Mechanical Surface Treatments

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Abstract

In the present work, an overview of modern mechanical surface treatments is given. The available technologies are classified by the type of tool – workpiece interaction. Selected treatments are presented in detail. Besides the description of each process technology, main focus is given to the characteristic resulting surface layer states. To this end, typical residual stress profiles and work hardening states as well as surface topographies are presented and compared for those processes.

Keywords surface treatments, surface layer states, residual stresses, topography, shot peening, ultrasonic shot peening, deep rolling, diamond finishing, machine hammer peening, laser shock treatment, high pressure water peening, cavitation shotless peening.

Introduction

Technological practice today, particularly in the spring-manufacturing, automotive and aerospace industries, is hardly imaginable without mechanical surface treatments [1]. Such treatments are used to reinforce the workpiece surface layer which is often subjected to the highest loading. Reinforcement is achieved by local plastic deformation of near-surface areas which leads to compressive residual stresses and work hardening. The main goals of surface treatment are the increase of resistance against fatigue, wear and corrosion. Since Tilgham in 1871 invented the sand blast process, i.e. the precursor of present-day shot peening [2], [3], the correlation between mechanical surface treatment and increased fatigue strength was established by Föppl in 1929 [4], [5], and the systematic examinations of the relation of rolling and fatigue strength, corrosion fatigue and fretting fatigue were carried out by Thum in the early 1930s [6]–[8], a great variety of mechanical surface treatments with specific properties have been developed. Most of them are used for mechanical components subjected to cyclic loadings during operation, since they can improve the fatigue strength. Yet, each technology produces specific resulting surface layer characteristics, which, in turn, have direct impact on the work piece properties.

		Plastic deformation without relative movement between workpiece and tool	Plastic deformation with relative movement between workpiece and tool		
			Rolling	Sliding	
				Solid tool	Liquid tool
Static		Embossing	Deep rolling, finish rolling, size rolling	Spinning, diamond finishing	Autofretting, stressing
Impulsive	Regular	Machine hammer peening, laser shock treatment, high pressure water peening			
	Irregular	Shot peening, variants of shot peening			

Figure 1: Overview of mechanical surface treatments

This paper aims to provide an overview of modern mechanical surface treatments and to present the surface layer states achieved by different mechanical surface treatments. A systemized compilation of non-cutting surface treatment processes is given in Fig. 1. The treatments are divided whether they are with or without relative movement between the tool and the workpiece and the latter are subdivided whether the tool contact is static or impulsive. The description of methods without relative movement is limited to impulsive impact. Comparison of surface layer states is carried out exemplarily on quenched and tempered low alloy steel AISI4140 (German grade 42CrMo4) provided that experimental data are available.

Procedures of mechanical surface treatments without relative movement between workpiece and tool – impulsive irregular

Shot peening, as defined by ASTM B851 [9], is a "process for cold working surfaces by bombarding the product with shot of a solid and spherical nature propelled at a relatively high velocity", where surface-near plastic deformation leads to compressive residual stresses and work hardening. Rotating wheel, compressed-air, injector and injector gravitational peening systems are utilized for accelerating the shot which acts as "tool" in the shot peening process. The most important shot materials used on metals are cast steel, cut wire, glass beads and ceramic beads [10]–[12], while the latter have also been tried out for shot peening of composites [13]. Hard metal peening media have been used for the strengthening of ceramic samples [14]–[16]. Steel workpieces are usually treated with steel shot. The shot diameter typically varies between 0.05 mm and 2.5 mm [17] while the hardness must be, at least approximately, equal to the hardness of the workpiece [11], [18], [19]. Type and size of the shot must fit to the workpiece. Glass and ceramic beads are often used to avoid contamination with iron, e.g. for aluminum and titanium alloys [12]. Owing to their hardness, these shot media are also an option for achieving high compressive residual stress states. However, it must be taken into account that their lower density results in a smaller impulse upon impact on the workpiece and thus, less deep influence of the peening process [20]. Due to the achieved process cleanliness, dry ice has been examined as shot peening medium and showed great potential for special applications [21], [22]. Recent investigations by [23] have focused on the development of a clean peening technology using recirculating shot accelerated by water jets in a water-filled chamber, thus avoiding sparks and dust explosions. Due to its high flexibility, the shot peening process is applied in technical mass production, such as for springs, con-rods, gears, stepped or grooved shafts and axles, turbine vane and blade bases and heat-affected zones of welded joints [1].

Warm peening is a modified shot peening process mostly used on steels, in which the workpiece exhibits an elevated temperature. The latter usually ranges from 170 °C to 350 °C [24]–[29] and leads to static and dynamic strain ageing effects stabilizing the dislocation structure. Thus, more stable residual stress states are reached. A nozzle used for warm peening is shown in Fig. 2. The shot should not be heated up significantly to avoid a decrease of hardness due to annealing effects. Similar effects with reduced complexity can be achieved by a combination of conventional shot peening with subsequent annealing [30], [31]. Examinations of warm peening applications in technological practice have so far focused on the surface treatment of steel springs (see: [25], [32], [33], for instances).

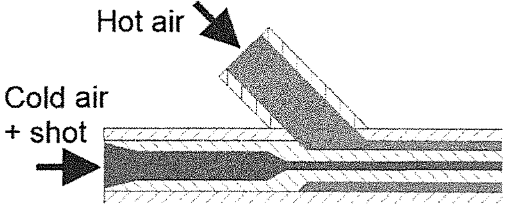

Figure 2: Nozzle for warm peening, schematically [28]

Stress peening is a modified shot peening process in which mechanical prestress of the same direction and sign as the future operational load is applied to the workpiece during the peening treatment [34]–[37]. This prestressing is used to shift the residual stress state resulting from the shot peening process towards higher compressive values [1], [38]. Stress peening is primarily used in the final treatment stage of leaf, coil, turning-rod and brake accumulator springs [39]–[41]. Combined warm and stress peening processes have been tried out on different materials [13], [28], [33], [38].

Ultrasonic peening is a widely used variant of shot peening. The shot, usually ball bearings, and the workpiece are placed together in a chamber and are exposed to a strong ultrasonic field at frequencies of about 20 kHz [42], [43]. The shot is accelerated by this field and interacts with the workpiece surface in an impact process at similar velocities as in conventional shot peening procedures. As the shot deviates only slightly from exact spherical shape, the aim is to achieve lower degrees of surface roughness [42], [44].

Micropeening is a variant of shot peening with micro shots (diameter: $d < 100$ µm) and currently in development. The shots, usually glass beads or ceramic particles, are accelerated to high velocities ($v < 200$ m/s) [45]. Besides compressive residual stresses and work-hardening, the generation of nanocrystalline surface layers has been observed in literature [46].

Dual shot peening denotes successively applied shot peening processes with different parameters. Peening with coarse shot and subsequently with fine shot is used for surface roughness reduction [47]–[49] after generation of residual stresses while the opposite case is used for welded joints [11], [18], [19].

In recent years, peening processes utilizing cavitation have been developed. Here, gas bubbles work as "tool". Ultrasonic wet peening is a mechanical surface treatment where the workpiece is held within a suspension exposed to a ultrasonic field. Plastic deformation on the surface occurs based on the acceleration of blasting shots in a fluid by ultrasonically induced cavitation [46]. Cavitation shotless peening merely uses the effects of cavitation [50] and has successfully been applied in water and in air [51]–[53]. Because of its retarding effect on hydrogen assisted fatigue crack growth and stress corrosion cracking, cavitation shotless peening has been used on several components of stainless steel and Ni-base alloys in nuclear power plants [50], [54].

Procedures of mechanical surface treatments without relative movement between workpiece and tool – impulsive regular

Machine hammer peening denotes mechanical surface treatment by repetitive regular mechanic impulses. Conventional machine hammer peening technologies usually make use of electromechanical transducers or pneumatic or hydraulic pressure to generate a regularly oscillating indenter movement [17], [55]. Depending on the application, indenter diameters commonly vary between 2 mm and 20 mm [56]. Electromechanical and pneumatic machine hammer peening are used for the surface finish treatment of molds and pressing dies [17], [57], [58]. Portable, pneumatically driven machine hammers with adjustable frequencies (~ 200 Hz), are often used for post-weld processing [59].

Ultrasonic impact treatment is a machine hammer peening process where the workpiece surface is deformed by repetitive regular impulses at ultrasonic frequency. Tool and workpiece are usually in contact under static pressure. The ultrasonic oscillation (~ 20 kHz) is transduced to mechanical oscillations which are amplified by a booster, as shown in Fig. 3. Ultrasonic impact treatment is commonly used in post-weld processings [60]–[62]. As reported by [63], [64] and [50], the ultrasonic impact treatment can be used to generate nanocrystalline surface layers (UNSM, "Ultrasonic Nanocrystalline Surface Modification").

Currently being developed, piezo peening is a machine hammer peening treatment similar to the UIT technology [65]. In contrast to UIT, however, hammering can be adjusted independently from ultrasonic resonance frequency.

Laser shock treatment, usually carried out using Nd:Glass [66], [67], Q-switched Nd:YAG [50] and XeCl-Excimer lasers [68], denotes the exposition of the workpiece surface (direct ablation [69]) or a thin coating on the workpiece surface (confined ablation [70], [71], see Fig. 4) to laser pulses with a pulse duration in the nanosecond range [68]. Due to intensities in the GW/cm^2 range, the affected area is transformed into plasma [71]. The expanding plasma causes a shock wave in the surface layer, which induces plastic deformation provided that the Hugoniot condition is fulfilled [50]. A detailed process description can be found in the literature [1], [60], [68]. Modified laser shock treatments at elevated [70] and cryogenic [72] temperatures and under prestress [73] have been tried out recently. Typical applications of laser shock treatment can be found in the aerospace industry. High pressure water peening makes use of the pressure induced by incontinuous drop flow. A detailed process description can be found in literature [74], [75] where the technology was examined in detail. Process modifications, such as ice peening, could serve as a combined water and shot peening process, since partially frozen drops could increase the residual stress depth [74].

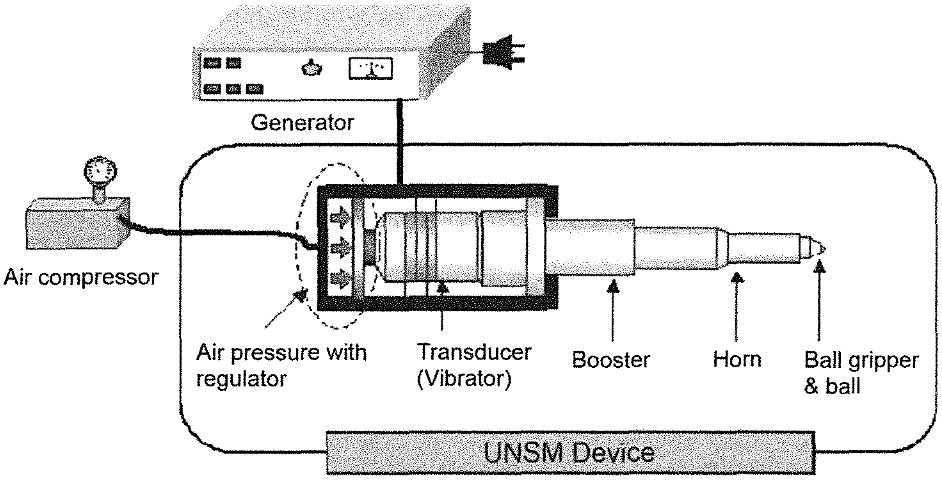

Figure 3: UIT / UNSM device, schematically [64]

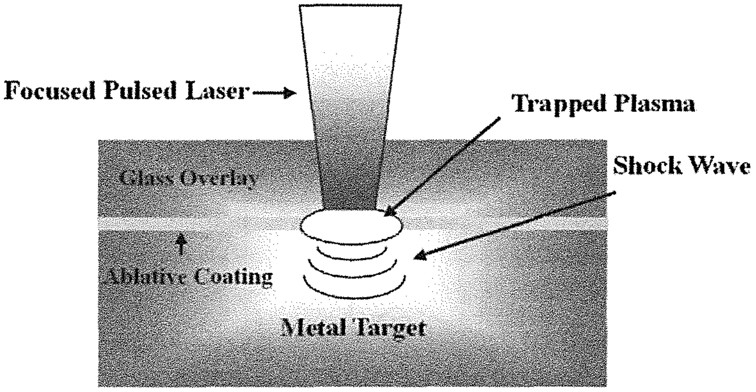

Figure 4: Laser shock treatment process, schematically [70]

Procedures of mechanical surface treatments with relative movement between workpiece and tool

Being counted among the fine surface rolling methods (according to VDI guideline 3177 [76]), deep rolling is a mechanical surface treatment which generally entails rolling off the tool and the workpiece against each other repeatedly at a defined pressure (Fig. 5). This induces a continuously increasing plastic deformation in the near-surface region [77], [78]. Deep rolling is generally applied to workpieces with rotational symmetry, such as crankshafts, valve shafts, screws, bore-holes, axles, bolts and threaded parts. Therefore the treatment is widely used in automotive industry.

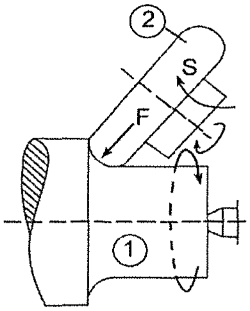

Figure 5: Deep rolling process – schematically [78]

Modified deep rolling processes, such as deep rolling of steels at elevated temperature, have been examined in literature [79], [80].

Diamond finishing is a mechanical surface technology similar to deep rolling. However, instead of rolling contact, there is sliding contact between workpiece and tool. Recent investigations also focus on surface enhancement by cutting methods, whose traditional aim is defining shape and topography and not the improvement of fatigue strength [81], [82].

Autofrettage is not a classical surface treatment, but a technology used for tube systems subjected to pulsating inner loads, such as injectors, pumps and canons [60], [83]. It denotes an initial tensile overload by pressures inside the tube which are far beyond the operating pressure, leading to compressive residual stresses in fatigue critical areas [84].

Surface layer states after mechanical surface treatments

The severe plastic deformation of surface-near regions due to mechanical surface treatment can lead to changes in shape, topography, lattice structures, macro residual stress state, phase fractions, textures and density as well as to crack initiation [1], [48], [60], [85]. To evaluate the achieved surface layer states, objective measures are required. In the following section, we will limit ourselves to the description of changes in topography, residual stress profile and work hardening state induced by mechanical surface treatment, represented by the roughness (R_z, R_t, R_a), the macro residual stresses (σ^{rs}) and the hardness (HV) as well as the full width at half maximum of the X-ray interference lines (FWHM), respectively. These measures are shown in Fig. 6 [86].

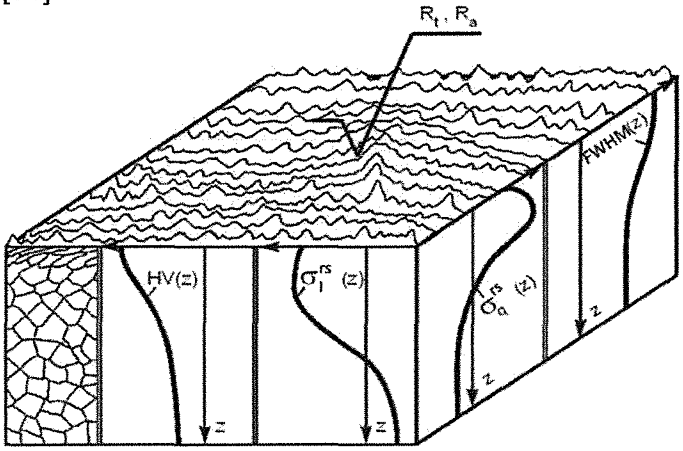

Figure 6: Surface layer characteristics, schematically [86]

For the generation of macro residual stresses, local plastic stretching of surface-near areas is necessary. The surface layer characteristics are mainly governed by the workpiece material and initial state (hardness etc.), environment (temperature etc.) and the process properties.

The following section aims to present characteristic surface layer states after selected mechanical surface treatments of the low alloy steel AISI4140 (42CrMo4) in a quenched and tempered state (610 °C for high pressure water peening; 450 °C for all other mechanical surface treatments). Selected surface treatments are: Shot peening ("SP"; shot: S170, 56 HRC; pressure: 1.6 bar; Almen intensity: 0.3 mmA) [87], stress peening ("SSP"; shot: S170, 56 HRC; pressure: 1.6 bar; Almen intensity: 0.3 mmA; longitudinal stress state; prestress: 600 MPa) [87], deep rolling ("DR"; pressure: 250 bar; path spacing: 0.04 mm; ball diameter: 6.35 mm), piezo peening ("PP"; frequency: 500 Hz; amplitude: 18 µm; indenter diameter: 5 mm; path spacing: 0.2 mm) [65], laser shock treatment ("LST"; Nd:glass slab laser; energy density: 168 J/cm^2; wavelength: 1053 nm; pulse width: 18 ns; layers: 2; overlap: 50%) [71], micropeening ("MP"; glass beads; pressure: 1.5 bar; Almen intensity: ~0.04 mmN) [88], ultrasonic wet peening ("UWP"; frequency: 20 kHz; process time: 30 min) [46], diamond finishing ("DF"; feed: 0.6 mm; path spacing: 0.04 mm; ball diameter: 2 mm) and high pressure water peening ("HPWP"); pressure: 1000 bar; nozzle diameter: 1.5 mm; impact time: 3 s) [74].

The measured residual stress profiles of the selected surface treatments are shown in Fig. 7. Four distinct types of residual stress profiles can be observed. Some surface treatments generally lead to steep residual stress gradients close to the surface (< 100 µm; typically micropeening, ultrasonic wet peening, high pressure water peening). Others lead to deep-lasting compressive residual stresses (> 100 µm; typically deep rolling and laser shock treatment). Several mechanical surface treatments can lead to high maximum compressive residual stresses (typically deep rolling) while others are not able to reach higher levels of compressive residual stresses (typically high pressure water peening).

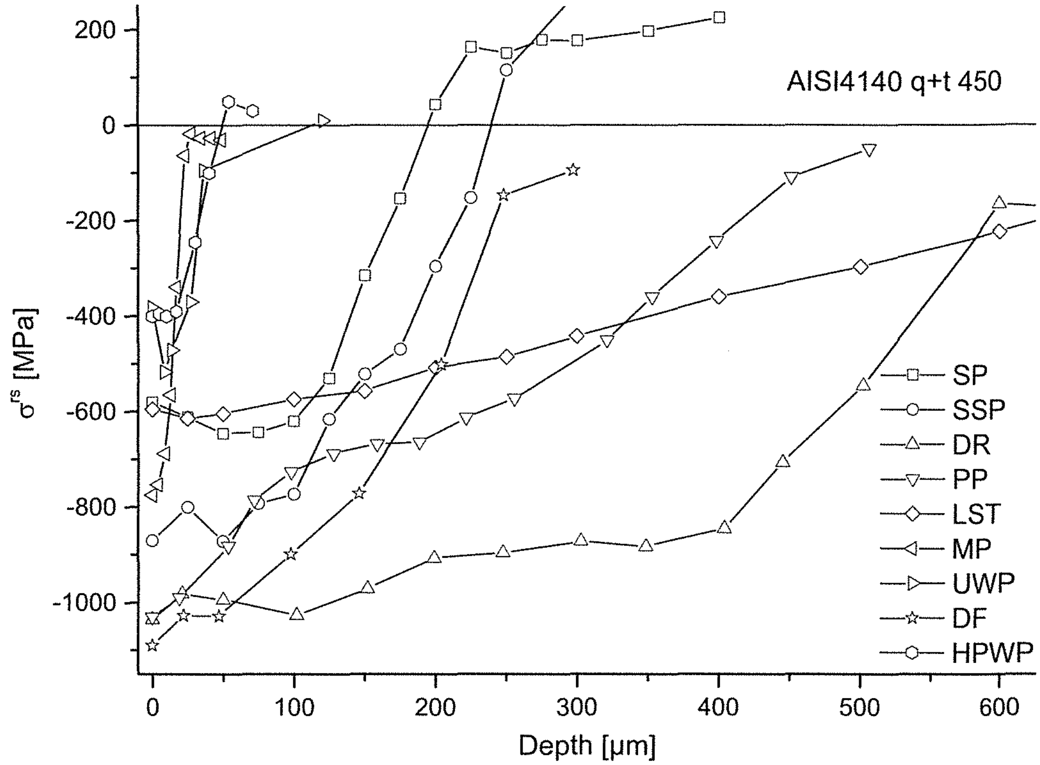

Figure 7: Residual stress states on AISI4140 q+t 450 after selected surface treatments (for process parameters and references see text above)

Fig. 8 shows the FWHM values for the same processes (some are kept off for clarity). Many mechanical surface treatments do not significantly increase the FWHM in surface-near areas (typically deep rolling), i.e. changes in the work-hardening state of the surface layer are negligible. Other treatments do increase the FWHM values considerably (typically shot peening and micro peening). High FWHM values are measured due to high strain rates and the associated cross slip impediment of screw dislocations, the latter being main carriers of plasticity in bcc metals and alloys [89], [90].

In Fig. 9, characteristic changes in roughness after selected mechanical surface treatments are shown compared to the roughness of the initial surface state. Changes in topography are strongly dependent on the intrinsic characteristics and properties of each process and more or less pronounced. While some mechanical surface treatments are used to introduce compressive residual stresses accepting an increased surface roughness (typically shot peening), surface smoothening can be one main goal in others (typically deep rolling, diamond finishing). Some treatments do not or negligibly change the workpiece roughness (typically high pressure water peening).

It must be noted, though, that some surface treatments allow for the generation of a wide range of possible surface layer states (typically piezo peening). Therefore, findings are often limited to a small range of process parameters.

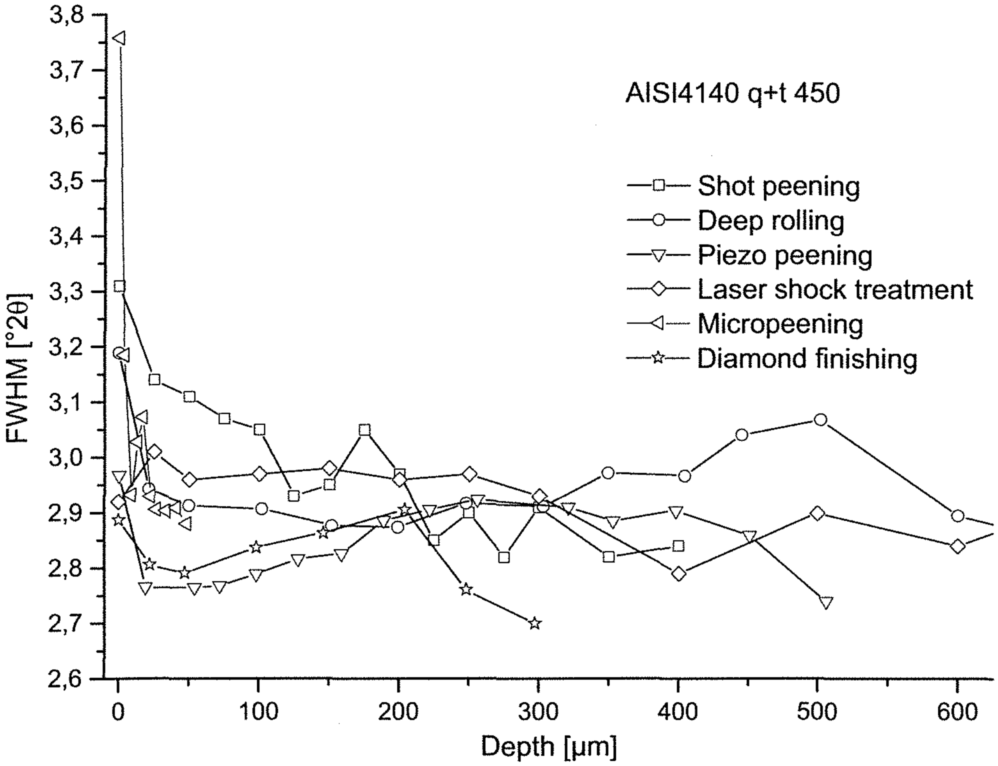

Figure 8: FWHM values on AISI4140 q+t 450 after selected surface treatments (for process parameters and references see text above)

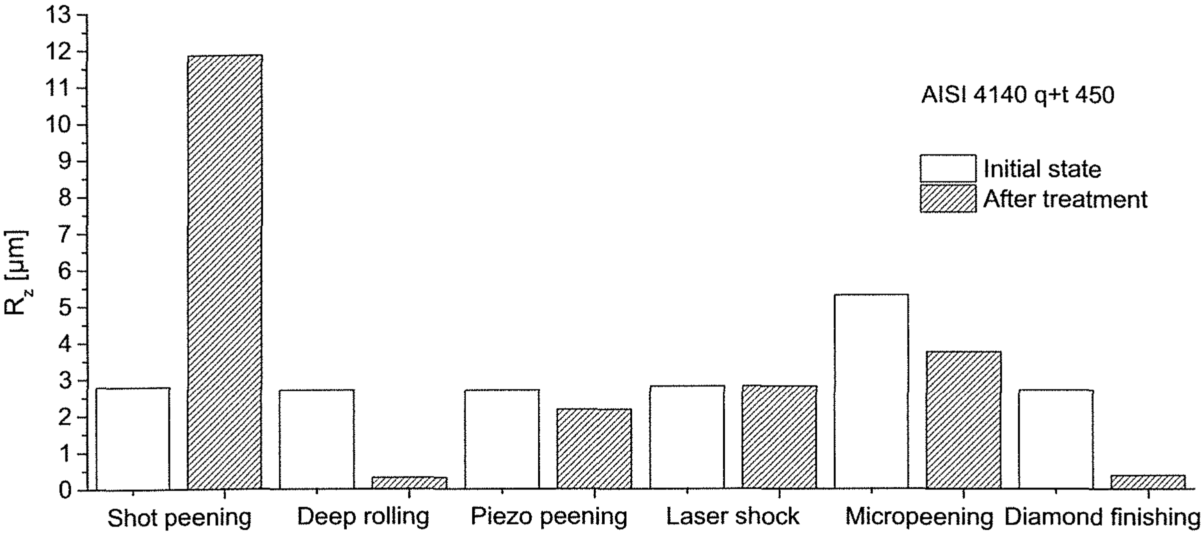

Figure 9: Surface roughness (R_z) after selected surface treatments (for process parameters and references see text above)

Summary

The available variety of mechanical surface treatments allows for the establishment of determinable and reproducible surface layer states. As a workpiece characteristic induced by the treatment process, the surface layer directly affects the workpiece operational properties. Even though the variation of process parameters leads to different surface layer states and allows for a certain degree of freedom, each mechanical surface treatment has its specific individual limit with regard to the maximum achievable residual stresses, residual stress depth, work hardening state and topography. The results of mechanical surface treatments always depend on the characteristics of the process (impulsive, static ...), applied process parameters (pressure, feed rate ...), the workpiece characteristics (hardness, geometry ...) and the environment (temperature ...). When these interactions are known in detail, reproducible surface layers can be generated and used to our advantage.

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