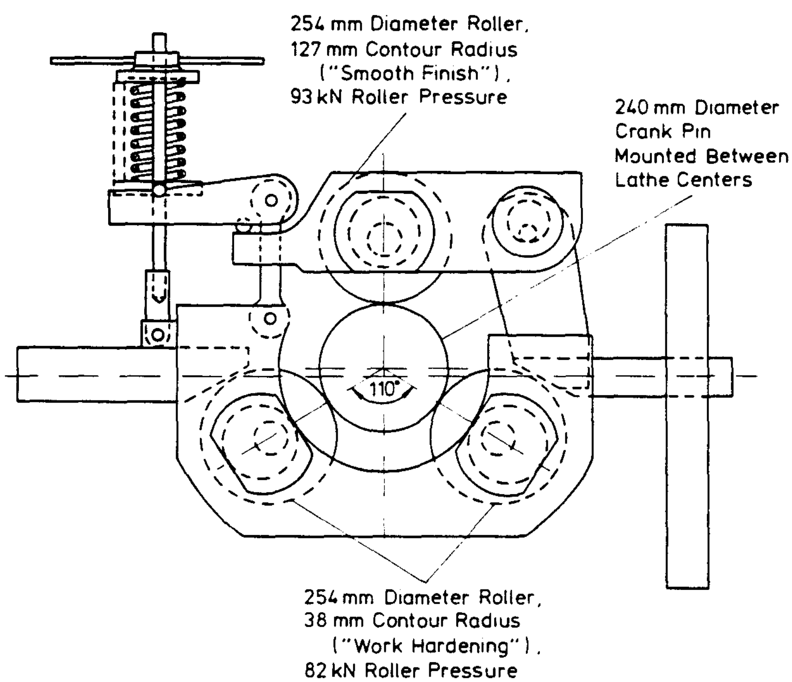


Fig. 12: US-patented surface rolling equipment for shafts of large diameters

4. Surface strengthening by hammering, shot blasting or shot peening

Tab. 3 summarizes some important contributions to this field for the period from about 1920 to 1960. There is no doubt that very early hammering or hand peening was directly or indirectly used to improve the fatigue life of technical components or parts /1, 2/. However, no quantitative data can be found in literature up to the 1920's. For example, peening of piston rings was a well-accepted technology. In the early 1920's, it was reported that handpeening of crankshaft fillets of European race cars with specific hammers resulted in an enhancement of their fatigue resistance. However, shot blasting or shot peening used as a process of cold working of metal surfaces by pelting with granular shots of relatively high velocity was realized not earlier than in the middle of the 1920's. It obviously was the consequence of the accidental observation that parts which were sandblasted for cleaning purposes showed an increased fatigue life.

Table 3: Development of surface strengthening by hammering, shot blasting or shot peening.

Author(s) Institutions	Year	Statements/Proposals	Ref.
American automotive industries	1926/28	Steel shot blasting	1
E.G. Herbert	1927	Workhardening due to abrasion ("cloudburst process")	29
O. Föppl	1929	Cold-hammering improves bending fatigue behaviour of structural steel	9
German Patent Nr. 573 630	1929	Steel shot blasting of springs	30
E.E. Weibel	1935	Increased fatigue resistance due to shot blasting	31
J.H. Frye G.L. Kehl	1938	Influence of cleaning procedures on fatigue behaviour	32
R.Z. v. Manteuffel	1939	Improved fatigue strength of sand blasted steel springs	33
F.P. Zimmerli	1940	Shot blasting and its effect on fatigue fracture life	34
H. Wiegand	1940	Increased security of surface treated aircraft motor components against fracture	35
J.O. Almen	1943	Improved fatigue strength of shot peened engine parts; method for measuring peening effects	36 37 38
E.W. Milburn	1945	X-ray diffraction applied to shot peened surfaces	39
H.O. Fuchs R.L. Mattson	1946	Residual stress measurement at shot peened springs	40
A.J. Gould U.R. Evans	1948	Improved corrosion fatigue behaviour of shot peened parts	41
J.C. Straub D. May	1949	Stress peening yields superior enhancements of fatigue strength	42
R.L. Mattson J.G. Roberts	1959	Analysis of residual stress states induced by strain peening	43

The earliest work concerning the process which is now known as shot peening was the paper "The workhardening of steel by abrasion" published by E. G. Herbert in 1927 /29/. In this paper, the so-called "cloudburst process" ("a rain of steel balls") was described, which produces a workhardened surface on metals by pelting with hard steel balls. However, E. G. Herbert was only interested in increasing the hardness of the metals investigated. No indication can be found that the cloudburst method should also be used-for improving the fatigue behaviour of the materials under investigation.

The first scientist who stated a beneficial influence of peening on the fatigue resistance of metals was O. Föppl in 1929 /9/. Four of five specimens which were cold-worked with a hammer of a 4 mm ball end broke under fatigue loading in the non-hammered section. In the same year, a German patent on steel shot blasting was published /30/.

Then, not earlier than 1935, E. E. Weibel /31/ quantitatively described the use of shot blasting to improve the fatigue failure behaviour of steel wires. Three years later, J. H. Frye and G. L. Kehl /32/ discussed the effects of some cleaning methods on the fatigue resistance of steels and demonstrated that only in particular cases, shot blasted specimens showed an increased fatigue limit. Typical results of this investigation are shown in Fig. 13. As can be seen, sand blasting never enhanced the fatigue properties. However, blasting with steel shot or steel shot and steel grit produced marked improvements of the fatigue limit.

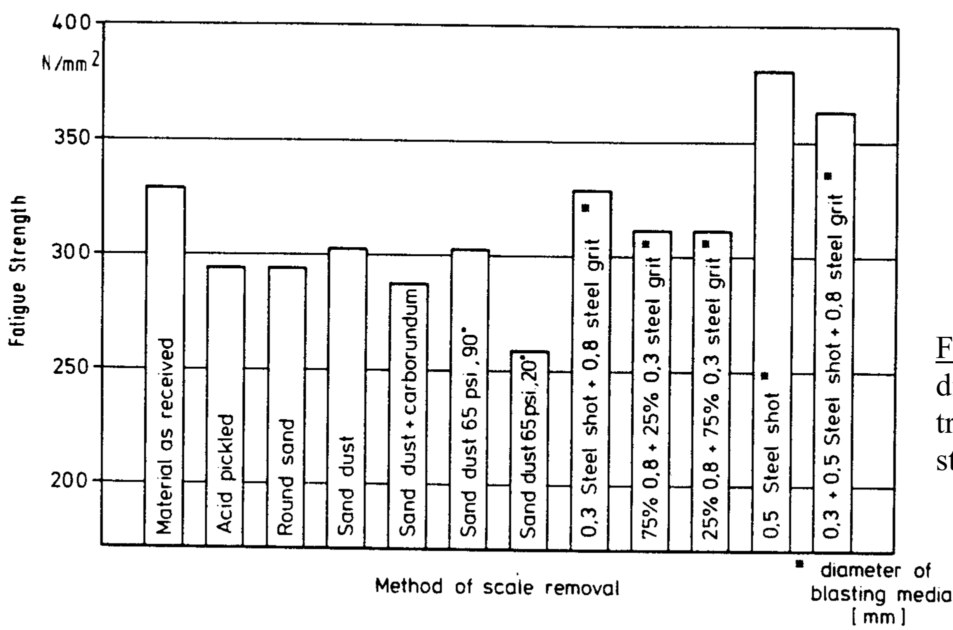


Fig. 13: Influence of different shot blasting treatments on the fatigue strength of steel wires

On the other hand, in the period from 1936 to 1939, R. Z. von Manteuffel who systematically studied the consequences of sand blasting on the fatigue behaviour of quenched and tempered chrome vanadium steel springs clearly demonstrated that accurate sand blasting can produce beneficial effects on the fatigue life of springs. He summarized the results of this work in his doctor thesis /33/ published in 1939.

Very important for the history of the surface strengthening processes is the paper "Shot blasting and its effect on fatigue life", which was published in 1940 by F. P. Zimmerli /34/. Besides of the statement that already in 1929, the company with which the author was associated shot blasted springs, for the first time the results of a systematic study of the influence of a process parameter on the fatigue behaviour of blasted springs were presented. Fig. 14 shows characteristic data. The springs investigated in these experiments were not decarburized. In fluctuating torsion tests with constant τmin a fatigue strength

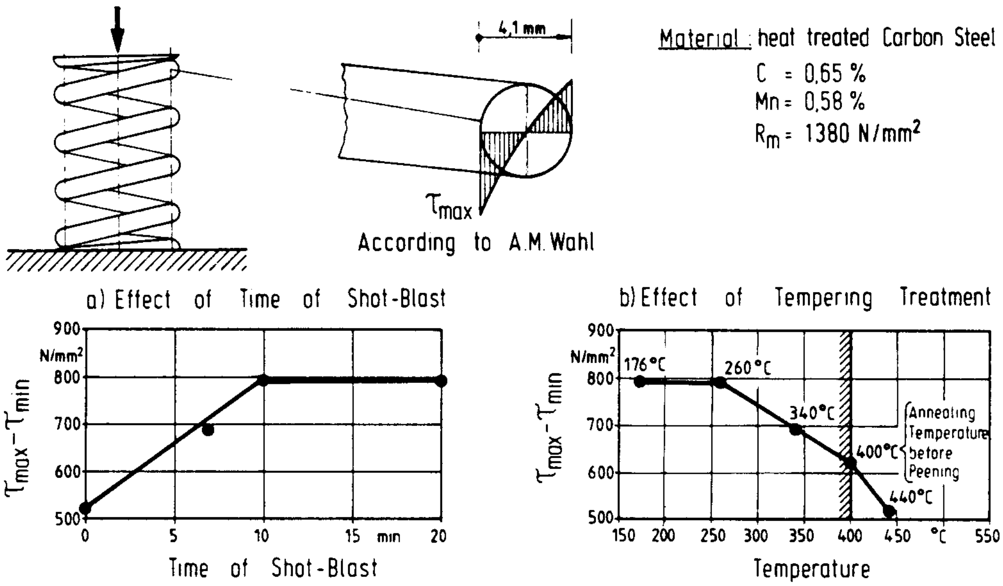


Fig. 14: Fatigue strength of springs in dependence of shot blasting time and subsequent heat-treating

of about 500 N/mm² in the unblasted state was observed. As can be seen, markedly higher fatigue strengths were obtained with blasted springs. However, an increase in the blasting time up to values higher than 10 min did not further improve the fatigue resistance. Blastings with steel balls of 0.39 mm and 1.19 mm diameter changed the surface roughness of the springs, but did not influence the fatigue lifetimes. The right part of Fig. 14 illustrates that the improvement of the fatigue strength due to blasting can completely be reduced by annealing at sufficiently high temperatures. In the mentioned paper, F. P. Zimmerli closed the discussion with the following statement:

> "The development of this process and its industrial application will in our opinion be a great step forward in industrial metallurgy. New fields are now awaiting exploration and many steels can be put to new uses."

In the course of the development of shot peening in Germany, H. Wiegand /35/ systematically studied for the first time the influence of shot blasting on the fatigue resistance of aluminum and magnesium alloys. The scatter of fatigue resistance data obtained with electron castings could without doubt be attributed to irregularities in the castings. Besides of the improved endurance limits found for the aluminum and magnesium alloys investigated, the author also pointed out the reduced production time for surface finish operations when parts were shot blasted.

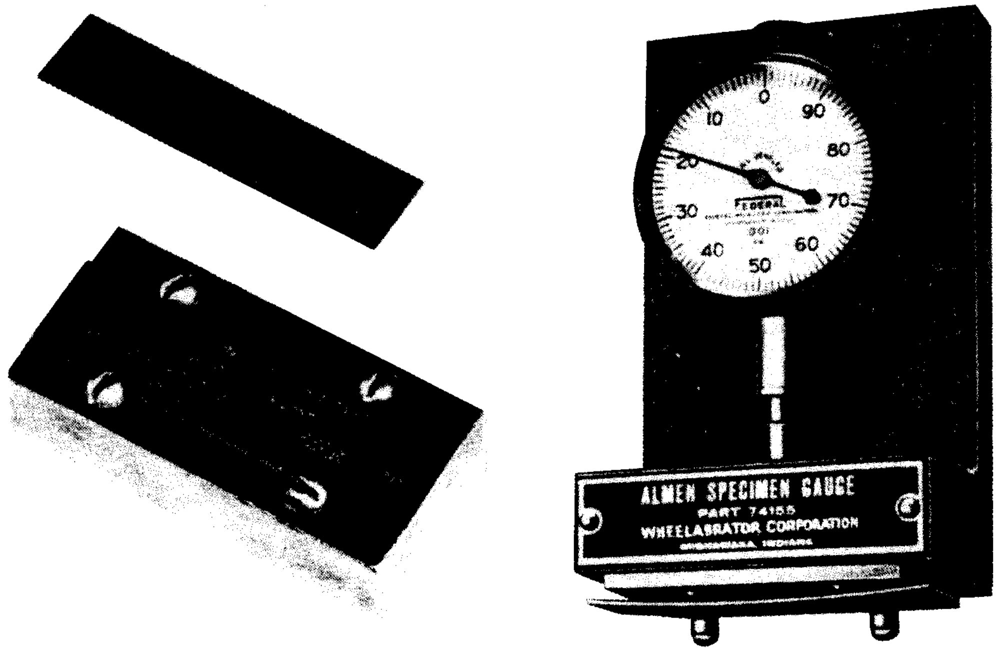


Fig. 15: Almen test devices

The development of the shot peening process successfully advanced in the following years. In practice, a large number of further applications were realized. However, the contributions of J. O. A1men /36 - 38/ were of particular importance for the improvement of the shot peening procedures. He has done outstanding work in many research projects including surface strengthening effects caused by shot peening. He also invented and introduced the Almen Gauge, a single device for measuring the intensity of a shot peeving treatment. The Almen Test has without doubt to be assessed as an important step in the extension of the industrial potential of shot peening. The Almen Strip and the Almen Specimen Gauge shown in Fig. 15 became the most effective device in controlling automated shot peeving productions.

It was not before 1945 that the surface residual stress values of shot peeved parts were determined quantitatively. E. W. Milburn /39/ was the first to apply X-ray diffraction to shot peeved surfaces. Nearly at the same time, a thorough investigation of the residual stresses of shot peeved torsion bar springs was performed by H. O. Fuchs and R. L. Mattson /40/. Two years later, in 1948, A. J. Gould and U. R. Evans /41/ showed that shot peeved parts reveal an improved corrosion fatigue behaviour. These observations initiated several further investigations on this important subject.

Another outstanding development for increasing the lifetime of technical parts is the stress peening process introduced for the first time by J. C. Straub and D. May in 1949 /42/. This procedure is a special kind of shot peeving during which the part is statically stressed in the same direction as the stress to be sustained in service. It could be shown that stress peening gives a substantial improvement in lifetime of leaf springs and coil springs. Characteristic examples are presented in Fig. 16.

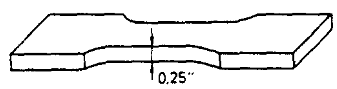
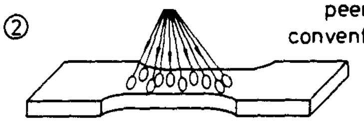
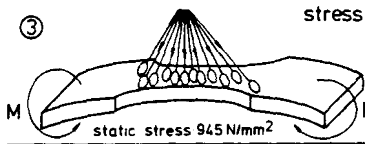
Material SAE 9260 steel, quenched and drawn, 40 to 45 HRC	Pulsating Tension Stress 945 N/mm²		Improvement of Minimum Lifetime
	Cycles to Failure		
	Minimum	Average of group	
① not peened 	38.000	55.000	1
② peened conventionally 	131.000	1.132.000	3,45
③ stress peened 	923.000	7.264.000	23,2

Fig. 16: Improvement of fatigue life by shot peening and stress peening

The sketch of the historical development of shot peening shall be concluded with the citation of the important work of R. L. Mattson and J. G. Roberts /43/ published in 1959. The authors analyzed the residual stress states induced by strain peening in and near the very surface of leaf springs. Fig. 17 illustrates that the sign of the applied strain during peening markedly influences the fatigue behaviour of the peened parts. Specimens peened in tension exhibit larger compressive residual stresses in the surface than conventionally shot peened ones. In the right-hand part of the figure, the resulting residual stress distributions beneath the surface are shown.

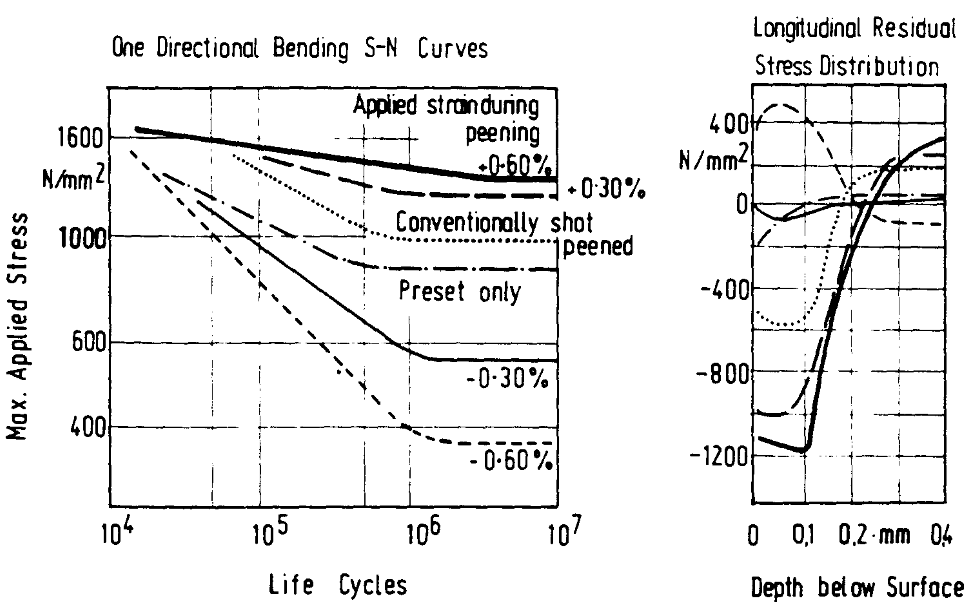


Fig. 17: Woehler-curves and appertaining residual stress distributions of differently strain peened leaf springs

5. Some newer contributions to the improvement of the fatigue behaviour of metallic materials by surface strengthening

In the last 25 years, a large amount of basic and applied work was done to come to a better understanding of the processes which at least are responsible for the improved fatigue response of surface strengthened materials and which also determine the limitations of the application of surface strengthening methods. Furthermore, investigations were carried out to gain more experiences in the application of surface strengthening procedures to particular areas of technology.

From the large amount of interesting contributions to the field of surface strengthening, for reasons of space, only some observations can exemplarily be selected and described in the last part of this paper. More information can be obtained from newer conference proceedings /44, 45/ and from some review papers which appeared recently /46 - 50/.

5.1 Surface strengthening by machining

The surface states produced by shape-forming machining processes depend on many parameters. Apart from materials composition and geometry, the pre-machined heat-treatment of the parts is of essential importance for the effectiveness of the mechanical surface processings which are supposed to improve the fatigue behaviour. An objective assessment of the consequences of machining processes on the fatigue strength was only possible when surface states with the same roughness, the same workhardening state, but with residual stresses of different signs and magnitudes could be produced. In 1976, this problem was successfully solved /51/. It was shown that the bending fatigue strengths of normalized steel specimens were independent of machining surface residual stresses. However, quenched and tempered as well as hardened steels showed a marked influence of the surface residual stresses on the fatigue behaviour, in the course of which hardened steels revealed a stronger residual stress sensitivity than quenched and tempered ones.

In the meantime, the same statements could be confirmed for machined notched specimens /52/. A typical result is displayed in Fig. 18. Bending notch fatigue strengths are drawn vs. surface residual stresses in the root of notched specimens with K_t = 1.7 of a plain carbon steel (Ck 45). The values belong to comparable workhardening and roughness states in the notch root. Neither positive nor negative residual stresses show any influence on the fatigue strength of normalized specimens in contrast to quenched and tempered specimens and hardened ones. It is remarkable that quenched and tempered specimens with large positive residual stresses exhibit smaller fatigue strengths than normalized ones.

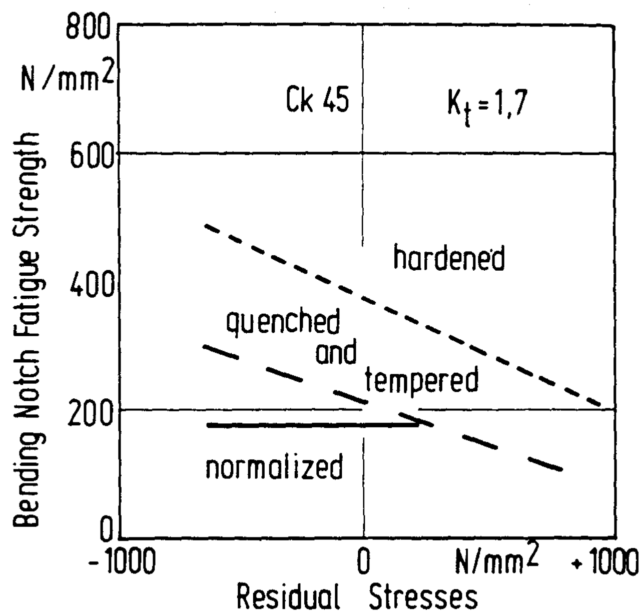


Fig. 18: Influence of machining residual stresses on the notch bending fatigue strength on normalized, quenched and tempered and hardened steel specimens

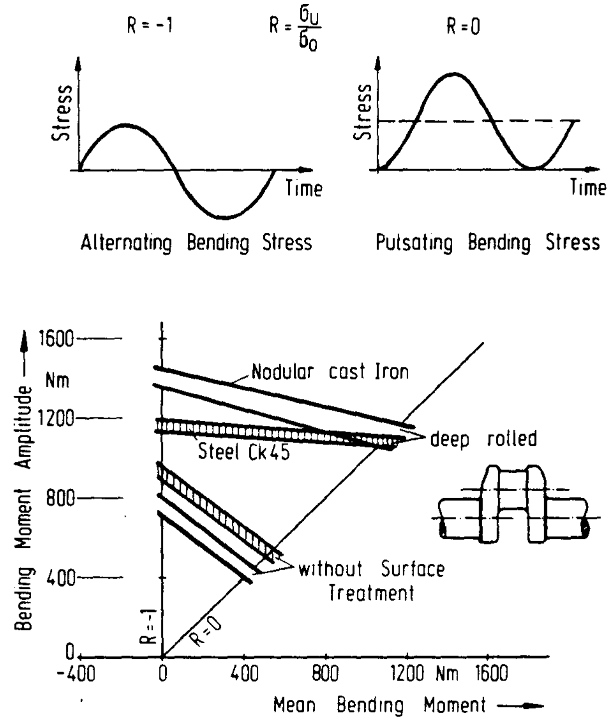


Fig. 19: Fatigue properties of cast and forged crankshafts with and without surface rolling

5.2 Surface strengthening by deep rolling

Surface rolling has gained several new fields of application during the last years. An important example is the surface rolling of relief grooves of casted crank shafts made of malleable cast iron and nodular cast iron, respectively. In 1969, a very important paper concerning this field was published /53/. The investigations were carried out with nodular cast iron of the quality GGG 70. For reasons of comparison, the same experiments were also performed with forged crankshafts of the steel Ck 45 in the quenched and tempered state. The Haigh-diagram shown in Fig. 19 illustrates that the fatigue strengths of the investigated parts, which depend on the applied mean bending moments, are strongly influenced by the applied surface rolling treatment. At lower mean bending moments, the bending fatigue strengths of the rolled nodular cast iron are higher than those of the rolled plain carbon steel. It is interesting to note that the ranking of both materials in the rolled and unrolled states is inverse.

Also with respect to the optimization of process parameters in the field of surface rolling, significant progress was achieved recently /54/. Starting from maximum bending fatigue strength values of small specimens obtained with optimized rolling forces, a procedure was developed to calculate for given geometries of tools and specimens the required rolling forces also for specimens of larger dimensions /55/.

In Fig. 20, typical results of deep-rolled smooth and notched specimens ($K_t = 2.0$) of a steel 37CrS4 with a tensile strength of 1150 N/mm^2 are shown /56/. The bending fatigue strength values are drawn as a function of the rolling load which is expressed by the equivalent stress calculated according to the distorsion energy hypothesis considering rolling to be a Hertzian pressure. It can be seen that under optimized rolling conditions, the fatigue strength of the notched specimens is greater than that of the smooth ones. Obviously, the notch effect on the fatigue strength can completely be removed by surface rolling.

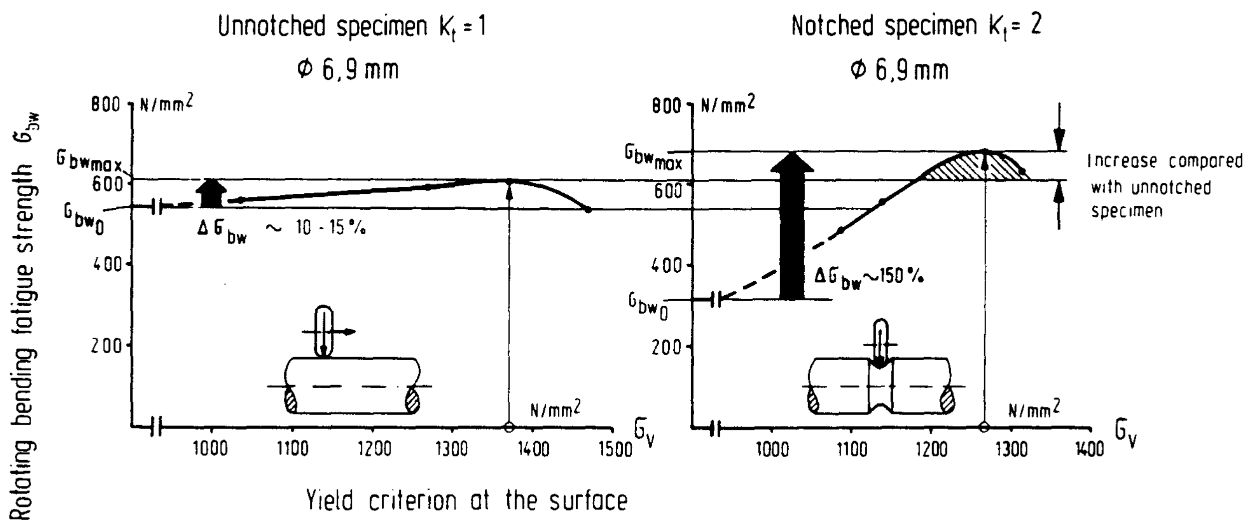


Fig. 20: Increase in fatigue strength of smooth (left) and notched (right) specimens of 37Cr54 (tempered, R_m = 1150 N/mm^2) due to deep rolling with different rooling forces

5.3 Surface strengthening by hammering or shot peening

In 1964, it was shown how the improved bending fatigue strength of notched and shot peened specimens of the quenched and tempered steel SAE 86 B 45 can be attributed to residual stresses and workhardening effects /57/. This progress could be achieved with Woehler-curves determined from unpeened and peened as well as from peened specimens the residual surface stresses of which were compensated by mean stresses of opposite sign but the same magnitude. A typical result is presented in Fig. 21, which is valid for a hardness value of 49 HRC. Compared with the Woehler-curve of the unpeened specimens, that of the peened specimens is markedly shifted to higher stress amplitudes. On the other hand, the Woehler-curve of the peened and mean-stressed specimens lies lower than that of the unpeened ones. It can be concluded that I. kind residual stresses are mainly responsible for the gain in fatigue strength and that the possibly existing small positive effect of workhardening may be compensated by surface roughness effects.

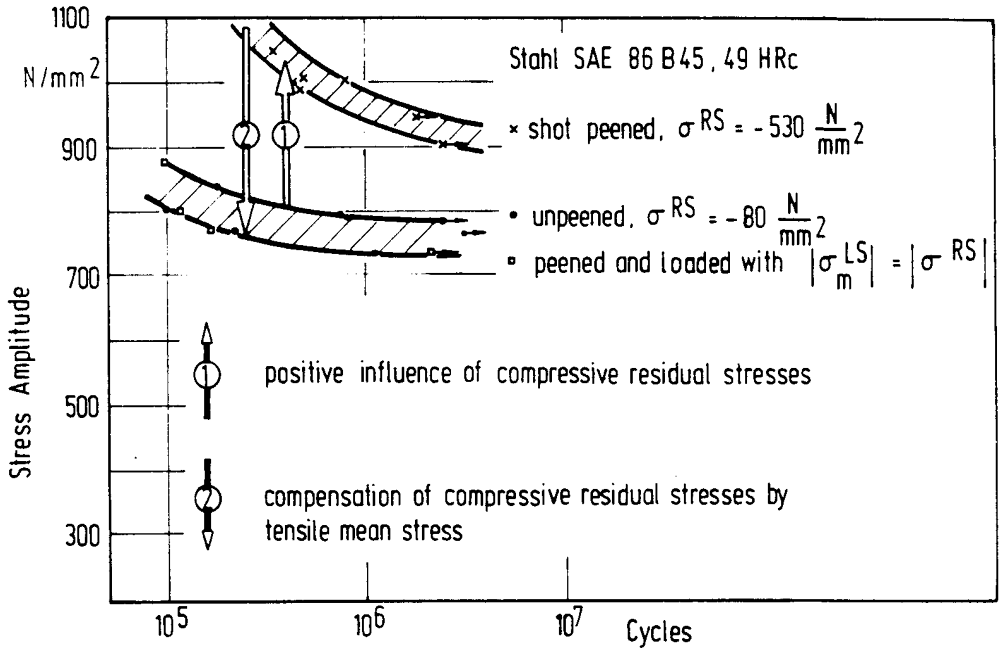


Fig. 21: Consequences of shot peening residual stresses and their compensation on the Woehler-curves of SAE 86 B 45

Another interesting contribution to the fatigue behaviour of hardened and shot peened steel specimens was published in 1979 in connection with the development of the local fatigue strength concept /58/. It was assumed that the measured axial residual stress distribution σRS(x) mainly determines the local fatigue strength $R_F(x)$ according to a modified Goodman equation $R_F(x) = R_{bF}\ (1 - \sigma^{RS}\ (x)\ /\ R_m)$ with x the distance to the surface, R_{bF} the fatigue strength of the residual stress-free material and R_m the tensile strength. In Fig. 22 the thick curves represent $R_F(x)$ for two shot peening treatments. The thin lines specify the loading stress distributions for different amplitudes of the applied bending moments. As can be seen, cracks initiate in agreement with the expectations at or in some distance to the surface, where the loading stresses exceed the local values of the fatigue strength.

For the time being, the potential of the sintering technique is widely used in the development of modern materials. An increasing demand can be stated for sintered parts with improved fatigue properties. In this respect, combinations of thermochemical and mechanical surface treatments are of particular interest. The possibilities of improving the fatigue behaviour of differently sintered FeCu- and FeCuNi-alloys with density levels of 7.1 and7.4 g/cm^3 by such methods were studied recently /59/. Unnotched cylindrical specimens with 10 mm diameter and notched cylindrical cantilever specimens with K_t = 1.49 and a diameter of 25 mm were tested. The experiments were performed with sintered, sintered and shot peened, carbonitrided as well as carbonitrided and shot peened specimens. A characteristic result is presented in Fig. 23. Fully reversed bending fatigue tests with 15 Hz resulted in the Woehler-curves shown. The applied shot peening treatment increased the fatigue

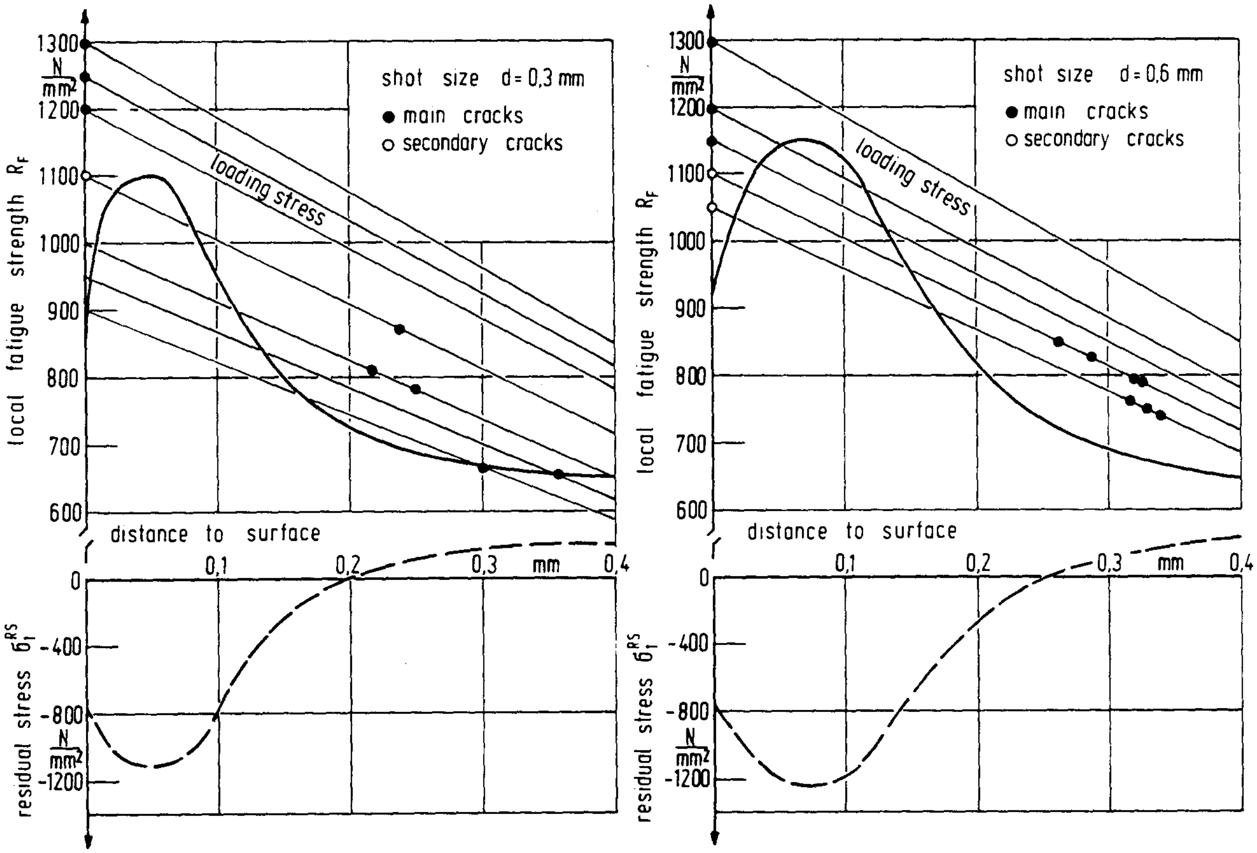


Fig. 22: Local fatigue strengths near the surface of shot peened bending specimens calculated according to the Goodman relation and experimentally determined crack sites

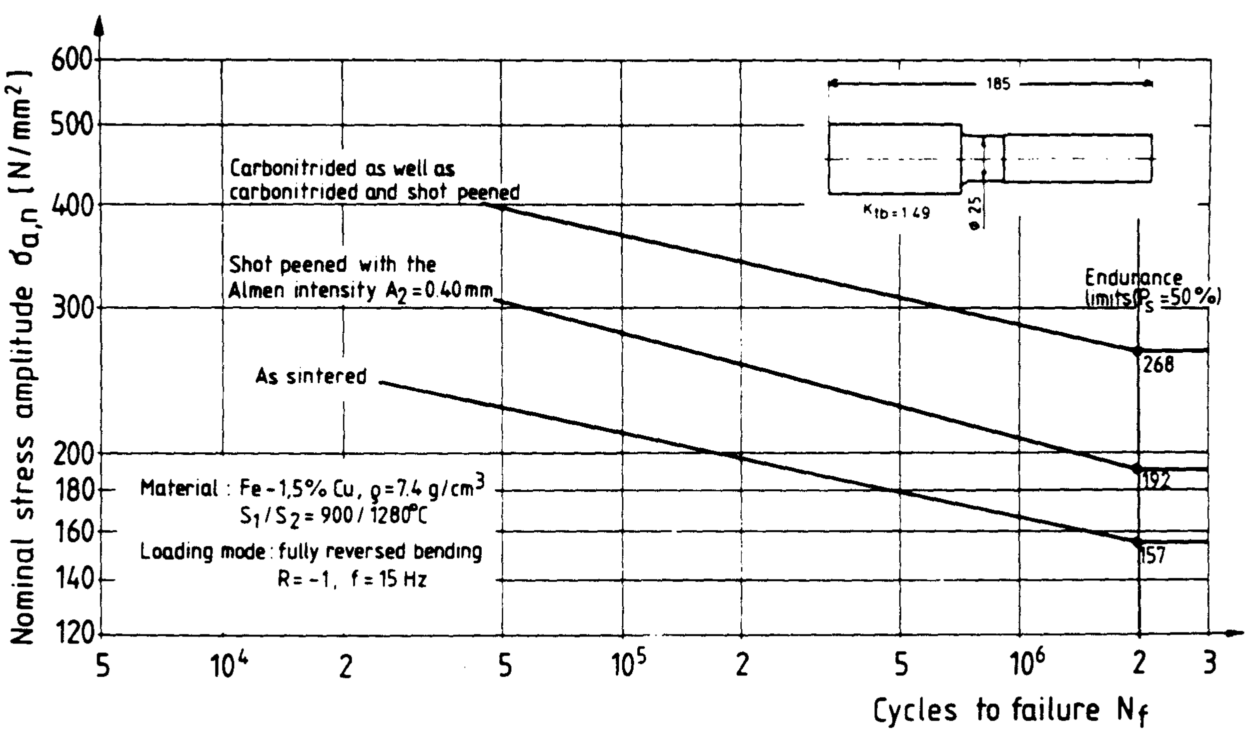


Fig. 23: Fatigue improvement of a sintered FeCu-alloy by shot peening as well as carbon nitriding and shot peening

strength of the sintered parts by 22 %. Carbonitriding, on the other hand, enhanced the fatigue strength of the sintered specimens by 72 %. However, subsequent shot peening carried out after carbonitriding yielded no further improvement of the fatigue behaviour of the notched specimens. It is interesting to note that the fatigue strengths achieved with the sintered materials considered are comparable with those of high quality nodular cast iron and wrought SAE 1046 steel.

In the last decade, strong efforts were also made to take full advantage of postweld improvement techniques for the purpose of enhancing the fatigue strength of welded structures. The most effective procedure in this respect comprises geometric modifications of critical welded areas and/or the introduction of beneficial residual stress states at this places. Frequently used techniques are hammering or shot peening. To apply these and other techniques to offshore welded structures, an "European Community Offshore Steels Research Programme" with various national programmes was established. These activities have recently be reviewed /50/. Weld toe hammer peening modifies the geometry of a weld seam and produces large surface compressive residual stresses. The effectiveness of hammering, which is carried out by a pneumatic system, depends on the power output, the hammer frequency and the number of passes. Remarkable results can be achieved using this method. Fig. 24 illustrates typical results /60, 61/. Woehler-curves for as-welded and four-pass hammered specimens with cruciform joints are shown. Furthermore, results are indicated for hammer peened and cathodic-protected specimens which were fatigued in seawater. At 2 • 10^6 cycles, an improvement of the fatigue strength of 145 N/mm², that is about 150 % is observed. If cathodic protection is applied in seawater, the fatigue behaviour of hammered joints is fully comparable to that observed in air.

Very recently, the postweld shot peening conditions for getting the best fatigue behaviour of welded high-strength structural steels were systematically optimized /62/. Constant amplitude tests on specimens and variable amplitude tests on full-scale parts were carried out, the welded joints of which were mechanically post-treated. It was clearly outlined that optimum shot peening requires the full knowledge of the relation between the peening parameters and the properties of the peened materials. Fig. 25 shows the fatigue strengths of butt-welded high-strength steels St E 500, St E 690 and St E 890 with yield strengths of

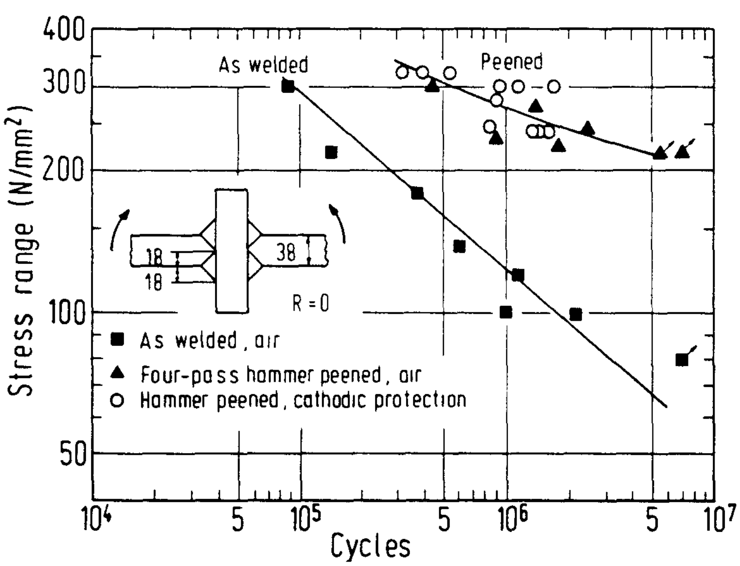


Fig. 24: Woehler-curves for as-welded and hammer peened specimens fatigued in air and seawater

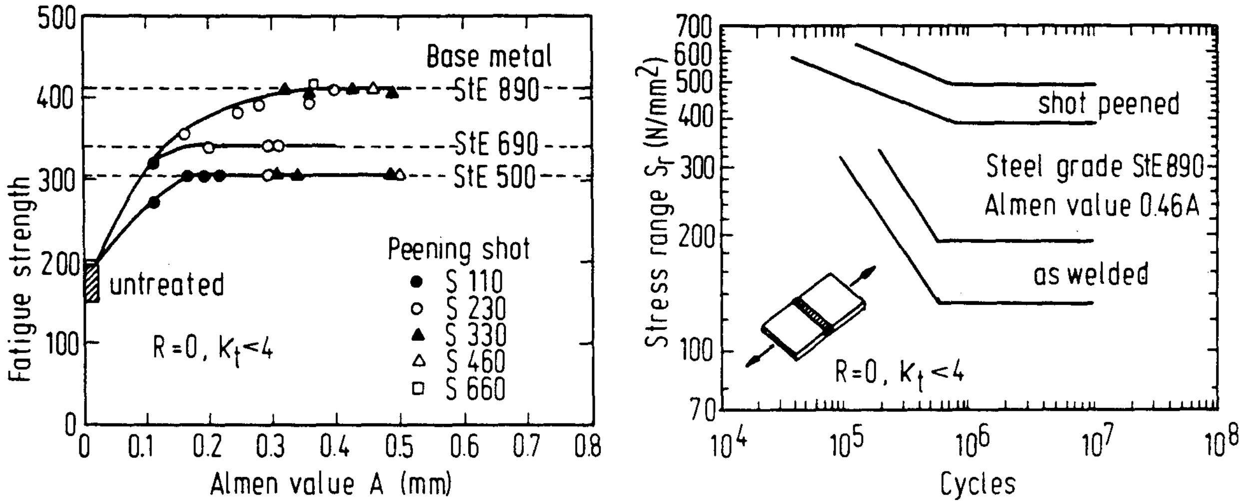


Fig. 25: Relation between Almen values and fatigue strength of butt welds of different high-strength steels

500, 690 and 890 N/mm² in dependence on the Almen value A. These results were derived from experiments of which one example is shown in the right part of Fig. 25. The Woehler-curves presented there belong to welded joints of St E 890 in the as-welded state and in the as-welded and subsequently, with 0.46 A, shot peened state. An improvement of the fatigue strength of the welded joint of more than 150 % can be stated.

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