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-

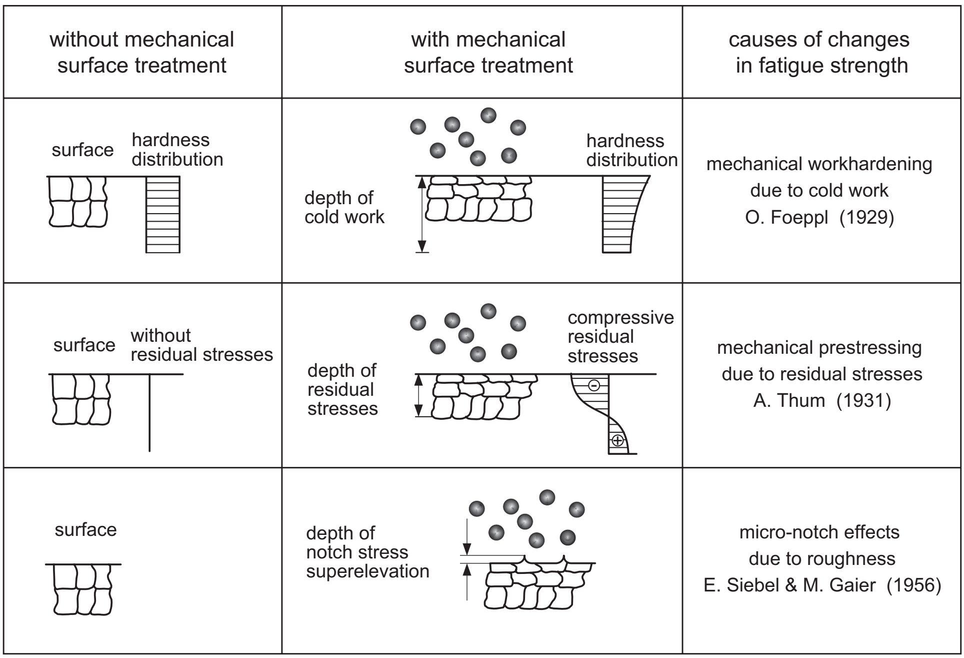

Fig. 1.1: Approaches for the explanation of changes in fatigue behaviour due to mechanical surface treatments

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

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