Volker Schulze

Modern Mechanical Surface Treatment

States, Stability, Effects

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Contents

1
Introduction

Technological practice today, particularly in the spring-manufacturing, automotive and aerospace industries, is hardly imaginable without mechanical surface treatments. The origins of these processes date back to ancient history. [1.1] states that in the city of Ur, gold helmets were hammered and thus mechanically enhanced, as early as 2700 BC. The knights of the Crusades used the same method to reinforce their swords when shaping them. The first modern-day applications, again, are to be found in military technology, but also in railroad technology. [1.1] reports that in 1789, the outer surfaces of artillery gun barrels were hammered in order to improve their strength, and by 1848, train axles and bearing bolts were evened out by rolling. Until that point, the methods had been intrinsically connected to the skill and experience of the craftspeople, who used strict confidentiality in passing on their knowledge in order to keep their competitive advantage.

It was only in the 1920s and -30s that surface treatment evolved into technical processing methods. Föppl's seminal treatises of 1929 [1.2, 1.3] establish the correlation between mechanical surface treatment and increased fatigue strength, indicating significantly higher fatigue strength in surface-rolled samples than in polished samples. Consequently, Föppl's group [1.4] extended their examinations to include notched components and found that the fatigue strength increased by 20–56 % in the case of deep-rolled thread rods. These findings were confirmed by Thum [1.5] in his systematic examination of the relation of rolling and fatigue strength, published in 1932. Thum also found that resistance to corrosion fatigue [1.6, 1.7] and fretting fatigue [1.8] increased.

An alternative to deep rolling emerged in the form of shot peening. Its precursor was developed in 1927 by Herbert [1.9], a process he termed "cloudburst", in which large quantities of steels balls are "rained" onto component surfaces from a height of 2–4 meters. Herbert observed increases of hardness, but did not give any indications regarding contingent increases of fatigue strength. In his aforementioned [1.2, 1.3] paper of 1929, Föppl showed that samples treated with a ball-shaped hammer also exhibit significantly higher fatigue life under cyclic stress than polished samples do. In 1935, Weibel [1.10] independently proved that sandblasting increases the fatigue strength of wires. This additional precursor of present-day shot peening methods builds on the British patent taken out by the American, Tilgham [1.11], in 1870, which was originally geared at drilling, engraving and matting of iron and other metals and deals with surface treatment using sand accelerated by pressurized air, steam, water or centrifugal force. In 1938, Frye and Kehl [1.12] proved the positive effect of blast cleaning treatments on fatigue strength, and in 1939 v. Manteuffel [1.13] found higher degrees of fatigue strength in sandblasted springs than in untreated springs. Crucial systematic examinations were published in the US in the early 1940s. Working at Associated Springs Co., Zimmerli [1.14] used shot peening to increase the fatigue strength of springs and analyzed the influence of peening parameters. At General Motors, Almen [1.15, 1.16] demonstrated fatigue strength improvements in engine components and achieved increased reproducibility of the peening process by introducing the Almen strips named after him. In 1948, fatigue strength improvements were proven also for shot peened components under conditions of corrosion [1.17].

The development of special methods brought an additional impetus for the technical application of mechanical surface treatment processes. Straub and May [1.18] were the first to report increases of fatigue strength in springs which were shot peened under pre-stress. While they presented models in which the state of residual stress was to be shifted toward higher compressive residual stress by means of tensile prestressing, this was not proven until 1959, when Mattson and Roberts [1.19] analyzed residual stress states after 'strain peening' combined with tensile or compressive prestrains. Today, this method is called stress peening and is predominantly used on springs [1.20–1.25], but also on piston rods [1.26, 1.27]. Supplying thermal energy simultaneous or consecutive to the actual peening process constitutes an approach for increasing the effect of the mechanical surface treatment even further. Warm peening, i.e. shot peening at high workpiece temperatures, was first suggested in a 1973 Japanese patent [1.28] to achieve increased fatigue strength in springs by using the "Cottrell effect". In the meantime, applications in the spring manufacturing industry have been examined [1.29–1.35] and fundamental research by the Vöhringer and Schulze group [1.36–1.38], in particular, has been pushing toward a deeper understanding of the processes and an optimization of warm peening. Conventional shot peening and consecutive annealing was examined more closely by the teams of Scholtes [1.39] as well as Vöhringer and Schulze [1.41] as an alternative method. These examinations show that appropriately selected annealing temperatures and times are able to achieve effects comparable to warm peening, while complexity is reduced. Wagner and Gregory [1.42–1.46] increased the density of nuclei for re-crystallization or precipitation in the surface layers of titanium and aluminum alloy workpieces which is effective during annealing after shot peening or rolling, and thus enables fine grain formation and selective or preferred surface hardening. These procedures, too, allow for considerable increases of fatigue strength at room temperature or higher temperatures. A completely new method has been developing since the 1970s in the form of laser shock treatment. However, it has attained technical relevance only gradually. Its importance has started to increase since suitable laser technologies have become available and the enhancement process has been transferred from laboratory lasers, which are irrelevant for technical applications, to industrially applicable lasers [1.47–1.52].

In the course of method development, at first the question remained which surface changes of the workpieces the observed increases in fatigue strength could be attributed to. Samples manufactured by machining were used to prove and to quantitatively record the influence of surface topography on fatigue strength. Houdremont and Mailänder [1.53] demonstrated that the difference in roughness between polished and coarsely cut surfaces leads to fatigue strength changes which become more pronounced the greater the strength of a material is. Siebel and Gaier [1.54] in 1956 stated a factor for roughness that expresses the effect on fatigue strength and decreases linearly with the logarithm of roughness. At first, an intense and controversial debate centered on whether the cause for fatigue strength increases was to be found in the effects of mechanical workhardening, as postulated by Föppl and his team [1.2, 1.3], or the effects of the induced compressive residual stress states, as Thum and his team [1.5, 1.55] assumed. Fig. 1.1 summarizes the essential approaches. Today it is commonly accepted knowledge that the inhomogeneous plastic deformations required for generating residual stresses always involve local alterations of the material state, which may affect a component's fatigue strength. However, the residual stress stability within the given operating conditions of a component determines whether the residual stresses are to be treated as loading stresses, in which case they are predominant in comparison with the effect mentioned first. Both effects may be taken into account in the so-called concept of the local fatigue limit [1.56, 1.57] and be super-

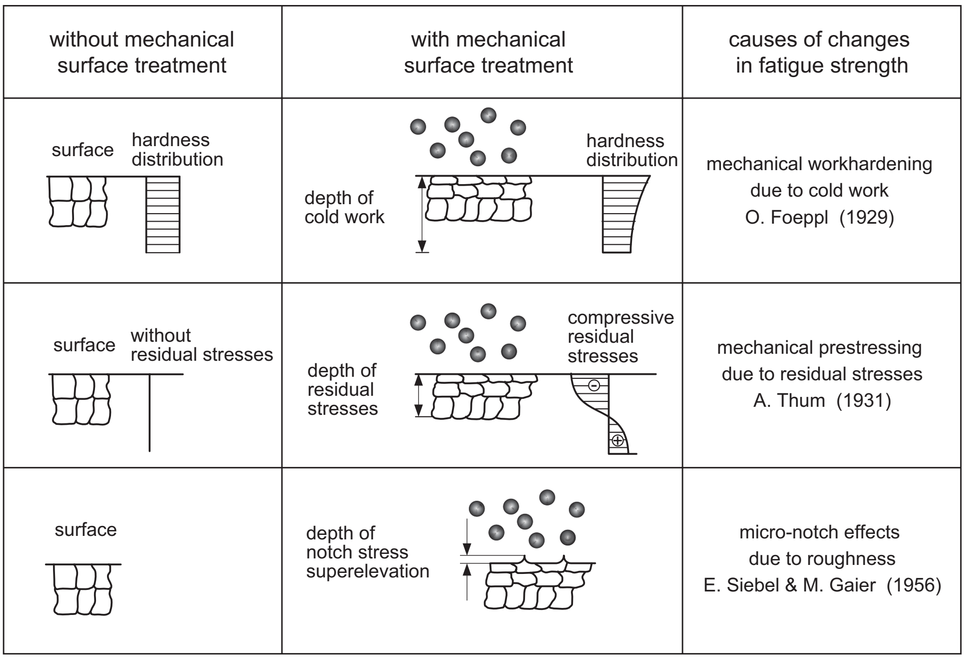

Fig. 1.1: Approaches for the explanation of changes in fatigue behaviour due to mechanical surface treatments

posed with the aforementioned roughness effects and those of additional potential phase transformations.

Mechanical surface treatment processes commonly used today may be roughly divided into cutting and non-cutting methods. The main focus of cutting methods is on shaping, while achieving optimal surface layer states for later use is only a secondary objective. Therefore, study is restricted to describing non-cutting methods which serve to enhance the surface layer state with respect to the future application. Fig. 1.2 shows a systematized compilation of these methods. The methods indicated are subdivided into those without or with relative movement between the tools and the workpiece and those with a static or an impulsive tool impact. The description of methods without relative movement is limited to impulsive impact, which has a repetitive irregular pattern in shot peening and a repetitive regular pattern in laser shock treatment. Among the methods involving relative movement, the focus is on the rolling movement of deep rolling. The aforementioned process modifications are always included in the description. As indicated earlier, it is crucial for the effects of mechanical surface treatment on component properties that the modifications imparted on the surface layer state are as stable as possible and are not reduced significantly during loading. This applies, in particular, to the residual stress states created. Therefore, the following description of the individual methods and the surface layer alterations they cause goes on to examine their stability during thermal, quasi-static and cyclic loading and combinations thereof. In addition to the experimental results and the causes, the focus is also on approaches toward a quantitative modeling of the changes of the surface layer state. In conclusion, the effects of mechanical surface treatments on cyclic loading behavior are discussed systematically and integrated into quantitative model approaches, as well.

<table>
<tr><th colspan="2" rowspan="3"></th><th rowspan="3">without relative movement</th><th colspan="4">with relative movement</th></tr>
<tr><th colspan="2">rolling</th><th colspan="2">sliding</th></tr>
<tr><th>without slip</th><th>with slip</th><th>solid medium</th><th>liquid medium</th></tr>
<tr><td rowspan="2">static</td><td>singular</td><td>smooth embossing, flat embossing, size embossing</td><td colspan="2" rowspan="4">deep rolling, finish rolling, size rolling</td><td rowspan="4">spinning, smooth drawing, smooth spinning</td><td>autofretting, stressing</td></tr>
<tr><td>repetitive regular</td><td></td><td></td></tr>
<tr><td rowspan="3">impulsive</td><td>singular</td><td></td><td></td></tr>
<tr><td>repetitive regular</td><td>hammering,
laser shock treating
high pressure water peening</td><td></td></tr>
<tr><td>repetitive irregular</td><td>shot peening, needle peening, ultrasonic peening</td><td></td><td></td><td>brushing</td><td></td></tr>
</table>

Fig. 1.2: Overview of the principal non-cutting processes of mechanical surface treatment

References

1.1 G. F. Bush, J. O. Almen, L. A. Danse, J. P. Heise: How, when and by whom was mechanical prestressing discovered, In: Sociecty of Automotive Engineers ISTC, Div. 20 Meeting, SAE, Colorado Springs, Colorado, 1962

1.2 O. Föppl: Stahl und Eisen (1929) 49, pp. 775.

1.3 O. Föppl, G. v. Heydekampf: Dauerfestigkeit und Konstruktion, Metallwirtschaft Wissenschaft und Technik 8(1929) 45, pp. 1087–1094.

1.4 H. Isemer: Die Steigerung der Schwingungsfestigkeit von Gewinden durch Oberflächendrücken, In: Mitteilungen des Wöhler-Instituts, Braunschweig, 1931.

1.5 A. Thum, H. Wiegand: Die Dauerhaltbarkeit von Schraubenverbindungen und Mittel zu ihrer Steigerung, Verein Deutscher Ingenieure Zeitschrift 39(1933), pp. 1061–1063.

1.6 E. Hottenrott: Mitteilungen des Woehler-Instituts, Braunschweig(1932) 10, pp. 1.

1.7 A. Thum, O. Ochs: Verein Deutscher Ingenieure Zeitschrift 76(1932), pp. 951.

1.8 A. Thum, F. Wunderlich: Verein Deutscher Ingenieure Zeitschrift 77(1933), pp. 851.

1.9 E. G. Herbert: The work-hardening of steel by abrasion, with an appendix on the “cloudbrust” test and superhardening, Journal of Iron and Steel 11(1927), pp. 265–282.

1.10 E. E. Weibel: The Correlation of Spring-Wire Bending and Torsion Fatigue Tests, Transactions of ASM(1935) 57, pp. 501–516.

1.11 I. Horowitz: Oberflächenbehandlung mittels Strahlmitteln – Handbuch über Strahltechnik und Strahlanlagen – Band 1: Die Grundlagen der Strahltechnik, Vulkan-Verlag, Essen, 1982.

1.12 J. H. Frye, G. L. Kehl: The fatigue resistance of steel as affected by some cleaning methods, Transactions of ASM(1938), pp. 192–218.

1.13 R. Z. v. Manteuffel: Dissertation, TH Darmstadt, 1939.

1.14 F. P. Zimmerli: Shot blasting and its effects on fatigue life, In: Surface Treatment of Metals, ASM, Metals Park, 1941, pp. 261–278.

1.15 J. O. Almen: Peened surfaces improve endurance of machine parts, Metal Program 43(1943) 2, pp. 209–315.

1.16 J. O. Almen: Shot blasting to increase fatigue resistance, SAE Transactions 51(1943) 7, pp. 248–268.

1.17 A. J. Gould, U. R. Evans: The effect of shot-peening upon the corrosion-fatigue of a high-carbon steel, Journal of the Iron and Steel Institute 10(1948), pp. 164–168.

1.18 J. C. Straub, D. May: Stress Peening, The Iron Age(1949), pp. 66–70.

1.19 R. L. Mattson, J. G. Roberts: The effect of residual stresses induced by strain peening upon fatigue strength, In: G. M. Rassweiler, W. L. Grube (eds.), Symposium internal stresses and fatigue in metals, New York, 1959, pp. 338–357.

1.20 C. G. Robinson, E. Smart: The use of specialised shot peening techniques an tapered leaf suspension springs for road vehicles, In: H. O. Fuchs (ed.), Proc. Int. Conf. Shot Peening 2, American Shot Peening Society, Paramus, 1984, pp. 79–83.

1.21 B. Kaiser: Randschichtverfestigung und Schwingfestigkeit hochfester Parabelfedern, VDI Bericht 852, VDI-Verlag, Düsseldorf, 1991, pp. 587–600.

1.22 J. M. Potter, R. A. Millard: The effect of temperature and load cycling on the relaxation of residual stresses, Advances in X-Ray Analysis 20(1976), pp. 309–320.

1.23 L. Bonus, E. Müller: Spannungsstrahlen von Fahrzeugtragfedern – Untersuchungen des Relaxationsverhaltens von spannungsgestrahlten Schraubenfedern, Draht 47(1996) 7/8, pp. 408–410.

1.24 E. Müller, L. Bonus: Lebensdauer spannungsgestrahlter Schraubenfedern unter Korrosion, Draht 48(1997) 6, pp. 30–33.

1.25 E. Müller: Der Einfluß des Plastizierens und des Kugelstrahlens auf die Ausbildung von Eigenspannungen in Blattfe-

dern, Hoesch Berichte aus Forschung und Entwicklung,1992, pp. 23–29.
1.26 F. Engelmohr, B. Fiedler: Erhöhung der Dauerfestigkeit geschmiedeter Pleuel durch Kugelstrahlen unter Vorspannung, Materialwissenschaft und Werkstofftechnik 22(1991), pp. 211–216.
1.27 F. Engelmohr, B. Fiedler: Festigkeitsstrahlen unter Vorspannung, Auswirkungen auf Eigenspannungszustand und Schwingfestigkeit von Bauteilen, In: 1991, pp. 77–91.
1.28 I. Gokyu: Japanisches Patent 725630, 1973, Japan.
1.29 A. Tange, H. Koyama, H. Tsuji: Study on warm shot peening for suspension coil spring, SAE Technical Paper Series 1999–01–0415, International Congress and Exposition, Detroit, 1999, pp. 1–5.
1.30 A. Tange, K. Ando: Study on the shot peening processes of coil spring, In: Proc. Int. Conf. Residual Stresses 6, IOM Communications, Oxford, 2000, pp. 897–904.
1.31 L. Bonus: Versuchsbericht Warmverdichten am Funker 2000, Abteilung EF12 Hoesch-Hohenheimburg, Fedenwerke, 1989.
1.32 G. Kühnelt: Der Einfluß des Kugelstrahlens auf die Dauerfestigkeit von Blatt- und Parabelfedern, In: A. Niku-Lari (eds.), Proc. Int. Conf. Shot Peening 1, Pergamon, Paris, 1981, pp. 603–611.
1.33 J. Ulbricht, H. Vondracek: Möglichkeiten zur Federwegvergrößerung bei Drehstäben, Estel-Berichte(1976) 3/76, pp. 125–132.
1.34 M. Schilling-Praetzel: Einfluß der Werkstücktemperatur beim Kugelstrahlen auf die Schwingfestigkeit von Drehstabfedern, Dissertation, RWTH Aachen, 1995.
1.35 MAN: Die Trucknology Generation – TG-A der MAN Nutzfahrzeuge, Automobiltechnische Zeitschrift 102(2000) 9, pp. 666–674.
1.36 A. Wick, V. Schulze, O. Vöhringer: Kugelstrahlen bei erhöhter Temperatur mit einer Druckluftstrahlanlage, Materialwissenschaft und Werkstofftechnik 30(1999), pp. 269–273.
1.37 A. Wick, V. Schulze, O. Vöhringer: Effects of warm peening on fatigue life and relaxation behaviour of residual stresses of AISI 4140, Materials Science and Engineering A293(2000), pp. 191–197.
1.38 R. Menig, A. Wick, V. Schulze, O. Vöhringer: Shot peening and stress peening of AISI 4140 at elevated temperatures – Effects on fatigue strength and stability of residual stress, In: K. Funatani G. E. Totten (eds.), 20th ASM Heat Treating Society Conference, ASM, Metals Park, 2000, pp. 257–264.
1.39 I. Altenberger, B. Scholtes: Improvement of fatigue behaviour of mechanically surface treated materials by annealing, Scripta Materialia 42 (1999), pp. 873–881.
1.40 I. Altenberger: Mikrostrukturelle Untersuchungen mechanisch randschichtverfestigter Bereiche schwingend beanspruchter metallischer Werkstoffe, Dissertation, Universität Gesamthochschule Kassel, 2000.
1.41 R. Menig, V. Schulze, D. Löhe, O. Vöhringer: Shot peening plus subsequent short-time annealing – A way to increase the residual stress stability and alternating bending strength of AISI 4140, Technical Paper Series 2002–01–1409, Society of American Engineers, Las Vegas, 2002, pp. 1–8.
1.42 L. Wagner, C. Müller, J. K. Gregory: In: Proc. Fatigue 93, EMAS, 1993, pp. 471.
1.43 J. K. Gregory, C. Müller, L. Wagner: Bevorzugte Randschichtaushärtung: Neue Verfahren zur Verbesserung des Dauerschwingverhaltens mechanisch belasteter Bauteile, Metall 47(1993), pp. 915–919.
1.44 L. Wagner, J. K. Gregory: Thermomechanical surface treatment of titanium alloy, In: Second European ASM Heat Treatment and Surface Engineering Conference, ASM, Metals Park, 1993, pp. 1–24.
1.45 L. Wagner, J. K. Gregory: Improve the fatigue life of titanium alloys, Part II, Advanced Materials & Processes 145(1994) 7, pp. 50HH-50JJ.
1.46 F. Bohner, J. K. Gregory: Mechanical Behavior of a Graded Aluminium Alloy, In: W. A. Kaysser (ed.), Proc. Functionally Graded Materials 1998, Trans Tech Publications, 1999, pp. 313–318.

1.47 J. J. Daly, J. R. Harrison, L. A. Hackel: New laser technology makes lasershot peening commercially affordable, In: A. Nakonieczny (ed.), Proc. Int. Conf. Shot Peening 7, Warschau, 1999, pp. 379–386.

1.48 A. H. Clauer: Laser Shock Peening for fatigue resistance, In: J. K. Gregory, H. J. Rack, D. Eylon (eds.), Proc. Symp. Surface Performance of Titanium, Cincinnati, 1997, pp. 217–230.

1.49 A. H. Clauer, D. F. Lahrman: Laser Shock Processing as a Surface Enhancement Process, In: Durable Surface Symposium, International Mechanical Engineering Congress & Exposition, Orlando, 2000.

1.50 M. Obata, Y. Sano, N. Mukai, M. Yoda, S. Shima, M. Kanno: Effect of laser peening on residual stress and stress corrosion cracking for type 304 stainless steel, In: A. Nakonieczny (ed.), Proc. Int. Conf. Shot Peening 7, Warschau, 1999, pp. 387–394.

1.51 Y. Sano, N. Mukai, K. Okazaki, M. Obata: Residual stress improvement in metal surface by underwater laser irradation, Nuclear Instruments and Methods in Physics Research B 121(1997), pp. 432–436.

1.52 K. Eisner: Prozeßtechnologische Grundlagen zur Schockverfestigung von metallischen Werkstoffen mit einem kommerziellen Excimerlaser, Dissertation, Universität Erlangen-Nürnberg, 1998.

1.53 E. Houdremont, R. Mailänder: Archiv für das Eisenhüttenwesen(1929) 49, pp. 833.

1.54 E. Siebel, M. Gaier: Untersuchungen über den Einfluß der Oberflächenbeschaffenheit auf die Dauerschwingfestigkeit metallischer Bauteile, Verein Deutscher Ingenieure Zeitschrift 98(1956) 30, pp. 1715–1723.

1.55 H. Oschatz: Gesetzmäßigkeiten des Dauerbruches und Wege zur Steigerung der Dauerhaltbarkeit, Dissertation, Mitteilungen der Materialprüfungsanstalt an der Technischen Hochschule Darmstadt, 1933.

1.56 H. Wohlfahrt: Einfluß von Eigenspannungen, In: W. Dahl (ed.), Verhalten von Stahl bei schwingender Beanspruchung, 1978, pp. 141–164.

1.57 E. Macherauch, H. Wohlfahrt: Eigenspannungen und Ermüdung, In: D. Munz (ed.), Ermüdungsverhalten metallischer Werkstoffe, DGM-Informationsgesellschaft Verlag, Oberursel, 1985, pp. 237–283.

2
Procedures of Mechanical Surface Treatments

2.1
Shot Peening

2.1.1
Definition and Delimitation of Procedure

DIN 8200 [2.1] defines peening as mechanical surface treatment processes in which peening media with a specific shape and a sufficiently high degree of hardness (compare DIN 8201 [2.2]) are accelerated in peening devices of various kinds and interact with the surface of the treated workpiece. The methods summarized in Table 2.1 are to be distinguished depending on the objective. The creation of compressive residual stresses close to the surface is the main focus of the shot peening process, whereas in the other methods, these effects are more or less significant side effects. Accordingly, shot peening is the sole method used for increasing the load capacity of technical components. Therefore, the following report is limited to this peening process.

2.1.2
Application Examples

Due to its flexibility, shot peening may be used on components of almost any shape, particularly on those possessing a complex geometry. It is thus predestined for use on cross-sectional variations, chamfers, boreholes and bore edges. Components which are typically shot peened in technical mass production are springs, con-rods, gears, stepped or grooved shafts and axles, turbine vane and blade bases and heat-affected zones of welded joints. Due to the positive effects on resistance to stress corrosion cracking and corrosion fatigue, shot peening is also used in apparatus engineering and plant construction, in order to protect e.g. interior pipe surfaces against corrosive media.

Tab. 2.1: Subdivision of peening treatments

Peening Type	**Shot Peening**	**Blast Cleaning**	**Finish Peening**	**Abrasive Peening**	**Peen Forming**
Main Aim	Generation of compressive residual stresses and work-hardening close to the surface	Removal of contaminants, coatings (rust, scale), laquers	Generation of a uniform rough or smooth surface structure	Machining of the workpiece with geometrically undefined cutting edge	Forming, Straightening
Side Effects	Mostly increase of roughness, cleaning	Generation of compressive residual stresses and work-hardening in usually very thin surface layers	Generation of compressive residual stresses and work-hardening in usually very thin surface layers	Generation of compressive residual stresses and work-hardening in usually very thin surface layers	Generation of compressive (convex, small depth of deformation) or tensile (concave, large depth of deformation) residual stresses, workhardening and increase of roughness
Applications	Cyclically, wear, corrosively or fretting corrosively loaded components, generation of compressive residual stresses prior to coating	Fettling, removal of tarnish at CrNi-steels, descaling, derusting, desanding, cleaning prior togalvanizing	Surface roughening prior to coating, improvement of load capacity and lubrication properties, optical effects as roughening, smoothing, polishing or matting	Deburring, removal, separation	Sheet components, integrally reinforced plankings
Peening Media	Round: rounded cut wire shot, cast steel shot (d = 0.2 to 3 mm), ceramic (d = 0.15 to 1.5 mm) or glass (d = 0.05 to 0.85 mm) beads	Chiselled: chilled cast grit, corundum, quartz sand, glass beads, polymer granulate	Round or chiselled: steel, aluminum, ceramic, glass, silicon carbide	Chiselled: chilled cast grit, corundum	Round: steel balls of high hardness (d = 2 to 10 mm)

2.1.3
Devices, Tools and Important Parameters

According to Fig. 2.1, shot peening may be applied using rotating wheel, compressed-air, injector and injector gravitational peening systems that are distinguished by their respective technique for accelerating the shot. A rotating wheel peening installation consists of one or more rotating wheel units. The rotating guide vanes receive the shot through the wheel hub and centrifugal forces thus serve to accelerate the shot. These systems are characterized by a high throughput of the shot, but also by a broad velocity distribution within the cross section of the shot stream. The drop velocity of the shot is controlled by the rotation of the rotating wheel. In compressed-air peening systems, the shot is conveyed from an unpressurized storage container to a pressurized storage container by a supply system. The shot is then passed into a jet of air of equal pressure via a shot dispensing unit. The mixture of air and shot is finally accelerated through a nozzle onto the surface of the workpiece. The essential factor which determines the velocity of the shot is the pressure of the air/shot mixture. In contrast to rotating wheel systems, the shot delivery rate and the spread of shot velocities are comparatively low. Compressed-air peening systems are primarily suited for the treatment of geometrically complex components due to the greater freedom of movement of the nozzle, and for high-intensity treatment of small areas because of the small jet diameters. Injector peening systems use the effect of suction to transfer the shot from a storage container into the air stream. The shot is transported by the air stream and accelerated through nozzles onto the workpiece surface, as in compressed-air systems. The simple construction of these systems allows for high delivery rates and medium velocity spreads of the shot, while nozzle mobility and shot intensity are reduced in comparison to compressed-air systems. In injector gravitational peening systems the storage container is located above the workspace and the supply of shot to the air stream is thus supported by the force of gravity. This permits improved control of velocity and delivery rate.

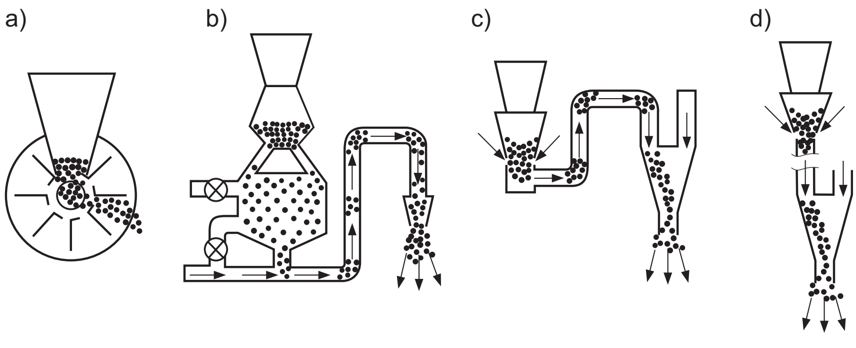

Fig. 2.1: Different devices for shot peening treatments: rotating wheel (a), compressed air (b), injector (c) and injector gravitational (d) peening devices, [acc. 2.3]

A special form of shot peening is represented by ultrasonic shot peening, in which the shot and the workpiece are placed in a chamber together and are exposed to a strong ultrasonic field at frequencies of about 20 kHz. This field accelerates the ball bearings that are used as shot. The shot interacts with the surface of the workpiece in an impact process at similar velocities as in conventional shot peening methods. Appropriate chamber design permits use of the method for large component surfaces and mobile applications [2.4]. Furthermore, the encapsulation of the shot prevents contamination by small shot and shot particles. As the shot deviates only slightly from exact spherical shape, the aim is to achieve lower degrees of surface roughness [2.4].

The shot acts as the tool of the peening process. Depending on type, the shot is delivered either as balls, chiseled grit, rounded cut wire, beads or granulate. According to Fig. 2.2, the classification distinguishes between metallic shot – such as chilled cast steel or steel in the form of rounded cut wire –, inorganic nonmetallic shot – such as ceramic or glass beads –, organic shot – such as polymer granulate –, and a number of natural materials. It is characterized by its chemical composition, size, size distribution, shape, stiffness, hardness and density. While dry rotating wheel systems, for instance, generally use iron-based shot, special applications in wet shot peening systems in the nonferrous metals industry also call for the use of nonferrous metal shot whenever contamination of the workpiece by shot dust of different material is to be avoided. Among the types of inorganic nonmetallic shot, glass beads and beads made of zirconium oxide, silicon oxide and corundum are particularly significant. Organic peening media, some of which are of natural origin, are also used for special applications, specifically superfinishing [2.5].

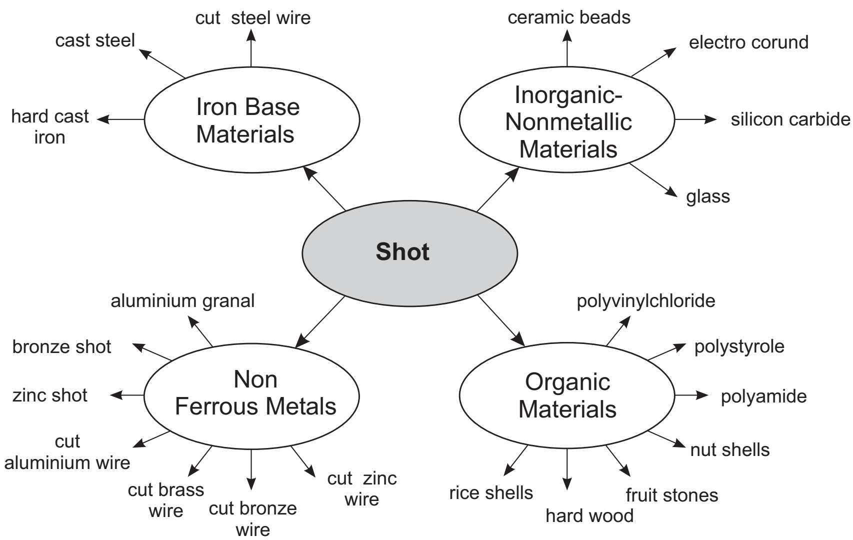

Fig. 2.2: Media for shot peening

According to the detailed discussion of the elementary processes of shot peening in Sect. 3.1.1, the hardness of the shot must, at least approximately, equal the hardness of the workpiece. Therefore, hardened or case hardened steels require the use of steel shot of at least grade 54–58 HRC instead of the common cast steel shot of grade 46–51 HRC [2.6]. Owing to their hardness, glass or ceramic beads are also an option for achieving high compressive residual stress states. It must be taken into account, however, that their lower density results in a smaller impulse upon impact on the workpiece and thus, less deep action of the peening process [2.7,2.8].

The shot size is to fit the dimensions and geometry of the components to be treated. On the one hand, the shot size must be sufficiently small to reach areas which are hard to access, such as small notches. This also serves to avoid notch effects due to impact-induced roughness. On the other hand, the dimensions and shape of thin-walled components are not to be changed inadmissibly [2.9]. Regarding the quality of a peening process, regular monitoring of the shot state is essential, as the shape and the size spread of the shot will change during application due to fragmentation and wear. Thus, the shot is conditioned [2.10–2.12] by removing dust, screening out particles that exceed an upper or lower limit and separating chiseled particles. One way of achieving the latter is to pour the shot onto a conveyor belt which is tilted sideways, thus allowing sufficiently round particles to quickly roll off [2.13].

Steel workpieces are usually treated with steel shot. Glass beads are primarily suited for low-intensity shot peening treatments and for components which would otherwise be contaminated and, for example, become more prone to corrosion. Therefore, they are used primarily on small-diameter components and on titanium or aluminum alloys sensitive to contamination by iron [2.14]. Ceramic beads combine high hardness with medium densities and are used e.g. for the shot peening of titanium alloys [2.14]. Recent research deals with shot peening using zirconium oxide and hard metal shot for the strengthening of ceramic samples made of silicon nitride and aluminum oxide [2.15–2.17].

In special cases, different shot types are used consecutively. After being treated with cast steel, case hardened gears may receive a secondary peening using glass beads to shift the maximum compressive residual stress closer to the surface [2.18,2.19]. This secondary treatment also reduces the roughness of components made of titanium alloys [e.g. see 2.20–2.23]. Shot of different size is used for peening welded joints [e.g. see 2.24,2.25]. Notches with small radii are primary treatment using fine shot, while the required intensity is achieved by using coarser shot subsequently.

Fig. 2.3 shows the essential parameters of the shot peening process. Apart from the factors defined by the peening system which influence the amount and the velocity of the shot and thus, peening intensity and coverage, the aforementioned properties of the shot are crucial. According to the detailed description in Sect. 3, the properties and the state of the workpiece, determined by its temperature and the degree of prestress, are so essential that alterations of these factors have led to a variety of methods, described separately below.

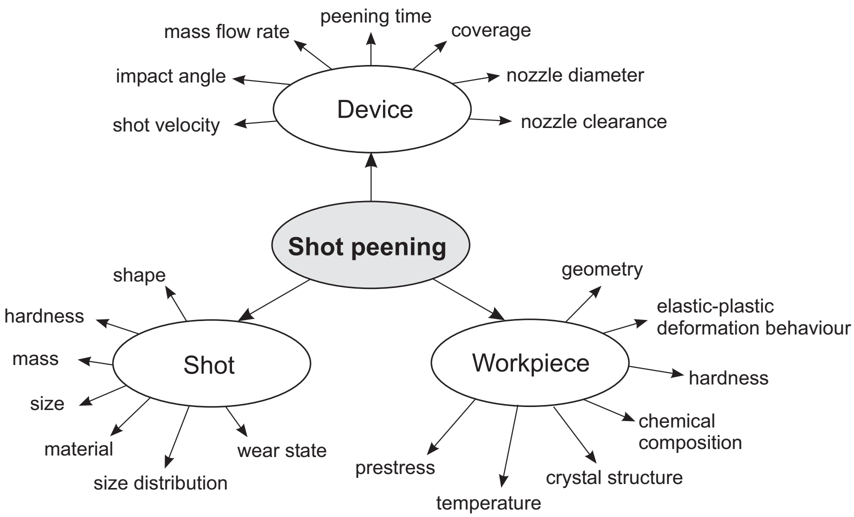

Fig. 2.3: Parameters influencing the results of shot peening treatments

2.2 Stress Peening

2.2.1 Definition and Delimitation of Procedure

Stress peening is a variant method of shot peening in which mechanical prestress of the same direction as the future operational load is applied to the workpiece during the peening treatment [e.g. see 2.26–2.35]. This prestressing is used to shift the residual stress state after the shot peening process towards higher compressive values. Since the stress peening process itself, aside from applying prestress, is identical to the shot peening process described in the preceding section, it requires the same equipment.

2.2.2 Application Examples

Stress peening is primarily used in the final treatment stage of springs, such as leaf, coil, turning-rod and brake accumulator springs [e.g. see 2.34–2.39]. There are also studies available regarding the use of stress peening on con-rod shafts [2.32,2.33]. Concerning components peened under torsional prestress, it must be taken into account that the resulting residual stress components vary significantly due to the biaxial load. In this particular case it is crucial that the future service load will not be alternating, but swelling, or should at least have a pronounced mean stress component.

2.2.3 Devices, Tools and Important Parameters

In terms of systems technology, there are no different prerequisites than for conventional shot peening. The same kind of shot is utilized for stress peening treatments as for conventional peening treatments. The only difference regarding the required installations is presented by the devices for applying pre-stresses, which are component-specific because they must permit load to be introduced in the same manner as service load on the component will be later. In the industrial area, the actual application of prestress is usually effected by screw connections [2.32], while within a laboratory environment prestress may also be applied hydraulically [2.31] or pneumatically [2.40]. The actuating variables of the conventional shot peening process, too, remain in effect without change. The amount of prestress applied is a significant additional factor. Concerning samples of simple geometry, the type and direction of prestress as determined by the future service loading of the component are important variables as well. Thus, the distinction is made between homogeneous uniaxial tensile prestressing, non-homogeneous uniaxial bending prestress and non-homogeneous biaxial torsional stress.

2.3 Warm Peening

2.3.1 Definition and Delimitation of Procedure

Warm peening is a variant of the common shot peening process used exclusively on steels, in which the workpiece exhibits an elevated temperature. Peening generally takes place at temperatures ranging from 170 °C to 350 °C [e.g. see 2.29,2.41–2.44]. Apart from the elevated temperature, the process is identical to conventional shot peening, and therefore principally requires the same equipment. An additional concern is that the effective temperature levels should only occur in the workpiece and that the shot, in particular, should not be warmed up significantly, as this would lead to decreases in hardness due to annealing effects and thus, to a reduced benefit of the peening process.

2.3.2 Application Examples

Examinations of warm peening applications in technological practice have so far focused exclusively on the surface treatment of various steel springs [e.g. see 2.29,2.44–2.49].

2.3.3
Devices, Tools and Important Parameters

As mentioned above, there are no particular requirements beyond heating the workpiece and avoiding undue warming of the shot. Industrial processes frequently utilize the residual heat of preceding heat treatments to achieve the desired workpiece temperature. However, maintaining a constant temperature can become problematic in case of even the slightest deviation from scheduled timing. Therefore, scientific research relies on a specific warming of the workpiece in compressed-air peening systems. It is achieved either by adding heated air streams to the mixture of air and shot, as indicated for the peening nozzle in Fig. 2.4 [2.40], or by inducing eddy current [2.50–2.52].

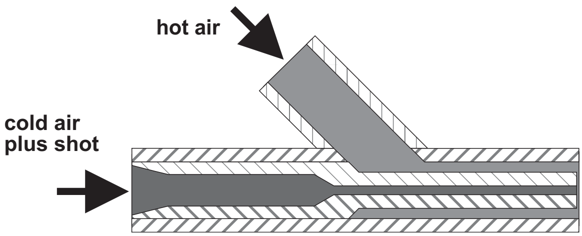

Fig. 2.4: Peening nozzle for shot peening at elevated temperatures [2.39]

2.4
Stress Peening at Elevated Temperature

To date, only a few examinations of stress peening at elevated temperatures [e.g. see 2.46,2.53,2.54] have been carried out. Applications, if economically relevant at all, are to be found in the spring manufacturing industry. The required technical systems and the actuating variables described in connection with stress peening and warm peening are to be considered jointly.

2.5
Deep Rolling

2.5.1
Definition and Delimitation of Procedure

Deep rolling is a non-cutting production method which, next to finish rolling and size rolling, is counted among the fine surface rolling methods (see Fig. 2.5) according to VDI guideline 3177 [2.55]. Finish rolling aims at creating surfaces with a plateau-like profile and especially low roughness, without significantly altering the geometric shape, in order to achieve good sliding and antifrictional qualities and to reduce wear. Size rolling is used to generate precise dimensions and thus create workpieces with an accurate fit. By contrast, the objective of actual deep rolling is to introduce workhardening and compressive residual stresses into near-surface regions in order to increase fatigue strength. In this goal-oriented rather than method-oriented classification, the transition from finish rolling to deep rolling is to be viewed as a fluent one, since increased strength is an additional aspect beyond mere smoothing. Deep rolling generally entails rolling off the tool and the workpiece against each other repeatedly at a defined pressure. This forces a continually increasing plastic deformation in the near-surface region [2.5,2.57–2.59]. If a translational motion is applied in addition to the rotational movement, this is called feed method when used on smooth or slightly notched components, and plunge method when used on heavily notched parts.

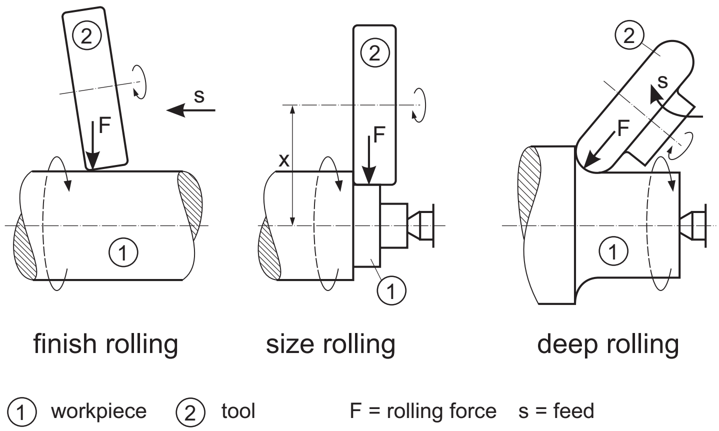

Fig. 2.5: Methods of surface rolling: smooth rolling and deep rolling using the feed method (a), size rolling (b) and deep rolling using the plunge method (c) [2.56]

2.5.2 Application Examples

In the automotive industry, in general mechanical engineering and, to a certain extent, in aircraft construction, deep rolling is used on crankshafts, valve shafts, screws, bore-holes, axles, bolts and threaded parts. Due to the rotation of both the tool and the workpiece required in the method, its application is generally limited to components or treatment regions of rotational symmetry. Special tools permit deep rolling of the interior surfaces of through holes, stepped holes or blind holes with a sufficiently large diameter. Due to its simple technical realization in standard machine tools, deep rolling is easily implemented in the same clamping after a cutting treatment, especially if this is preceded by turning processes.

2.5.3
Devices, Tools and Important Parameters

Deep rolling may generally be done on standard machine tools. A distinction is made between tools of a roller-type design and tools which are spherical, the latter exhibiting greater flexibility [2.60]. Using profiled rolls permits specific work on threads as well as precise sizing of notches with a special shape. Another distinguishing feature is the way in which loads are applied during the deep rolling process. In mechanically prestressed tools, the deep rolling force is regulated by spring elements, whereas hydrostatic tools generate the deep rolling force by means of the operating fluid pressure. In both cases, the rolling force is increased and decreased gradually during the beginning and ending stages of the work process in order to prevent the occurrence of stress peaks in the component.

In contrast to the descriptions mentioned above, deep rolling of crankshaft bearings involves special machinery. For work on the seats of rolling bearings the part is clasped by a pincer-shaped tool that consists of two large supporting rollers and two milling rollers, the latter working on the radii which lead to the crank cheeks [2.61].

Fig. 2.6 summarizes the essential actuating variables of the deep rolling process, which may be classified according to workpiece, tool, method or device used.

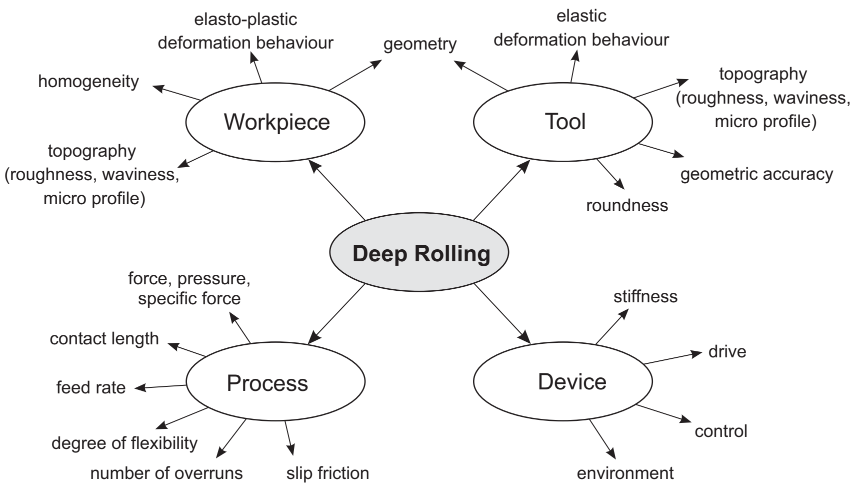

Fig. 2.6: Parameters influencing the results of deep rolling treatments

2.6 Laser Peening

2.6.1 Definition and Delimitation of Procedure

Laser shock treatment exposes the surface of a workpiece to laser pulses with a pulse duration in the nanosecond range, and is used for the mechanical treatment of the near-surface regions of the workpiece reaching surface depths on the order of millimeters. Building on numerous 1970s papers on laser-induced shock waves – which, however, dealt first with determining the pressure created by pulsed laser beams [2.63–2.65] and only later focused on the effects of the shock waves on the material and on applications for treating materials [2.66,2.67] – work on the modification of materials based on measurements of hardness and residual stress analysis has been intensified only since the late 1980s and 90s. The first laser systems used for this research were Nd:glass [2.68–2.71] and Nd:YAG [2.72,2.73] types, the majority of which were designed for research exclusively and exhibited only low pulse repetition rates, while they could produce pulse energy levels beyond the capability of industrial laser systems. The three system types shown in Table 2.2 are the present competitors in the emerging field of industrial application. Apart from phase-conjugated Nd:glass lasers [2.74–2.76] and q-switched and simultaneously frequency-doubled Nd:YAG lasers [2.77–2.81], XeCl-excimer lasers [2.82] are favored.

Tab. 2.2: Laser types used for laser shock treatments

Laser Type	Nd:Glass	Q-switched Nd:YAG	XeCl-Excimer
Country	USA, F	J, D	J
Reference	[2.72–2.74]	[2.75–2.79]	[2.80]
Wave Length [nm]	1053 or 527	532	308
Pulse Energy [J]	20–50	0.2	2
Pulse Duration [ns]	10–30	8	50
Pulse Rise Time [ns]	0.2	10	20
Pulse Frequency [Hz]	6	10	20
Beam Dimensions	□ 8 x 8 mm^2, ∅ 0.9–6 mm	∅ 1 mm	□ 40 x 50 mm^2
Sepcial Feature	SBS-Phase- Conjugation	Fiber Coupling	

Laser-induced compressive impacts are mostly created by ablation of materials applied to the workpiece or by ablation of near-surface regions, which is caused by absorption of intense laser radiation and is additionally increased by the vaporized material which forms on the workpiece surface [2.83]. For laser shock treatment use, a laser system should have a short rise time of the pulse on the order of a few nanoseconds, pulse durations on the order of tens of nanoseconds, a lowest possible beam divergence below one millirad, pulse energies of approx. one joule minimum, and wavelengths with a maximum of one micrometer [2.84].

2.6.2 Application Examples

To date, the laser types and the associated problems mentioned above have limited the number of technical applications that go beyond the experimental stage. At present, the most important application is found in aviation technology, where laser shock treatment is used to increase the fatigue strength and the foreign-object-damage tolerance of jet turbine vanes and blades [2.85]. In medical technology, laser shock treatment is used for treating the surfaces of knee and hip prostheses [2.76]. Applications for automotive technology have been tested [2.76]. In addition, laser shock treatment is used to reshape airplane wings and for labeling parts susceptible to tearing [2.76]. Finally, [2.77] reports its use in nuclear facilities as a way to increase the resistance to corrosion fatigue in weld joints.

2.6.3 Devices, Tools and Important Parameters

At present, there is only a small number of systems suitable for industrial use. Their fundamentally different types and some essential specifications are com-

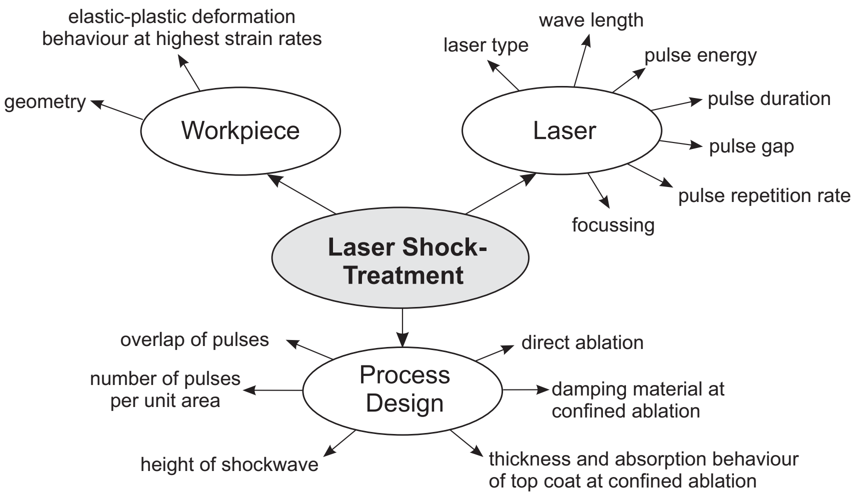

Fig. 2.7: Parameters influencing the results of laser shock treatments