History of Shot Peening in Germany

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Abstract
The paper offers information about the beginning and the further development of shot peening activities in Germany. After a representation of essential events some important programmes and results of different research directions are discussed in their chronological sequence as well as activities and results of industrial engagement in shot peening.

Keywords
Technical shot peening committee, shot peening conferences, activities of research instututes, industrial activities, peen forming, peening conditions, efficiency of shot peening concerning fatigue strength, residual stresses, peening of structural components,

Historical Events Concerning Shot Peening in Germany
According to [1] shot blasting of steel was already used by the American automotive industry in 1926/28. In Germany in 1929 hammering was employed for improving the fatigue behaviour of structural steel by Föppl and a patent on steel shot blasting of springs was gained. After this start, not earlier than 1940 Wiegand studied systematically the influence of shot blasting on the fatigue behaviour of aluminium and magnesium alloys. But the main effort on these techniques remained in the USA, for instance shot peening of engine parts by Almen.
One strongly important impulse for specific scientific research on shot peening in Germany was the interest of the gear producing company ZF Friedrichshafen (Zahnradfabrik), which was already aware of benefits from shot peening in practical applications, but was very keen to get more information about the possibilities of this technology on a sound scientific basis. Mr. Brugger, an engineer of the company and responsible for new technologies has to be cited within this context. He contacted in 1970 the Institute of Material Science at the University of Karlsruhe. Prof. Macherauch, the head of the institute, convinced the more practically oriented engineer that a really fundamental research programme should be necessary. This programme, which was supported by the German association of gear producing companies FVA, had the aim to investigate the possibilities of shot peening for the fatigue strength improvement of steel typical for the production of gears with special consideration of the causes for improvements. With quite a number of principal results the investigations have got a leading function for further research on shot peening in Germany and brought the research group of the institute in Karlsruhe in close contacts for instance to Dr. Niku Lari, who was interested to establish an international committee on shot peening at this time and further on to start international conferences on the topic. A first meeting was prepared in connection with an ASTM conference in Las Vergas in 1979, at which two German participants presented already papers on subsurface cracks after peening of a Titanium alloy [2] and of a steel [3].
The partnership in this group forming the International Shot Peening Committee from the beginning offered better knowledge about the research activities in other countries. The announcement of the International Committee for the 1st International Conference on Shot Peening in Paris in 1981 forwarded obviously the interest in shot peening and the activities on this subject in Germany. Already 13 scientific as well as industrial papers in German language have been presented at this successful conference [4], a clear indication that shot peening has been realised as a promising research field and an important technique.
As a consequence of the strong engagement of US scientists and industrial partners under the leadership of Prof. Fuchs, the grand old man of peening science, during the 1st conference, Chicago was chosen as location for the 2nd International Shot Peening Conference [5].
The German activity in the Shot Peening Committee (several German members) offered the chance of planning the 3rd conference in Germany. In order to promote this project the intention was to establish a German shot peening committee. A proposal about the tasks and aims of

this committee was prepared by Prof. Macherauch and me. After negotiations with the German Society of Material Science (Deutsche Gesellschaft für Metallkunde, DGM) the chairman of this society, Dr. Schumacher, could declare on February 2nd 1984 the foundation of the technical committee "Treatment of Materials by Peening" ("Fachausschuss Werkstoffbehhandlung mit Strahlmitteln"). In this committee scientists and users of shot peening should discuss and exchange knowledge about all possibilities and applications of shot peening. At the 1st session of the technical committee 32 scientists, industrial users and manufacturers of shot peening media and of peening facilities established the prospective programmes taking into account fundamental aspects of the technology as well as practical aspects and defining two sessions every year as a rule. Due to the exchange between scientists and group members of industrial companies the committee had a fruitful influence on the further development of shot peening activities in Germany.

An important first task of the committee was the organisation of the 3rd shot peening conference. In a good cooperation with the scientific board of the International Shot Peening Committee and with the DGM the congress could be conducted October 12. - 16.1987 in Garmisch-Partenkirchen with a wide international participation.

As well scientific institutes and also industrial users in Germany respected the real challenge of this international conference in their home country. Thus 27 fundamentally as well as practically oriented papers, that is more than one third of the 76 papers at the congress, have been of German origin and quite a number of industrial operators used the possibility of the exhibition at the congress [6].

As activities on shot peening in Germany have many connections with the technical committee, its actions and important events in the following years are listed in the next scheme. The frequent presentation of new technologies, application variants and efficiency results with intensive discussions in the technical committee and the transmitting of basic knowledge in appropriate seminars can be seen as a reason for the progress of shot peening in Germany.,

- In 1986 survey of literature and since that time forming of active task groups on topics like guide lines for strengthening by peening (data sheet), research activities, alternatives to the Almen intensity, continuous intensity measurement, comparison specimens for structural parts
- 1988 in cooperation with DGM installing of a technical seminar on mechanical surface treatments of metals, continued yearly at university institutes in Kassel, Braunschweig, Zwickau, Karlsruhe, Cottbus, Clausthal
- 1989 DGM Congress "Mechanical Surface Treatment" in Bad Nauheim [7]
- 1991 presentation of the technical committee with short papers, plenary papers and posters at the DGM general assembly in Graz/Austria
- 1994 Joint meeting with the French technical shot peening committee in Straßburg
- 1995 enquiry about the special interests of the committee members. Broad concern for an extension of the topics to all mechanical surface treatments. Change of the name to "Committee on Mechanical Surface Treatment"
- 1997 "Mechanical Surface Treatment" as one main theme at the DGM general assembly in Braunschweig
- 2002 09 16/20 8. International Conference on Shot Peening in Garmisch-Partenkirchen, Chairman Prof. Wagner in cooperation with DGM, 38 papers in German language indicated the highly increased interest in the topic, [8]
- 2006 2nd French-German Meeting "Mechanical Surface Treatment" at the University of Karlsruhe
- 2011 50th meeting of the technical committee on shot peening
- 2014 09 15/18 12th International Conference on Shot Peening in Goslar organized by Prof. Wagner as Chairman

Review of Activities of Research Institutes

Research activities are conducted in Germany in approximately 20 scientific institutes with a background mainly in materials science, but also in production engineering or metal forming.

The directions of their themes can be arranged under the following headlines, which will also be used as a guide line for the following survey of the development of research activities during the years, in which the efficiency of shot peening on strength properties will be treated as a key aspect with essential selected results.

- 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,

All kinds of technically important materials are included in the individual items, various kinds of steels and light metal alloys right from the start, thereafter sintered and nitrided steels, cast iron versions as well as copper and nickel based alloys. After 2000 hard, brittle materials like ceramics of the silicium nitride type or cemented carbide achieved special interest [10]. For sintered iron [11] and steel shot peening was successfully used as a method to reduce porosity and thus to improve the fatigue life under constant and variable amplitude loading [12].

Peen Forming

Peen forming was used and investigated since the seventies at the Institut für Bildsame Formgebung, Rheinisch-Westfälische Techn. Hochschule Aachen (Prof. Kopp). Some applications of shot peen forming for structural components with a rather wide curvature, e.g. a cylindrical segment for the Ariane 4 rocket, have been developed with industry. The institute started early with FEM analyses of the elastic-plastic forming process connected with shot peening and established an adaptive model for process control [13]. Later on publications concern the progress of FEM analyses and the development of double sided simultaneous shot peen forming used for instance for three-dimensional structural parts. The overall plastic deformation brought about by this method makes also narrow curvature radii possible [14].
At the TU Hamburg-Harburg (Institut gewerblich technische Wissenschaften) Prof. Clausen investigated in experimental tests and with modelling the forming by pointed ball shooting. This method is advantageous and was used for the detection of various influences on shot peen forming in steels, in nickel and in Al-alloys. Elementary spherical deformations could be predetermined as a function of different peening parameters [15]. Additionally a device for the determination of the important parameter impact velocity has been developed [16].

Use of Different Peening Techniques, Peening Media and Peening Parameters

Throughout the years a great variety of investigated topics could be summarized under these headwords. As nearly all institutes contributed to these subjects it would be difficult to order the different topics in a scheme in connection with the appertaining institutes. Therefore only a general overview is given here. Originally in the eighties publications report on the influence of all different parameters like peening media and Almen intensity for conventional shot peening techniques and also on standardisations of these techniques or of the Almen intensity. Around the beginning nineties an increasing number of papers concern more specialised peening techniques like ultra sonic peening, high pressure water peening, structural peening, micro blasting or peening and vacuum shot peening. Additionally other mechanical surface treatments like deep rolling, ball burnishing, laser shock peening and methods with a hammering device as machine hammer peening, Ultrasonic Impact Treatment, High Frequency Impact Treatment, Ultrasonic Nanocrystal Surface Modification and piezo peening (ca. 2011) got broader interest for research institutes, at least since the cited committee decisions in 1995. These mechanical surface treatment methods are no objects of this paper, but in many publications their effects are discussed in comparison with shot peening effects.

Efficiency of Shot Peening on Strength Properties of Metals

Fundamental investigations on the influence of shot peening on fatigue properties have to take into account at first the surface state after peening and secondly the efficiency of characteristics of the surface state. With the already mentioned research programme the Institut für Werkstoffkunde in Karlsruhe (Prof. Macherauch) has started systematic fundamental investigations under these aspects in the seventies and eighties. The results discussed on this subject are representative for steels, but offer principal information also for other alloys.

As a first result of the programme a complete survey has been established on the influence of essential peening parameters on the residual stress and work hardening state in surface layers of steels with different hardness levels. The overall influences of peening conditions on the typical distribution of residual stresses and magnitudes of X-ray line broadening (indicator for work hardening) are summarized in the schematic graph of Fig. 1 [17]. It can be concluded

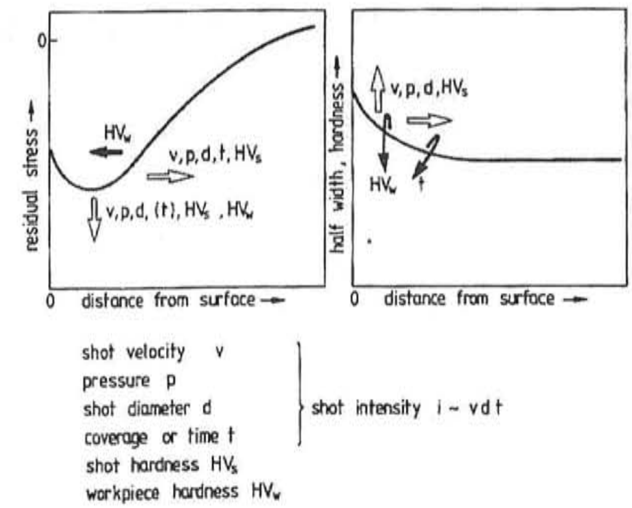

Fig. 1 Influence of peening parameters and material properties on the typical distributions of residual stresses, half width values and hardness values [17]

from the diagram that the shot hardness has to be adapted to the hardness of the material if one wants to get the highest possible magnitudes of compressive residual stres-ses, very hard materials require then a shot on an appropriate level. Additional experiments have shown, that shot peening in notches produces higher magnitudes of compressive residual stresses than on flat samples under the same peening intensity [18].

The ongoing investigations explored as an important fact that the influence of compressive residual stresses and work hardening on the fatigue strength depends not only on their magnitudes, but also on their special efficiency, which is different in soft and in hard materials. It was found that the residual stresses are the more effective the higher the hardness of the peened material is. Consequently the biggest improvement of the fatigue strength can be obtained in properly shot peened hard materials, as well in flat as especially in notched steel specimens [19, 20]. It has been revealed for steels and also for Al- and Ti-alloys that the relaxation of residual stresses during cyclic loading is responsible for these different efficiencies. Depending upon the ratio of load stress amplitude to the cyclic yield stress the residual stresses can be more or less stable during cyclic loading [21]. On the other side it was found, that strain hardening in surface layers is the less effective the harder the material, but can provide an important percentage of the fatigue strength improvement in soft materials [18].

Eventually it has been found, that the depth distribution of residual stresses in relation to the load stress gradient is important for the fatigue properties. A steep gradient of the compressive residual stresses versus depth below surface means also a steep gradient of strengthening effects below surface. In this case a load stress with a rather smooth gradient may overcome in a certain depth below surface the strengthening effect of the residual stresses. Then, as observed in hardened steels [3] and also in Ti-alloys [2], subsurface cracks may occur. The depth of these subsurface damages can be estimated in advance with a model developed in these investigations [22].

In the beginning nineties investigations involved more intensive metallurgical aspects in combination with shot peening, for instance the development of special microstructures due to peening at elevated temperatures or due to subsequent heat treatment procedures. At the Institut für Werkstoffkunde, University of Karlsruhe (Prof. Vöhringer) peening of the steel AISI 4140 (42CrMo4) at elevated temperatures was studied with the exciting finding of a bending fatigue strength of the carbon steel 37% higher after peening at 300 °C than after peeing at room temperature and also higher than after stress peening. The reason for this effect could be explained by a stronger strain aging and a more stable arrangement of dislocations resulting in a smaller respectively slower decrease of residual stresses during cyclic loading. The S-N diagram in Fig. 3 represents the results after different peening conditions [23].

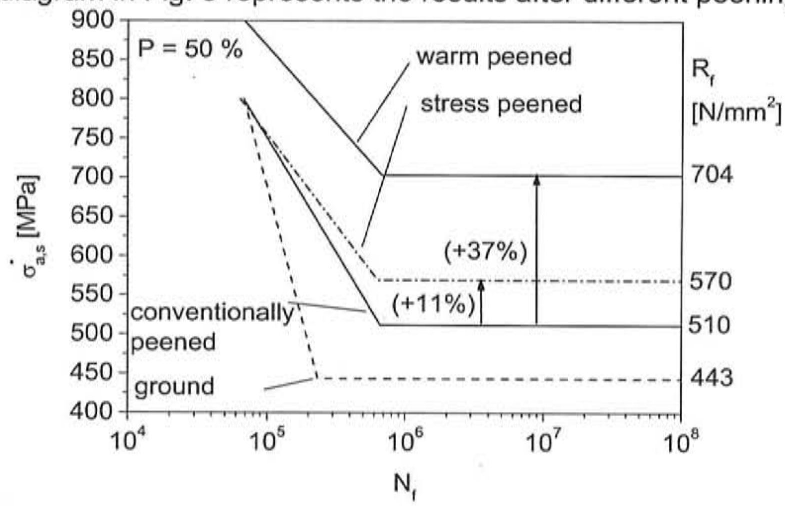

Fig. 2 S-N diagram for bending specimens of the steel AISI 4140 after conventional peening, stress peening and warm peening, [23]

Congenial investigations have been performed in the eighties and nineties at the Institute of Material Science and Engineering, Clausthal University (Prof. Wagner), using a combination of mechanical surface treatments with different heat treatments, in other words a thermo mechanical method for different Al- and Ti-alloys. Foregoing investigations started already in 1977 at the universities of Bochum, Hamburg-Harburg and Cottbus and accumulated a broad knowledge about optimum peening parameters, about the special behaviour of these alloys

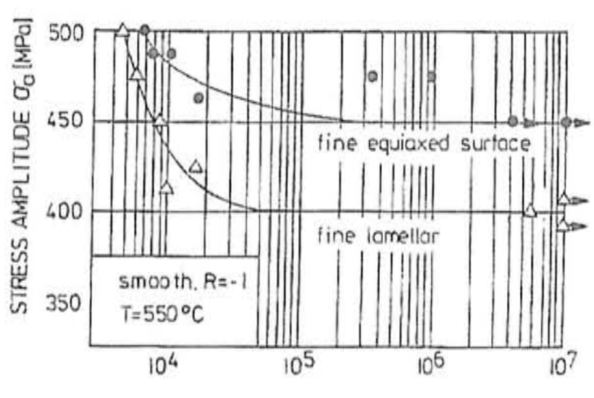

Fig. 3 S-N-curves for Ti-6242 at 550 °C with a creep resistant fine lamellar microstructure. A thermo mechanical treatment produces a fine equiaxed surface structure, the core remains fine lamellar [24]

under various loading types, also at higher temperatures. Then it was recognized that the work hardening in surface layers induced by mechanical treatments can be used to produce by subsequent heat treatments like recrystallisation or age hardening surface layers with especially small grains or very fine distributed precipitates. These surface layers have consequently an increased strength and a retarded crack nucleation tendency favouring an improved fatigue behaviour. The competing influences of the method on crack nucleation and crack propagation are discussed in detail. A typical example for the effectiveness of the method is the enhanced fatigue strength by ca. 20% of the coarse grained alloy Ti-8Al after shot peening and annealing for 1h at 820 °C [24]. Other results exhibit fatigue strength values higher than that after conventional age hardening or mechanical surface treatment for a mechanically induced favoured hardening of surface layers of AlCuMg2 [25] or a selective surface hardening in Ti-38-644 [24].

An advantage of these methods is the combination of the fatigue resistant hardened surface layers with a bulk material of an unchanged micro-structure, maintaining basic properties of the alloy. The bulk material shows for instance after shot peening and heat treating a creep resistant lamellar microstructure in α+β alloys for high temperature service whereas surface layers provide the necessary good fatigue behaviour by an equiaxed microstructure, Fig. 3, [24].
In further investigations on Al-alloys performed after the year 2000 the influences of shot peening and other mechanical treatments on fatigue properties in different age hardened conditions (T4 or T6 temper) have been compared, including the influence of peening on corrosion fatigue [26]. An earlier published advice for Mg-alloys is the necessity to use an adequate low Almen intensity in order to get an optimum fatigue strength improvement [27].
Also in the nineties started at the Institut für Werkstofftechnik, University of Kassel (Prof. Scholtes), intensive investigations on the influence of shot peening on all the various characteristics of the state and microstructure of surface layers. With sophisticated methods, like transmission electron microscopy and analyses of X-ray line broadening, typical features of the microstructure of surface layers have been explored in detail after peening with different

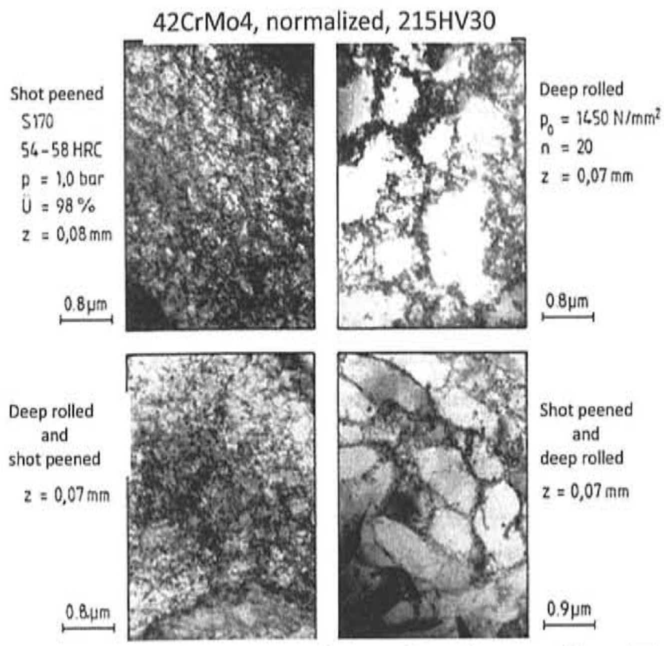

Fig.4 Irregular dislocation clusters after shot peening, dislocation cell structure after deep rolling [28]

parameters and in comparison after deep rolling. Thus it was possible to show that due to mechanical surface treatment of a relatively soft normalised steel (42CrMo4) the dislocation density in layers just below the surface increases considerably, but after shot peening irregular dislocation clusters are observed whereas after deep rolling the dislocations form a cell structure., Fig. 4. These differences are explained to be a consequence of the different forming velocities of the two surface treatments [28].
Due to the limited resolution power observations of dislocation densities are not possible in hardened materials. Information about microstructural features was then possible by an indirect method, a detailed analysis of X-ray diffraction lines which offers correlations to lattice deformations. Line broadening as a prime reference on work hardening in surface layers showed for instance a strong increase in the surface layers of a shot peened normalised steel (42CrMo4), whereas the increase after deep rolling of this steel was less drastic as consequence of the mentioned different dislocation arrangement. The depth of work hardening below surface, as well as the depth of induced compressive residual stresses, turned out to be much lower after shot peening than after deep rolling.
As a consequence of plastic deformation the surface crystals may get special preferred orientations, already present textures may be altered or new textures may develop. A texture analysis revealed in unalloyed carbon steel a shot peen induced texture, which is different after peening in vertical and in angular direction.

A detailed knowledge of the state of surface layers is also important in order to find reliable results about the influence of shot peening on corrosion fatigue. It was shown that shot peening improves the fatigue strength for finite life and the lifetime in corrosion fatigue, as well under conditions of passive (X35CrMo17) as under active corrosion (Ck 45). In the case of active corrosion the higher surface roughness after peening activated an early crack initiation, but the compressive residual stresses lowered the crack propagation rate and allowed a longer remaining lifetime [29]. Other investigations indicated that peening of Mg-alloys with steel shot results in a degradation of the fatigue properties by accelerated local corrosion as a consequence of the pronounced sensitivity to contact corrosion [30].

Peening of Structural Components

A broad overview on the efficiency of shot peening on various structural components is given in [31] (IABG, Ottobrunn, Dr. Schütz). Improvements of the fatigue limit due to shot peening between 20% and 80% are reported for components like steering levers, impellers, gear teeth or spring steels, also under variable amplitude loading or under corrosive conditions.

As well known, all kinds of springs are usually shot peened, mainly under stress peening conditions. The Institut für Werkstoff und Fügetechnik, Hochschule Bochum (Prof. Müller), is specialised since 1998 in investigations on the efficiency of stress peening for flat springs, parabolic or coil springs of appropriate steels. By optimising the residual stress profile and with compressive stresses of a magnitude up to 2/3 of the ultimate strength an extension of the fatigue life by a factor 3 is reported [32].

Important construction parts are gear-wheels and roller bearings. Research programmes have been conducted with the aid of the German association of gear producing companies FVA since the seventies, especially on the improvement of the bending fatigue strength of gear teeth by shot peening. Case hardened gears have been shot peened and individual teeth then tested. The fatigue strength improvement in gears with the modulus 5 reached nearly the same value (41%) after peening with a wheel machine (shot hardness 54-58 HRC) as after peening with an air blasting machine (same shot plus glass beads, 300% coverage, 43%). Gears with a modulus of 3 or of 8 had lower improvement values. A principal agreement with test results of gearlike samples proved their suitability as simulation parts [20, 33]. Another programme operated for instance with roller specimens simulating the combination of rolling and sliding loading of gear teeth respectively roller bearings in a special test rig. It could be revealed that in the very hard steel compressive residual stresses due to shot peening are reduced during revolving loading only partly and it was therefore concluded that pittings in shot peened ball bearing components will appear later than without peening [34].

The fatigue strength of welded joints can be improved drastically by shot peening as a strengthening effect is produced in the notches by the compressive residual stresses and in the weak heat affected zone by work hardening. Investigations at the Institut für Werkstoff-technik, University of Kassel, and at the Institut für Schweißtechnik, University of Braunschweig (Prof. Wohlfahrt), revealed that the fatigue strength improvement due to shot peening becomes the bigger the higher the ultimate strength of the structural steel of a welded joint is and that the combination of seam smoothening, e.g. by TIG-dressing, and peening, offers the possibility to reach the fatigue strength of the base material [35]. For welded joints of aluminium alloys (AlMg4.5Mn, AlZn4.5Mg1) special peening conditions, which respect the relatively low hardness of the material, have been identified in order to reach or overcome also the fatigue strength of the unnotched specimens of the base material [36]. Double peening with steel shot and then with glass beads is optimal as it lowers surface roughness.

With a specially adapted shot peening method compressive residual stresses can be produced in surface layers of ceramic materials, in cemented carbide and in chromium coatings of high hardness. With this method the load capacity of roller bearing rolls (Si_3N_4) could be improved nearly two times (Fraunhofer Inst. Werkstoffmechanik, Freiburg, Dr. Pfeiffer) [37].

Modelling and Simulation
As mentioned earlier, modelling and simulation started in the field of peen forming already in the seventies [13]. For estimations of residual stresses after strengthening shot peening foreign calculation programmes have been common at this time. Since the nineties the progress of the FEM-method caused even better possibilities for analyses of the peening process and reliable predictions of its consequences. Prof. Schulze (Institut für angewandte Materialien - Werkstoffkunde, University of Karlsruhe) tested in a three dimensional FE model an ordered dimple pattern [38] and a stochastic dimple model taking into account random shot impacts [39] in order to describe surface topography and residual stress state after peening. It could be shown that both models lead to a good prediction of the residual stress state, however only the stochastic model can predict surface topography realistically. Results on the influences of shot velocity, shot diameter and coverage on the penetration depth of the compressive residual stresses agreed well with experimental findings. Furthermore it has been shown that the combination of FE simulations with similarity mechanics is a powerful method for quick estimations of the surface material state after shot peening [40].

Industrial Activities
The background of industrial investigations is mainly to find optimum peening conditions in order to get either the highest possible strength for their products or to save material costs and weight. Under these aspects as well shot peening companies [41] as also producers of structural components have to fulfil special demands of their customers. A typical task for a shot peening company was for instance to find which conditions for controlled shot peening provide a reliable improvement of stress corrosion cracking in an austenitic steel [42].

Shot peening activities of spring producing companies have also the background of customer demands, for example for the residual stress state in bearing springs or valve springs of the automotive industry. The influence of the sequence of grinding, presetting and stress peening on the fatigue strength is an important research topic. Peening media like glass or ceramic beads are also used in order to get an optimum deburring, e.g. by double peening [43].

The gear manufacturing company ZF conducts strong peening activities. Strict specifications control peening intensity and peening media, especially shape and diameter of shots in the operational mixture. Demands for the minimum magnitudes of compressive residual stresses at the surface of a tooth and in a depth of 20 µm exist. The standard process is peening with cut wire shot in a wheel machine. A round robin test in several producing plants has shown that an improvement of the fatigue strength of gears of nearly 40 % compared with the original unpeened state can be reached surely. Additional peening with glass beads ("Duo-peening") allows an improvement of the fatigue strength of gears up to 66% [44].

The automobile industry is of course very interested to improve the resistance of their car or truck components against fatigue, corrosion fatigue or friction fatigue. The BMW Company (Bayerische Motorenwerke AG) has conducted a cooperative research project with detailed studies on the efficiency of shot peening on barrel springs. Shot peening lengthened the fatigue life by a factor of nearly 70 [45]. In a lightweight anti-roll bar a 100% increase of the fatigue life was possible due to peening the inner side of the hollow cross section with a deflector lance [46]. Very successful was the substitution of expensive surface polishing of connecting rods for racing cars by peening, The VW company (Volkswagen AG) was the first who had (1992) in technical drawings of peened gears demands on the required residual stresses: at the surface (> 600 MPa) and 20µm (> 800 MPa) and 50µm (> 400 MPa) below the surface [47]. In a cooperative programme research was undertaken on the suitability of shot peened TIMETAL instead of steel for springs [48]. Of course other automotive companies, as for instance the Daimler AG, use today similar standards for a specified control of externally and internally produced and mechanically surface treated components.

The MTU (Motoren und Turbinen Union) company uses under very strict specifications the injector method for peening of turbine blades and ultra sonic peening for strengthening of blisk airfoils. The reduction of negative influences on fatigue or wear resistance of the Ti- or Ni-base alloys, as for instance material defects or tensile residual stresses due to machining, is an important function of peening. In order to exploit the benefits of peening not only for enlarging

the safety margins of engine parts, but for a predictable extended service life, detailed investigations have been performed on possibly detrimental influences. As well known, the shift of crack initiation sites from surface to subsurface by compressive residual stresses can allow a life enhancement. But due to a reduction of residual stresses at the high service temperatures of engine parts, this effect is restricted to medium values of load stresses. At low load stresses resulting in high cycle fatigue subsurface crack initiation occurs anyway with and without shot peening. Consequently only a small "window" of load stresses for cyclic life enhancement due to shot peening exists, depending on the specific material and loading parameters. For predictions of life extensions this result has to be taken into account [49].
The Kugelstrahlzentrum Aachen (KSA), a spin-off from Aachen Technical University, was able to use the research background of the Institut für Bildsame Formgebung. Thus it was possible to implement a unique controlled shot peening process and to produce a significant number of side shells for aircrafts and, as a fascinating highlight for peen forming, the tank bulkhead segment for the Ariane 5 European rocket [50].

Conclusion

Intensive fundamental research activities in Germany have made a considerable contribution to the clarification of the different reasons for the beneficial effects of shot peening. With a detailed knowledge about the efficiency of compressive residual stresses and strain hardening in surface layers it was possible to establish optimum peening condition for different materials, material states and load profiles and to find advantageous combined methods of shot peening and heat treating. In accordance with the basic findings practical applications tested the suitability of shot peening for the varying materials and loading conditions of structural components. Altogether an increasing adjustment of peening conditions on different materials and structural components has emerged in combination with the use of 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.

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