Technische Universität Braunschweig

Institut für Füge- und Schweißtechnik

History of Shot Peening in Germany

Plenary Lecture

Prof. Dr.-Ing. Helmut Wohlfahrt

Content: History of major events, research activities of institutes, industrial activities

Events concerning shot peening in Germany

Early activities on shot peening (according to K.-H. Kloos, [1])

1927/28 Shot blasting, steel, American Automotive Industry

1929 **Cold hammering,** improving fatigue strength, steel, Föppl

Steel shot blasting, German patent, steel springs

1935 Shot blasting, improved fatigue strength of steel wires, detailed study, Weibel

1938 Steel shot blasting for cleaning, improved fatigue strength, Frye, Kehl

1939 **Sand blasting,** steel springs, improved fatigue strength, v. Manteufel

1940 **Shot blasting,** Al-, Mg-alloys, fatigue behaviour, Wiegand,

Events concerning shot peening in Germany

Early activities on shot peening (according to K.H. Kloos, [1])

1943 Shot peening, improved fatigue strength of engine parts, Almen test, Almen

1945 Shot peened surfaces, residual stresses by X-ray diffraction, Milbur

1946 Shot peened springs, investigation of residual stresses, Fuchs, Mattson

1949 Stress peening, superior enhancement of fatigue strength, Straub, May

1929/39 **Cold rolling,** increase of fatigue life and strength, 11 German citations: Föppl,Thum, Isemer, Hottenrott, Wiegand, Sachs (residual stresses 1931), Bühler

Events concerning shot peening in Germany

Some first impulses for research in Germany and consequences

Ca. 1970 Contact of ZF Friedrichshafen (gear manufacturer, Mr. Brugger) with Prof. Macherauch, Institute for Material Science, University of Karlsruhe: research programme on the improvement of the bending fatigue strength of a case hardened steel typical for gear manufacturing. Continued for many years, basic results.

Ca. 1970 Peen forming activities at the Institute of Metal Forming, Rheinisch-Westfälische Technische Hochschule Aachen, Prof. Kopp. Peen forming of components for aircraft structures, application of shot peening in cooperation with industry.

1977 Universities of Bochum (Institute for Materials) and later Hamburg-Harburg (Materials Science and Engineering), Prof. Lütjering, Dr. Wagner. Comprehensive studies on the consequences of shot peening for Ti-Alloys, subsurface crack initiation

Events concerning shot peening in Germany

Consequences of first impulses for research in Germany

Ca. 1979 Participation in the formation of the International Scientific Committee for Shot Peening ISCSP (Dr. Niku Lari) and membership in the committee. Participation at the 1st Int. Shot Peening Conference in Paris 1981 (Chairman Dr.. Niku Lari, 13 German papers) and at the 2nd Int. Coference in Chicago 1984 (Chairman Prof. Fuchs, 11 German papers)

1983 Initiative to form a German Shot Peening Committee (Prof. Macherauch, Prof. Wohlfahrt)

1984 Foundation of the German technical committee “Treatment of Materials by Shot Peening”, (Fachausschuss “Werkstoffbehandlung mit Strahlmitteln”) as a committee of the German Society for Materials (Deutsche Gesellschaft für Materialkunde, DGM, chairman at this time Dr. Schumacher)

Events concerning shot peening in Germany

3rd Int. Conference on Shot Peening, October 12th-16th 1987 in Garmisch-Partenkirchen

Organisation: German Technical Committee on Shot Peening in cooperation with DGM and ISCSP.
Conference chairman Prof. Wohlfahrt

Participants from 13 countries, 76 basic and practically oriented papers. In 8 sessions, 27 papers from Germany,

Exhibition on shot peening technology with users and providers of shot peening, peening equipment

A large number of German participants in all following International Shot Peening Conferences expressed the big interest of science and technology on shot peening in Germany.

Events concerning shot peening in Germany

Further activities of the German technical committee, meetings and conferences

1986 Compiling task groups on topics like "Guide lines for strengthening by peening"

1988 Installing of a technical seminar on mechanical surface treatments of metals (cooperation with DGM), held at university institutes in Kassel, Braunschweig, Zwickau, Karlsruhe, Cottbus, Clausthal and still continued yearly

1989 DGM Congress "Mechanical Surface Treatment" in Bad Nauheim

1994 and **2006** Joint meeting with the French technical shot peening committee in Straßburg and Karlsruhe

1995 "Committee on Mechanical Surface Treatment", increased interest of members

2002 09 16/20 8th Int. Conference on Shot Peening, Garmisch-Partenkirchen, cooperation with DGM/ISCSP. Chairman Prof. Wagner, 71 papers, 40 papers from Germany

Events concerning Shot Peening in Germany

Garmisch-Partenkirchen,
attractive location for conferences,
again site of the Int. Conference on Shot Peening September 16th - 20th 2002

Events concerning Shot Peening in Germany

8th Int. Conference on Shot Peening, September 16th - 20th 2002, Garmisch-Partenkirchen

Organisation: German Technical Committee on Shot Peening in cooperation with DGM and ISCSP
Conference chairman Prof. Wagner

Participants from 12 countries presented 71 basic and practically oriented papers.
9 session topics including “Alternative Mechanical Surface Treatment”, 40 papers from Germany.

Exhibition on shot peening technology with users and providers of shot peening, peening equipment and peening media.

Research activities of university institutes

Research topics on shot peening of German university institutes

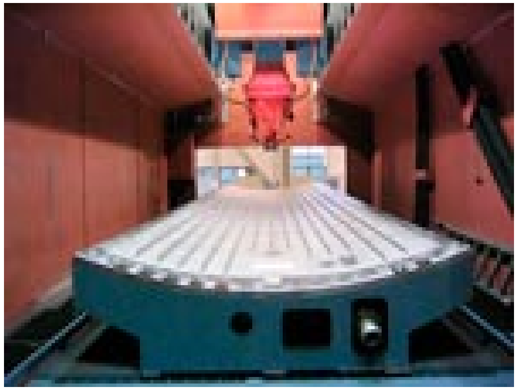
- Peen forming
- Use of different peening techniques, peening media and peening parameters
- Efficiency of shot peening on fatigue, corrosion fatigue and wear properties of metals including the influences of peening on basic characteristics of the state of surface layers (residual stresses, work hardening, surface roughness)
- Special peening conditions for different structural components
- Modelling and simulation of peening processes

Research activities of university institutes

Data on mechanical surface treatments and research intentions of institutes

Institute	year	method	parts	material	research route	load
IBF Aachen	1970	PF, FEM	sheets	Al-alloys	difficult shapes, 3D FEM	
TU Hamburg	1976	PF, ball	sheets	Al, Ti, Ni,Fe	influences on PF	
Institut Werk-stoffkunde Karlsruhe	1970 01/09 1995	**SP** *MP/ PP* FEM	speci. gears sheets	steel, Ti, Ni steel, steel, Ti, Ni	RS efficiency, fatigue improvement, RS prediction	cyclic bending
Werkstoffkun-de Clausthal	77/83 2003	**SP** FEM *DR*	speci-mens	Ti, Al, Cu, Ni, steel	Thermo-mechanical, HT, corrosion, crack init/prop	cyclic,
Werkstoff-techn. Kassel	1979 1992	**SP** FEM *DR*	speci-mens	steel, Al steel	fatigue, state of surface layers	cyclic, corrosive
Werkst. Füge.-techn Bochum	1998	**stress peening**	spring parts	spring steel	bending, torsion fatigue	cyclic
Schweißtechn. Braunschweig	1991 2004	**SP**, *HF-împact*	weld joints	structural steels	RS efficiency, fatigue improvement	cyclic
IWM Freiburg	81/88 2013	**SP**, *DR*, *HF*, FEM	speci. rolls	ceramic, hard metal	RS, fatigue, load capa-city, Hertzian pressure	cyclic pressing

Research activities: Shot Peen Forming



Peen formed structural component

Institute of Metal Forming (Institut für bildsame Form-gebung), RWTH Aachen, Prof. Kopp

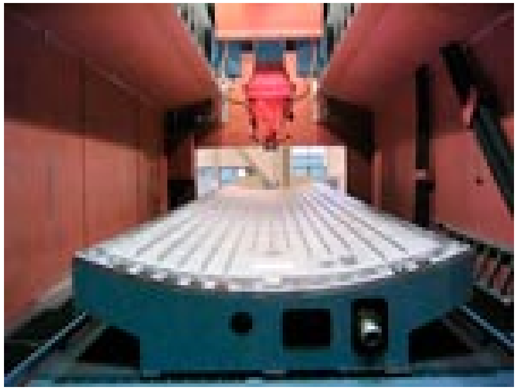
Since 1970: Development of shot peen forming of structural components

- cylindrical segments with wide or also narrower curvatures, (e.g. segments for the Ariane 4 rocket),

- double sided simultaneous peen forming of three-dimensional structural parts, cooperation with industry.

- early start (1970) with FEM analyses of the elastic-plastic forming process connected with shot peening [13, 14]

Research activities: Shot Peen Forming



Peen formed structural component

Institut gewerblich techn. Wissenschaften,TU Hamburg-Harburg, Prof. Clausen

Ca. Since 1976:.Investigations on peen forming by pointed ball shooting

- experimental tests and modelling of this advanta-geous method for detection of various influences on shot peen forming.[15]
- predetermination of elementary spherical deformat-ions as a function of different peening parameters, design of a device for determining impact velocities [16]

Research activities: Different Peening Techniques, Media, Parameters

Contributions of all research institutes to appertaining topics.

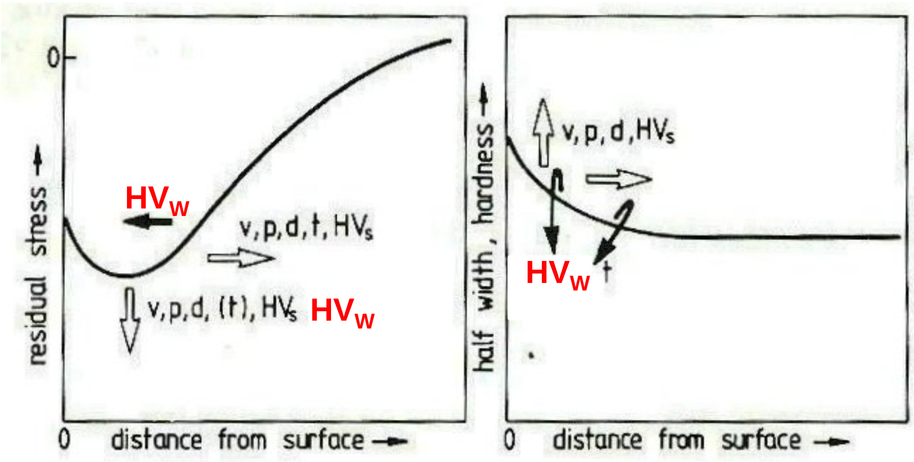
- **Seventies and eighties:** investigations on the effects of all parameters of conventional peening techniques, notably peening media and Almen intensity, discussions on the standardisation of these techniques and about the significance of the Almen intensity

- **Beginning nineties**: increasing number of investigations on more specialised peening techniques,
  e.g. ultra sonic peening, high pressure water peening, structural peening, micro blasting or peening, vacuum shot peening.

- **Also since the nineties:** increase of investigations on alternative mechanical surface treatments,
  e.g. ball burnishing, laser shock peening, piezo peening, methods with a hammering device (machine hammer peening: UltrasonicImpact Treatment, High Frequency Impact Treatment, Ultrasonic Nanocrystal Surface Modification), comparison with shot peening

Institute for Material Science , University of Karlsruhe, Prof. Macherauch:

Since 1970 Basic investigations on the influence of shot peening parameters



Shot velocity v
pressure p
Shot diameter d
Coverage or time t
Shot hardness HVs
Worpiece hardness HVw

Shot intensity i = vdt

Influence of peening parameters and material properties on distributions of residual stresses, half,width values and hardness values [17]

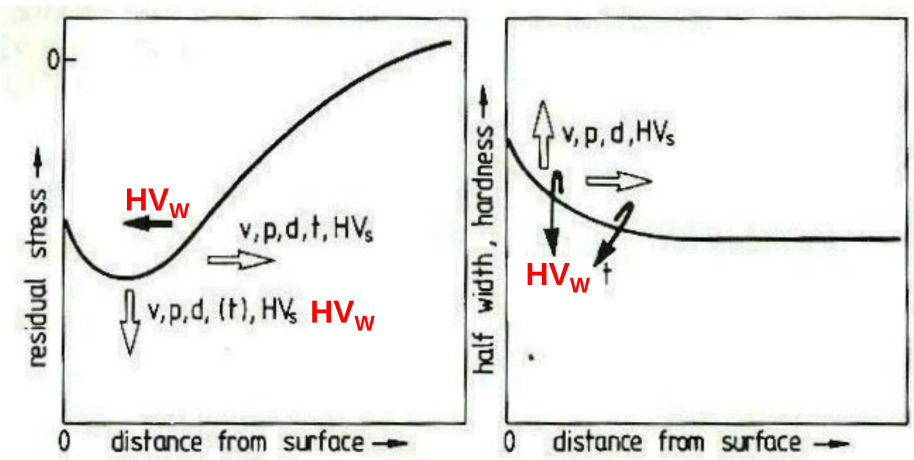
- Survey: influence of essential peening parameters on residual stresses and work hardening in surface layers of steels with various hardness

- Increase of magnitudes of peening parameters enhances maximum magnitude of compressive residual stresses, widens the stress distribution

Research activities: Efficiency of Shot Peening on Strength Properties

Institute for Material Science , University of Karlsruhe, Prof. Macherauch:

Since 1970 Basic investigations on the influence of shot peening parameters



Shot velocity v
pressure p
Shot diameter d
Coverage or time t
Shot hardness HVs
Worpiece hardness HVw

Shot intensity i = vdt

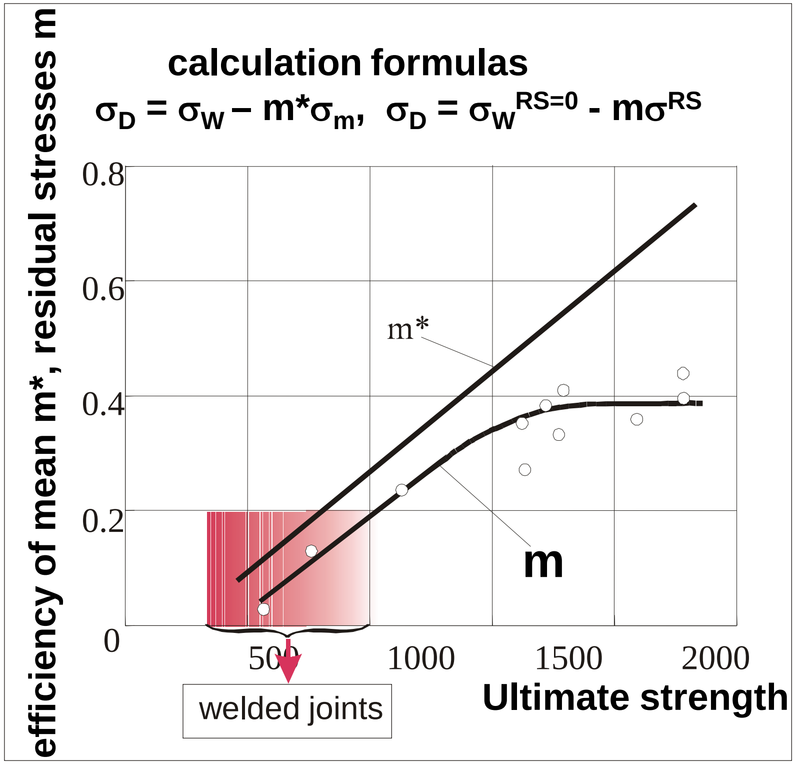
Influence of peening parameters and material properties on distributions of residual stresses, half,width values and hardness values [17]

- Magnitudes of compressive residual stresses become the bigger the harder the treated steel, but only in a narrower layer. Shot has to be hard enough

- Work hardening of surface layers is more pronounced in originally soft materials. Layer influenced by shot peening is thicker

Research activities: Efficiency of Shot Peening on Strength Properties

Institute for Material Science (Institut für Werkstoffkunde), University of Karlsruhe, Prof. Macherauch: **Since 1970 I**nvestigations on the influence of resutilng surface characterisits



Efficiency of mean stresses and residual stresses as function of the ultimate strength [18, 20]

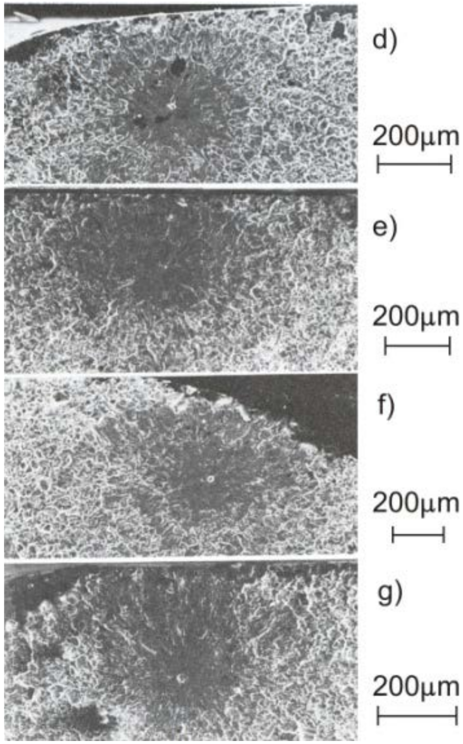
- Efficiency of residual stresses increases with the hardness of the treated material, mainly as a consequence of less relaxation of residual stresses in harder materials

- Fatigue strength improvement due to shot peening is extremely **strong in hard materials,** as the compressive residual stresses attain maximum magnitudes and are additionally very efficient. Negligible influence of work hardening

- Work hardening in surface layers has a notable influence on the fatigue strength in **soft materials**. The contribution of residual stresses is then less important.

Research activities: Efficiency of Shot Peening on Strength Properties

Institute for Material Science (Institut für Werkstoffkunde), University of Karlsruhe, Prof. Macherauch, Since 1975: Investigations on the efficiency of compressive residual stresses

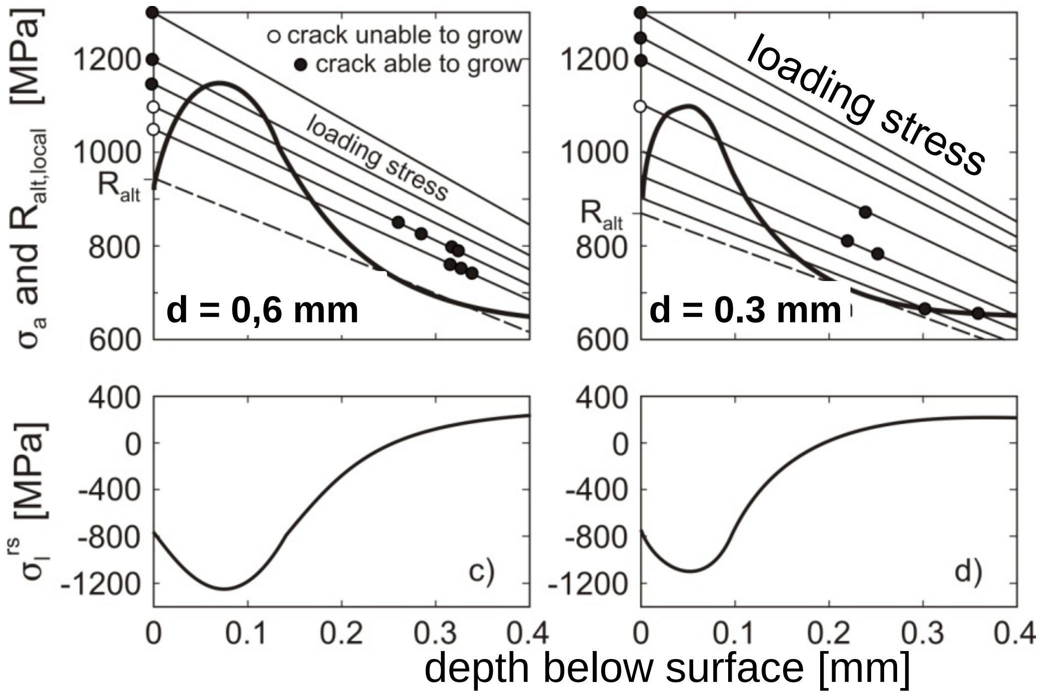


Subsurface cracking at load stress amplitudes at the surface of 1100 (d), 1000 (e), 950 (f), 900 MPa (g), peened bending specimens,[22]

- Subsurface crack initiation is observed in hard materials: steels, Ti-alloys
- Origin of subsurface cracks is the deeper the lower the cyclic load stress amplitude
- Depth distribution of residual stresses in relation to the load stress gradient is responsible for subsurface crack initiation, thus also important for fatigue properties.
- Local fatigue strength concept; assumes a locally improved fatigue strength according to the local magnitude of compressive residual stresses, the concept can predict subsurface crack depth.

Research activities: Efficiency of Shot Peening on Strength Properties

Institute for Material Science (Institut für Werkstoffkunde), University of Karlsruhe, Prof. Macherauch **Since 1975 i**nvestigations on the efficiency of compressive residual stresses



Representation of the local fatigue strength concept

• propagating cracks,

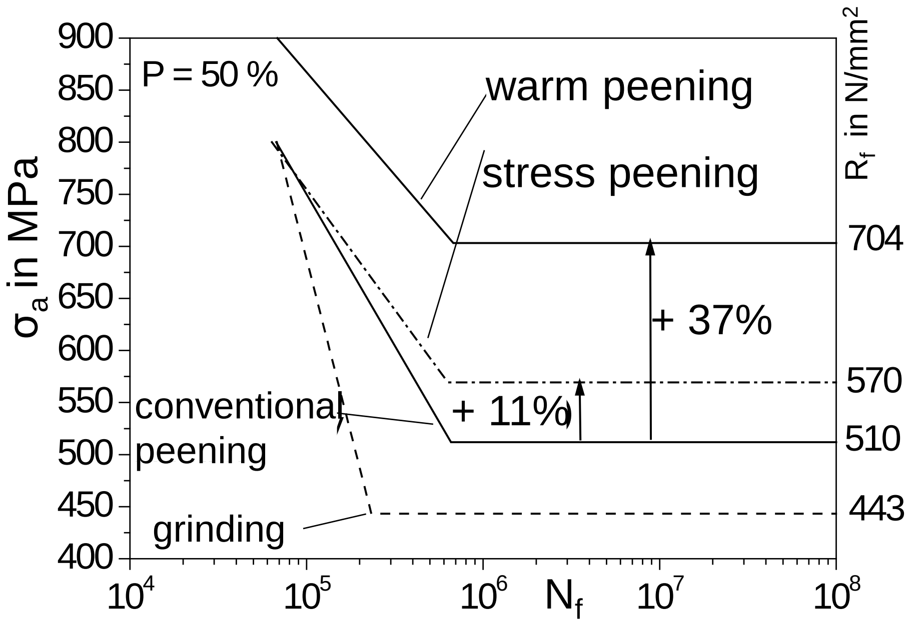
o non propagating cracks due to the barrier of the locally raised fatigue strength [3, 22]

Local fatigue strength concept

- From the course of compressive residual stresses an inverse course of the locally raised fatigue strength can be constructed.
- Cracks can **occur** only at load stress amplitudes which exceed the local fatigue strength.
- Cracks can **propagate** only, if there is no barrier of the local fatigue strength
- A shift of crack initiation sites from surface to subsurface results in an enhancement of the fatigue life

Research activities: Efficiency of Shot Peening on Strength Properties

Institute for Material Science (Institut für Werkstoffkunde), University of Karlsruhe,
Prof. Vöhringer: **Ca. Since 1980,1990:** Investigations with a deeper metallurgical oriientation

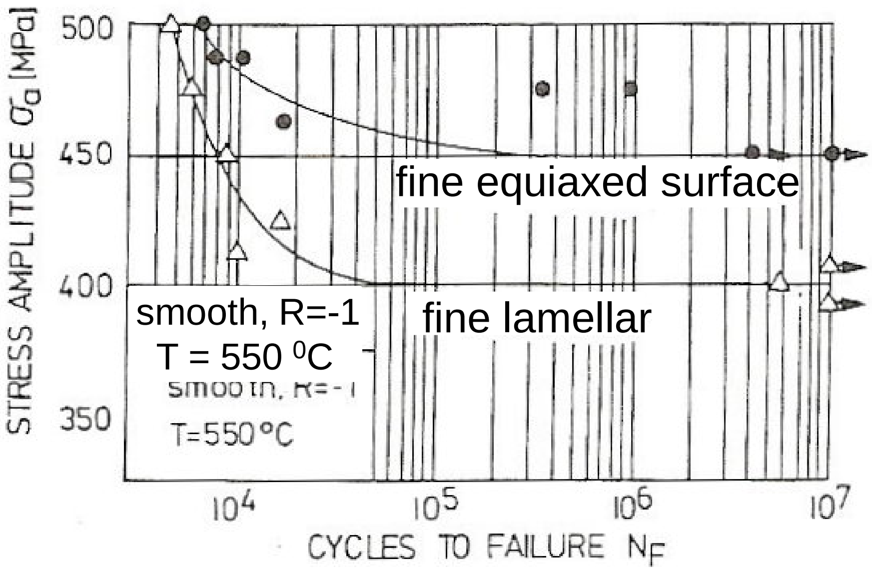


S-N diagram for bending specimens of the steel AISI 4140 (42CrMo4) after grinding, conventional peening, stress peening and warm peening, [23]

- Shot peening in combination with heating effects can result in very advantageous microstructures
- Warm peening at 300 ^{0}C results in a bending fatigue strength 37 % higher than after peening at room temperature
- Stress peening enhances the fatigue strength only by 11%
- Effect of warm peening: explained by stronger strain aging and a more stable arrangement of dislocations resulting in a smaller resp.slower decrease of residual stresses during cyclic loading

Research activities: Efficiency of Shot Peening on Strength Properties

Institute of Materials Science and Engineering, Clausthal University, Prof. Wagner
Ca. 1990 metallurgical investigations on shot peened Ti-, Al-, Mg alloys, especially thermo-mechanical treatment



S-N-curves for Ti-6242 at 550 °C with a creep resistant fine lamellar structure. Higher fatigue strength of a fine equiaxed surface structure after thermo-mechanical treatment, core remains fine lamellar [24]

- Work hardening in surface layers by mechanical treatments produces extremely small grains or very fine distributed precipitates in these layers if subsequent heat treatments like recrystallisation or age hardening follow

- The surface layers have consequently an enhanced strength and a retarded crack nucleation tendency favouring an improved fatigue behaviour.

Research activities: Efficiency of Shot Peening on Strength Properties

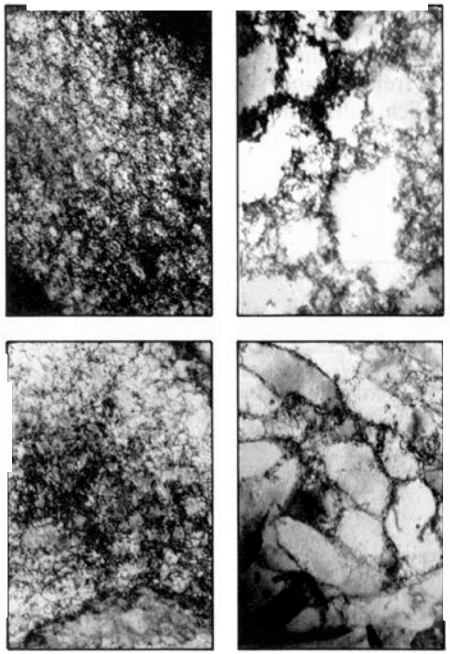
Institute of Materials Engineering, University of Kassel, Prof. Scholtes

Ca. 1995 Specific investigations on the state of surface layers after shot peening

42CrMo4, normalised, 215HV30

Shot peened
S 170,
54 - 58
HRC, p=1
bar
Ü= 98%,
z= 0,08 mm

Deep rolled
p=1450
N/mm^2
n=20
z=0,07 mm
0.8 µm



Deep rolled + shot peened
z=0,07 mm
0.8 µm

Shot peened + deep rolled
z=0,07 mm
0.9 µm

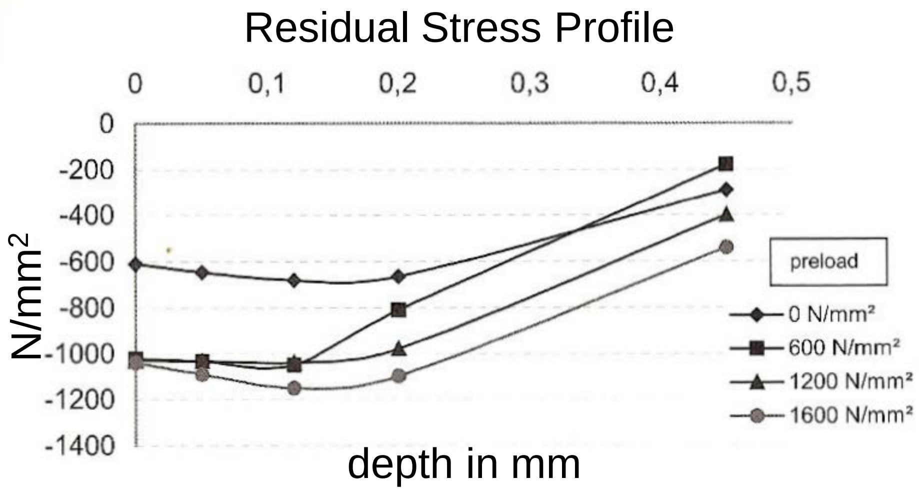
Irregular dislocation clusters after shot peening, dislocation cell structure after deep rolling [28]

- High tech methods: X-ray profile analyses, transmission electron microscopy for detection of all characteristics of surface layers (residual stresses, work hardening, grain and dislocation structure) after mechanical surface treatments.
- As a consequence of mechanical surface treatments the dislocation density in surface layers increases considerably.
- After shot peening irregular dislocation clusters are observed (left side), after deep rolling dislocations form a cell structure (right side)
- These differences are a consequence of the different forming velocities of the two treatment techniques.

Research activities: Shot Peening of Structural Components

Institut für Werkstoff und Fügetechnik, Hochschule Bochum, Prof. Müller

Since 1998 investigations on the efficiency of stress peening of springs



Residual stress profiles after shot peening with different preloads, depth of 0,45 mm: amount of residual stress is due to plastification before peening, 50CrV4 spring steel, cut wire shot, diameter 0,8 mm, In [8] , pp. 441- 446]

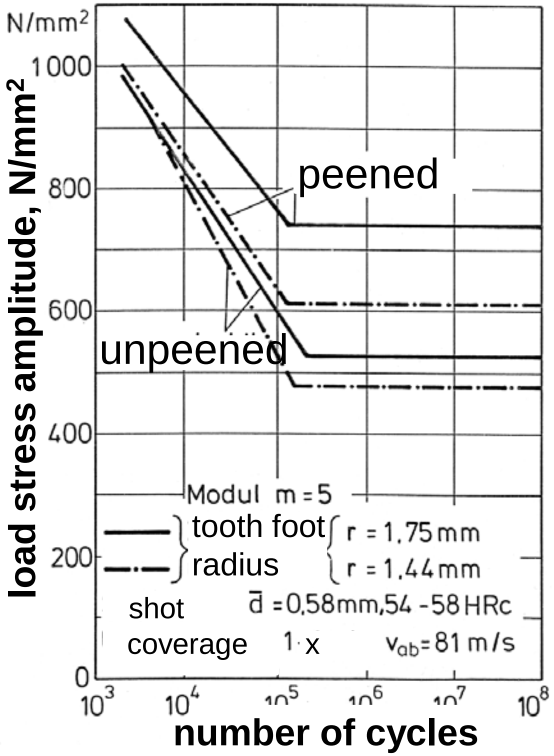
- Stress peening of flat springs, parabolic or coil springs of appropriate steels

- Extension of the fatigue life by a factor of 3, if an optimised residual stress profile shows maximum compressive stresses of 2/3 of the ultimate strength of the steel

- Compressive residual stresses with higher magnitudes and in deeper layers after deep rolling, but stress peening is less expensive..

Research activities: Shot Peening of Structural Components

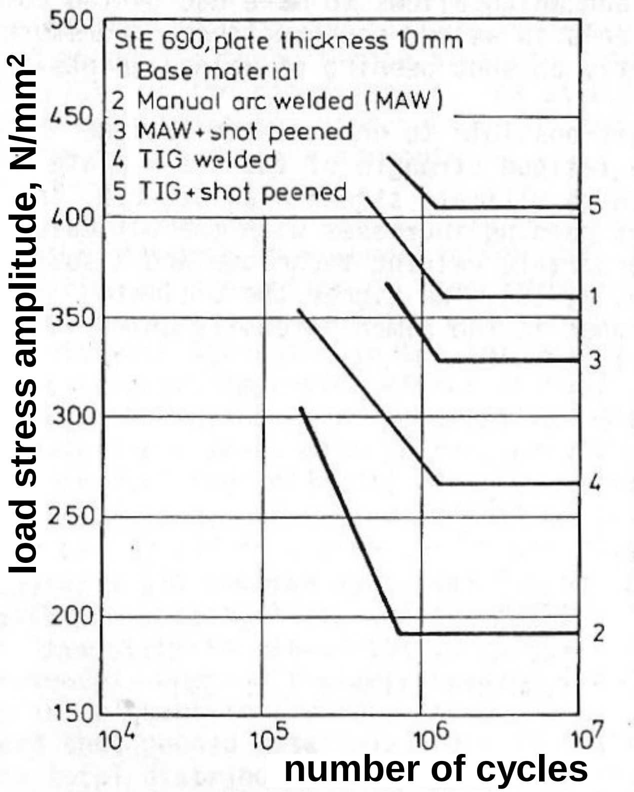
Institute for Material Science (Institut für Werkstoffkunde), University of Karlsruhe, Prof. Macherauch, Prof. Voehringer: Ca. 1980 Shot peening of gear wheels and roller bearings



S-N-curves of case hardened gear teeth, steel 16MnCr5, [33, Hirsch]

- Bending fatigue tests of individual teeth of case hardened gears, steel16MnCr5
- Unpeened state: enlarging of the radius at the gear foot from 1.44 mm to 1.75 mm: only small increase of the fatigue strength
- Shot peened state: enlarging of the radius at the gear foot by the same amount: siginificant larger increase of the fatigue strength
- Combination of reducing the peak stress at the notch and inducing compressive residual stresses is very powerful.
- Same effect can be used for fatigue strength improvement of welded joints.

Institute of Metrials Engineering, University of Kassel; Welding Institute, University of Braunschweig, Prof. Wohlfahrt: **Since 1979:** Fatigue strength optimisation of welded joints

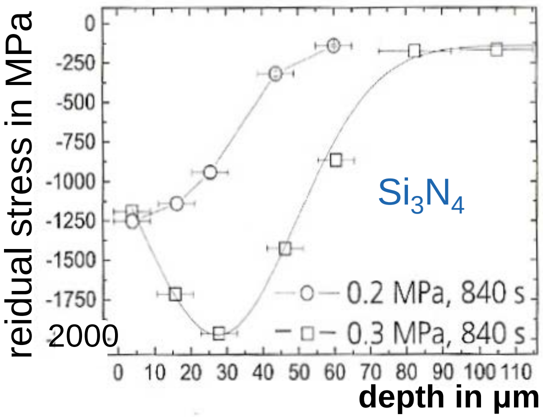


S-N-curves of differently treated welded joints, steel S690, plate thickness 10mm [35, Heeschen, Nitschke]

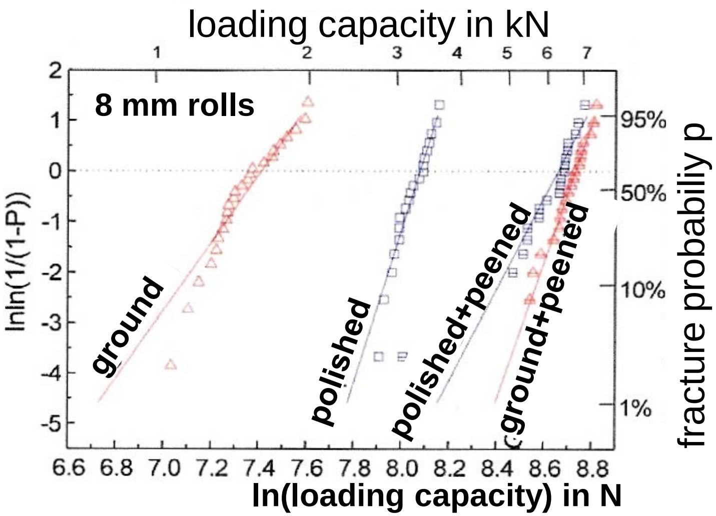
- Low fatigue strength of arc welded joints due to the notch at the toe, S-N curve 2
- Higher fatigue strength of TIG welded joints due to a smaller notch factor at the toe, S-N curve 4
- Even higher fatigue strength after shot peening of **arc** welded joints due to compressive residual stresses at the notch, S-N curve 3,
- but still below the value of the base material, S-N curve 1
- Higher fatigue strength than the base material after shot peening of **TIG welded** joints: powerful combination of reducing the notch factor + inducing compressive residual stresses and work hardening by shot peening, S-N-curve 5

Research activities: Peening of Structural Components

Fraunhofer Institute for Mechanics of Materials IWM, Freiburg: Dr. Pfeiffer



Residual stress distribution versus depth [9]



Statistic distribution of static loading capacity [37]

Since 2002 investigations on the possibility of shot peening of extreme hard materials

Specially adapted shot peening method, patented

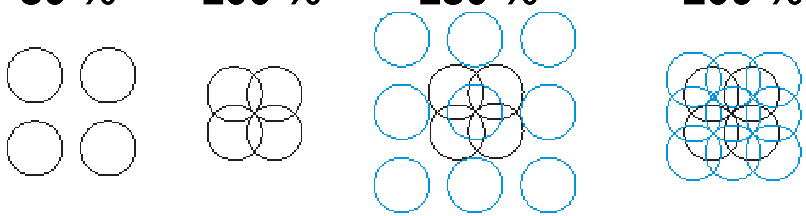
- Produces very high magnitudes of compressive residual stresses at the surface and in sufficiently thick layers of ceramic materials (Si_3N_4, 2000MPa), cemented carbide,hard Cr coatings.

- Loading capacity of roller bearing rolls (Si_3N_4): after grinding and shot peening much higher than after the costly finishing process (grinding + polishing)

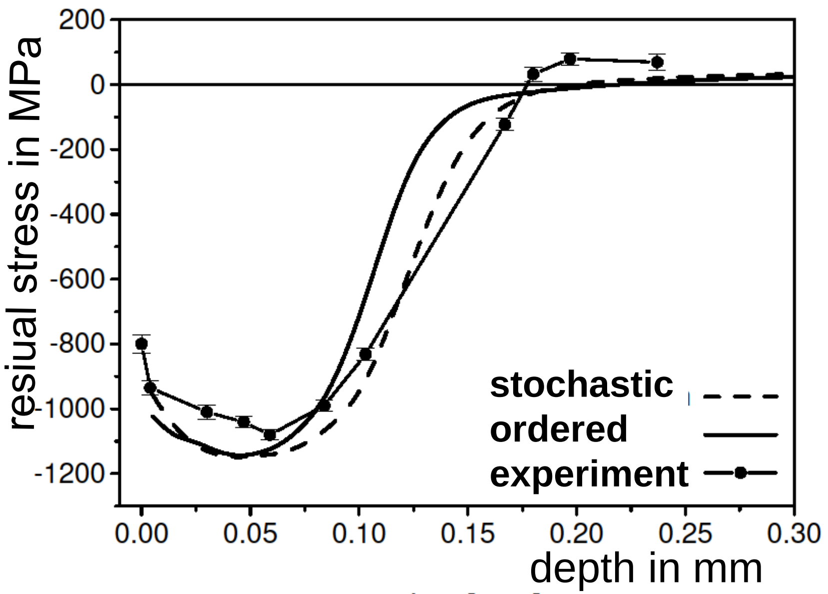
- Shot peening can overcompensate the damages produced by simple grinding.

Research activities: Modelling and Simulation

Institute for Applied Materials – Material Science, University of Karlsruhe, Prof. Schulze



Ordered dimple patterns for a different coverage



Residual stress distributions versus depth [38, 39]

Since 1995 Finite element modelling, Coverage effects during shot peening

- Classic approach: ordered dimple pattern
- Advanced approach: stochastic dimple pattern
- Both approaches led to a good prediction of the residual stress state.
- Only the stochastic model could predict surface topography realistically.
- Variations of the impact orders of the shots can result in 15% scatter of the magnitudes of residual stresses
- This result corresponds with the scatter of X-ray measurements at different positions.

Industrial Activities

Data on Shot Peening Activities of Industrial Companies

Company	year	parts	norm	mat.	aim	SP	shot	test	coop.
VW	1980/ 1990	springs gears	RS,VW 50019	steel	fatigue	wheel, air	CW glass	own RS	Univ. Inst.
MIC BRB	2002	gears turbine	RS magnit.	steel Al,Inco	fatigue SCC	wheel, air CNC	CW other	own R_t	Inst. appl.
MIC Curt. Wright	US46 G 81	needle rotor200t	VW 50019	Steels Al,cast ceram.	fatigue SCC forming	wheel air robotic	all kinds	own Inst.	Univ. Inst.
OSK	1984 1986	gears, car parts	DV611	Steel Ti-alloy	fatigue	wheel, air align- p.	CW	own Inst.	Inst. appl.
ZF	1970	car gears windmill	RS magnit.	steel caseh	root strength	wheel, air duo-peen	CW glass	own RS	Inst. appl.
Hegen-scheidt	*1920 38/57*	*journals cranks*	*deep rolling*	*steel*	*fatigue*	*burrish*		*own*	*Inst.*

Beside own research activities all companies use research cooperations with University Institutes.

ZF Friedrichshafen, Shot peening of gears: at least since 1970

Strength of the tooth roots of differently treated planet gears

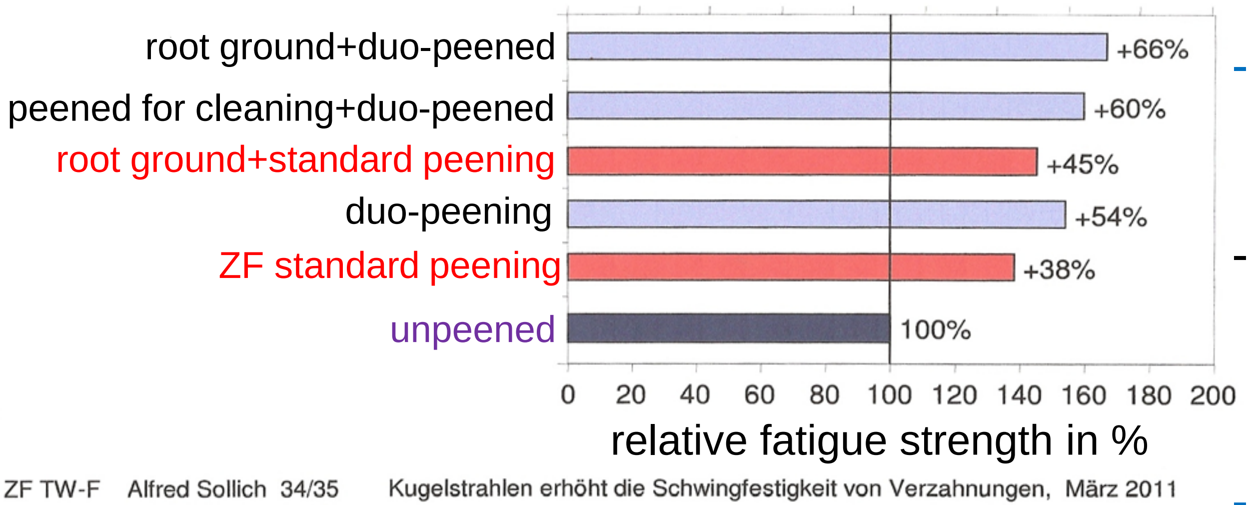


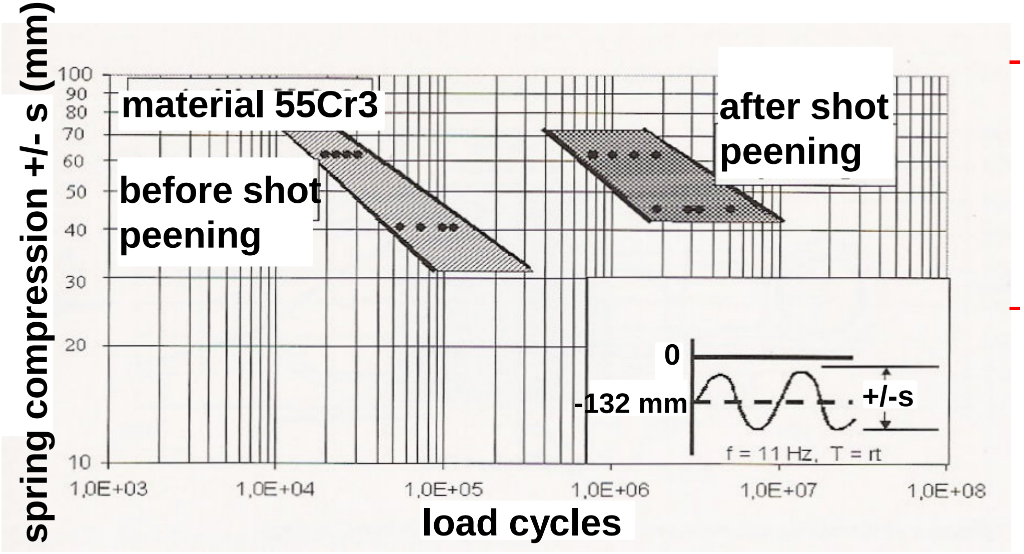
Illustration of the advantages of the duo-peening process: 1st grade standard process, 2nd grade peening with glass beads, air pressure machine [44, Sollich ZF]

- Strict ZFspecifications for peening media and peening intensity
- Standard process: peening with cut wire shot, wheel machine
- Demands for minimum magnitudes of compressive residual stresses at the sur-face, 20 µm below surface
- Round robin test in producing plants: fatigue strength improvement of ca. 40% is warranted.
- Duo peening: additional fati-gue strength improvement.

Industrial Activities

Automotive Companies (VW Volkswagen, BMW Bayerische Motorenwerke. Daimler AG)

Shot peening or stress peening of all kinds of springs, connecting rods, axle parts, anti-roll bars



S-N- curves for barrel springs before and after shot peening, [45, Hutmann BMW]

- VW: **1992** 1st demands in drawings for minimum magnitudes of compressive residual stresses [47]: surface > 600 MPa, 20 µm depth > 800 MPa
- BMW: research project with TU Darmstadt on the influence of various peening parameters on the fatigue life of barrel springs, maximum increase of fatigue life by a factor of ca. 70; substitution of surface polishing of connecting rods by stress peening
- Daimler: has common standards for a specified control of shot peened products, machine hammer peening, surface finishing of pressing moulds

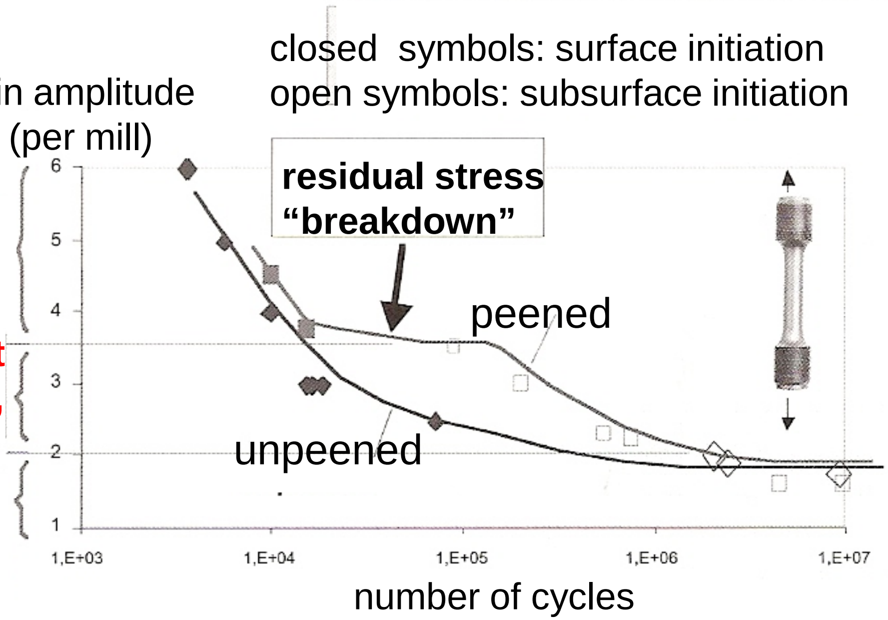
Industrial Activities

Aircraft Companies (MTU Motoren- u. Turbinen Union), Shot peening of turbine components

No peening benefits at high loads, crack initiation at the surface

Peening benefits at intermediate loads, subsurface cracks

No peening benefits at low loads, both sub-surface initiation



Effect of peening for LCF life, nickel base alloys, [49, König MTU]

But due to a reduction of residual stresses at the high loading temperatures this effect is restricted to medium load stresses

- Strict specifications for peening of turbine blades with the injector method, ultra sonic peening for strengthening of airfoils.
- Consideration of the shot peening effect on components of nickel base alloys operating at high temperatures
- Shift of crack initiation sites from surface to subsurface by compressive residual stresses can be used for life extension

Kugelstrahlzentrum Aachen GmbH: Dr. Wüstefeld: Since 1994 Peen forming for aircraft and spacecraft industry

Ariane 5 tank bottom, shot peen formed, dia-meter 5.80m, sheet thickness 1.4-3.5 mm

- Controlled shot peening with high-level process automation [50],
- visual representation of the amount of shot per second, shot velocity directly beneath the nozzle, shot coverage on the compound
- side shells for aircrafts (A 310), structural tank segments for Ariane 4
- Ariane 5 rocket: 5 spherical curved tank bulk-heads, for each 8 segments are assembled, special Al alloy 2219, spherical contour R = 3004,6 +/- 4 mm
- shot 4.75 – 9.575 mm, various steps in sequence, convex and also concave peening with high peening pressure and through-forging

Conclusion

- Research activities in Germany contributed to the clarification of the various **reasons** for beneficial effects of shot peening.

- This clarification provided a better chance to find optimum peening conditions for different purposes
  and advantageous combined methods like shot peening and heat treating
  or shot peening and deactivating of notches

- In accordance with the basic findings practical applications tested the suitability of shot peening for varying materials and loading conditions of structural components.

- An increasing adjustment of peening conditions on different materials and structural components has emerged in combination with more specialised variants of the conventional shot peening technology.

- Simulation methods and modelling have been promoted to practical applicability for strengthening peening and for peen forming.

Thank you very much for your kind attention.

I wish you a pleasant conference with fascinating new insights and interesting discussions.

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