# Influence of Mechanical Surface Strengthening on Nickel-base Superalloy DA718

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**Abstract**
To ensure safe turbine engine service life despite decreasing wall thicknesses of rotating parts, the component surfaces are subjected to specific mechanical strengthening processes. Widely-used materials for these rotating components are those of the group of nickel-base superalloys. One representative example is DA718 (Direct Aged) which is chemically identical with IN718 but differs in the production process. For DA718, the solution heat treatment in the production of the forging is omitted. Only a two-stage ageing process is used following quenching from the forging temperature. DA718 possesses a tensile strength superior to that of IN718 and a comparable high creep resistance.
Mechanical surface strengthening is achieved by shot peening or deep rolling. To investigate the influence of both strengthening methods on the fatigue behavior of the material, parameter studies were conducted. Shot peening was performed using peening media of various shot sizes and different Almen intensities. For deep rolling, the ball diameter, pressure, rolling speed and overlap of adjacent rolling traces were varied.
Residual stress-depth profiles were measured by means of X-ray diffraction on flat specimens that were also used for surface topography characterization. Specimens were subjected to load-controlled axial tests and rotating bending tests at room temperature to determine fatigue lifes and endurance limits as well.

**Keywords** DA718, shot peening, deep rolling, fatigue life, residual stress, rotating bending loading, axial loading

**Introduction**
For high temperature applications in jet engines, e.g. in the high pressure compressor or turbine, requirements call for materials with high creep resistance and high yield stress and tensile strength at elevated temperatures. Representative alloys belong to the group of nickel-base superalloys. A typical application temperature range for Ni-base alloys is between 540 °C and 760 °C [1]. A disadvantage of Ni-base alloys is their relatively high density which varies between 7.75 g/cm³ and 9 g/cm³ depending on alloy composition [2]. In order to compensate for the high density, design driven measures have to be taken to reduce the mass of components particularly in aircraft applications due to the ever increasing requirements for reduction in fuel consumption. One possibility is the reduction in wall thickness which in turn leads to an increase in the amount of acting stresses that would result in a decrease in lifetime of the component unless countermeasures are provided. Such countermeasures are of utmost importance in the aircraft industry where reliability and safe component life are of main concern.
It is widely known that mechanical strengthening methods such as shot peening and deep rolling can be used to induce high dislocation densities and residual compressive stresses in the surface and near-surface regions. While high dislocation densities are known to increase the resistance to fatigue crack nucleation, the superposition of external tensile stresses with residual compressive stresses reduces the effective stress intensities thus retarding microcrack growth rates [3, 4]. In the present study on DA718, the effects of shot peening and deep rolling were performed utilizing a wide variation in the relevant process parameters.

The verification of possible fatigue life benefits was achieved by rotating bending as well as axial testing on smooth specimens at ambient temperature.

**Experimental Methods**

The fatigue specimens were machined from a forged disk with the load axis in tangential direction. Rotating bending specimens as well as axial fatigue specimens were prepared. In addition, flat rectangular shaped blanks were taken for evaluating surface roughness, near-surface microstructures and residual stress states.

Shot peening was carried out on a CNC controlled direct pressure type peening machine. Spherically conditioned cut wire was used as peening media. For deep rolling, hydrostatic rolling tools were used in combination with a high pressure pump unit containing hydraulic oil. Flat specimens were rolled on a CNC controlled mill whereas for the fatigue specimens a lathe was used. In order to make sure that only one process parameter at a time was varied, the degree of rolling track overlap (*RO*) was introduced [5]. *RO* can be determined according to equation (1) with respect to **Figure 1** where *w* represents the width of a single rolling track and *f* equals the feed rate at which the tool is moved across the surface. By using *RO* instead of feed rate, the actual width of the rolling track is taken into account and therefore, it is possible to compare surfaces manufactured with different tools or using various hydrostatic pressures. To determine *RO* the width of a single rolling track needs to be measured before processing the whole surface. This is done using an optical microscope and digital picture analysis software. Turning speed and feed rate on the lathe were adjusted to match the process parameters used for the flat specimens.

$$RO = \frac{w - f}{w} * 100\%, \quad 0 < f \leq w \tag{1}$$

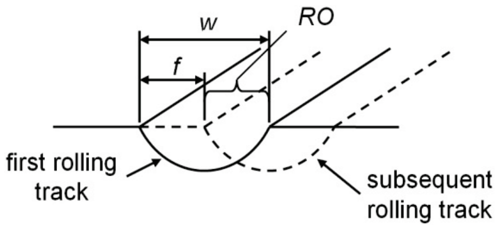


**Figure 1:** Illustration of feed rate, and degree of rolling track overlap

Before applying shot peening or deep rolling, test surfaces on the round and flat specimens were turned and milled, respectively and subsequently low stress ground. From an industrial point of view this as-machined surface condition can act as a suitable reference to which the various mechanically surface strengthened conditions will be compared. Residual stress measurements were performed on an X-ray diffractometer using the $\sin^2\Psi$ method. Measurements were carried out at 0° and 90° relative to the working direction which is defined by the grinding pattern

Rotating bending tests ($R$ = -1) were carried out using hourglass shaped specimens. For axial testing at $R$ = 0, specimens with a cylindrical test section were used.

**Experimental Results**

***Residual Stress Measurements***

All residual stress measurements (RSM) are shown in reference to the as-machined condition. E.g. in **Figure 2** it can be seen that the reference state exhibits only low residual compressive stresses which are limited to a depth of about 15 µm. The absolute stresses are somewhat higher in the 90° direction. The differences gradually level off with increasing distance to the surface. No such directionality of the stresses was observed after shot peening. Higher Almen intensities result in near-surface residual stress values slightly lower than those measured after low-intensity peening (**Figure 2**). The maximum value of the compressive stresses is essentially independent of the intensity. However, increasing Almen intensities lead to a shift of the location of the maximum value into greater depths. **Figure 4** confirms that for a given Almen intensity, residual stresses are independent of the shot size used.

**Shot Peening** | **Deep Rolling**

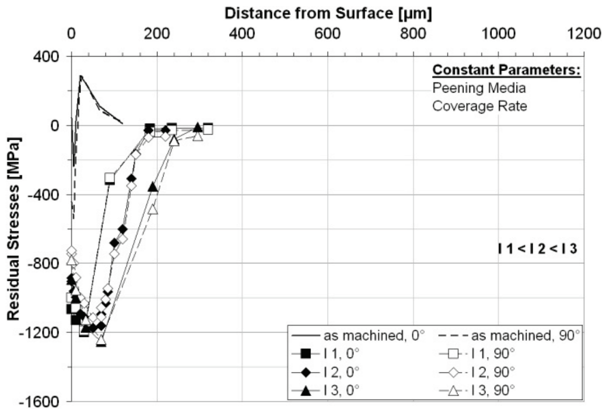


**Figure 2:** RSM for various Almen intensities (*I*) in shot peening

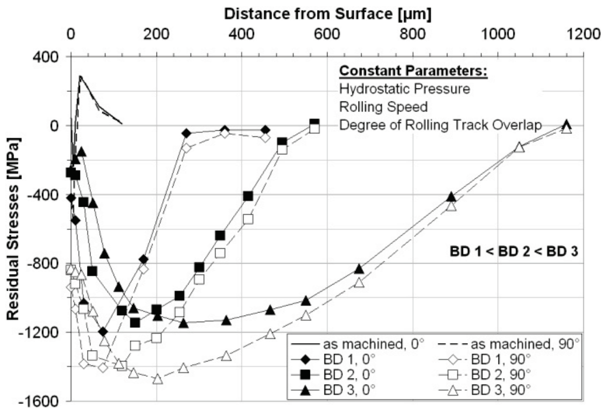


**Figure 3:** RSM for various ball diameters (*BD*) in deep rolling

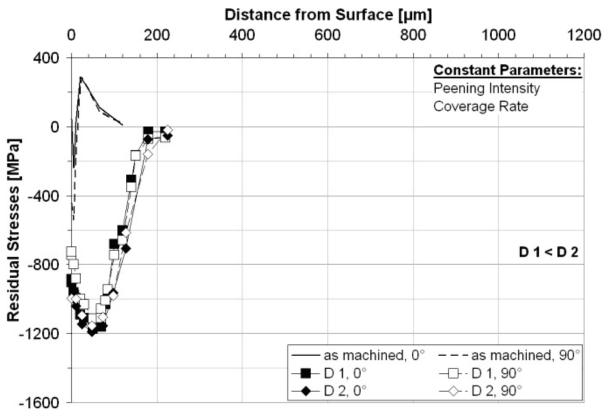


**Figure 4:** RSM for various shot sizes (*D*) in shot peening

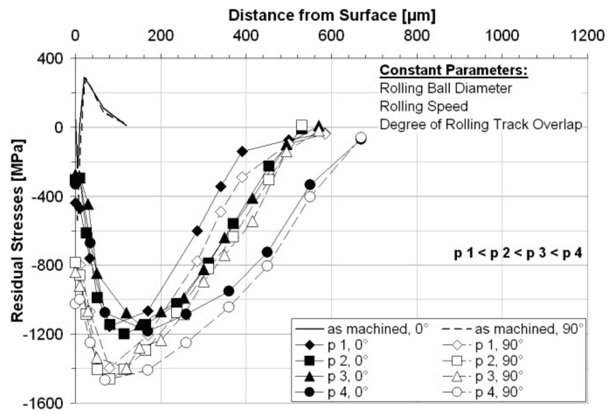


**Figure 5:** RSM for various hydrostatic pressures (*p*) in deep rolling

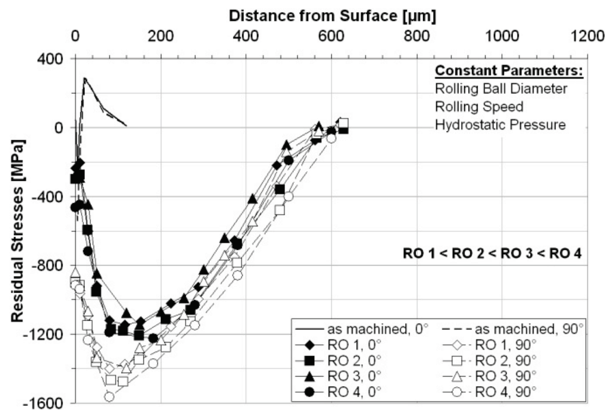


**Figure 6:** RSM for different degrees of *RO* in deep rolling

For deep rolling, directionality in residual compressive stress-depth profiles is evident (**Figures 3, 5, 6**). The absolute values of the near-surface residual compressive stresses meas-

ured in perpendicular direction are about 200 to 400 MPa higher than those measured in parallel direction. At depths beyond the location of residual stress maxima, these differences disappear.
By increasing the ball size in deep rolling (**Figure 3**), the maximum residual compressive stresses are shifted deeper into the material. This is due to the increased rolling force resulting from the bigger cross sectional area on which the hydrostatic pressure is exerted. The depth of the maximal residual compressive stress observed for the smallest ball in deep rolling is approximately the same as that observed for the highest Almen intensity in shot peening.
The influence of hydrostatic pressure on the residual stress profiles is depicted in **Figure 5**. There is no significant shift in the depth of the maximum stress level but the overall effective depth of compressive stresses until the zero-crossing increases with rising pressure.
Residual stress profiles for various degrees of rolling track overlap as shown in **Figure 6** are essentially the same. The Hertzian contact between surface and rolling ball results in a stress distribution below the surface which affects an area that is wider than that of a single rolling track. Therefore, no further strengthening is achieved by increasing the overlap while slight changes in surface waviness may still occur.

***Roughness/Waviness***
**Figure 7** illustrates the effect of Almen intensity on the surface roughness. For the used parameters, a linear increase of surface roughness with an increase in Almen intensity can be seen. The influence of the ball diameter in deep rolling is demonstrated in **Figure 8**. The absolute values of surface roughness are almost independent of ball size.

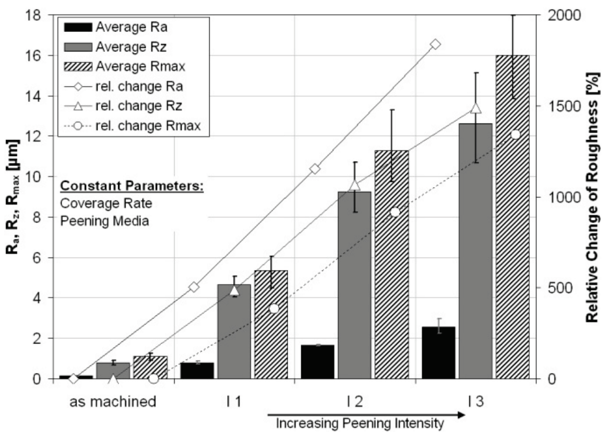


**Figure 7:** Effect of Almen intensity in shot peening on roughness

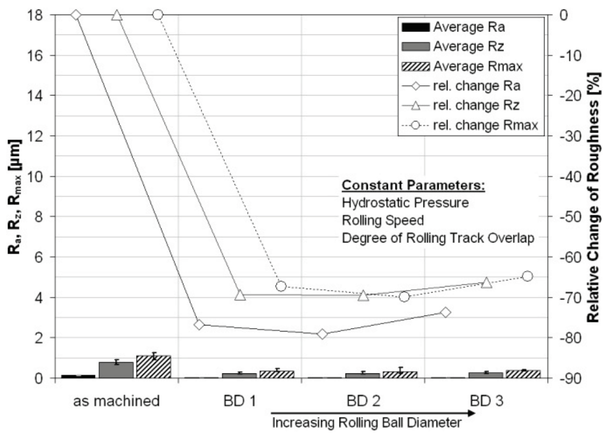


**Figure 8:** Effect of ball diameter in deep rolling on roughness

***Fatigue Results***
Based on the aforementioned results of the surface and surface layer property changes due to shot peening and deep rolling, fatigue testing was limited on evaluating the effects of Almen intensity and ball size in shot peening and deep rolling, respectively. The highest Almen intensity was omitted for fatigue testing. For each surface condition four identical specimens were tested.
The effect of shot peening and deep rolling on the fatigue life was examined at a maximum stress of 1200 MPa at $R = 0$ (**Figure 9**). The highest fatigue life improvements were observed after low intensity peening as well as after low intensity deep rolling.
Thus, the smaller the effective depth of induced plastic deformation (**Figure 2**, **Figure 3**) the higher is the resulting fatigue life improvement (**Figure 9**). It is interesting to note that differences in fatigue life between shot peened and deep rolled specimens being treated with low and medium intensities are very similar despite marked differences in surface roughness and waviness (compare **Figure 9** with **Figure 7** and **Figure 8**).

Fatigue crack nucleation is located at the surface for the as-machined condition (**Figure 10**) as well as after deep rolling using the biggest ball diameter. With this exception, all other deep rolled and shot peened specimens exhibit subsurface fatigue crack nucleation sites as illustrated in **Figure 11** and **Figure 12**. While surface crack nucleation is typically found at carbides, no carbides were seen at the subsurface crack nucleation sites.

After an exposure for 100 hours to a medium elevated temperature (I 2 & T and BD 2 & T in **Figure 9**), deep rolling is seen to preserve the beneficial effect of surface strengthening much better than shot peening does. Whereas only a slight drop in fatigue life after elevated temperature exposure is observed on deep rolled specimens, there is a marked drop in fatigue life of the shot peened specimens barely above the fatigue life of the as-machined condition.

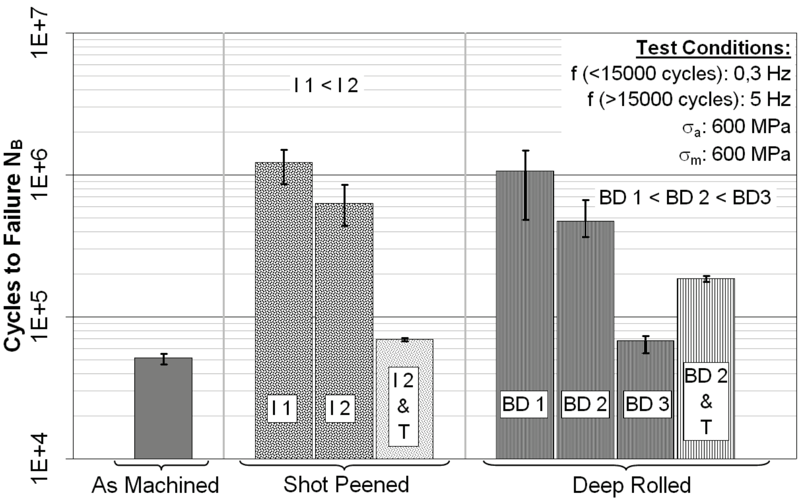


**Figure 9:** Fatigue results for axial testing

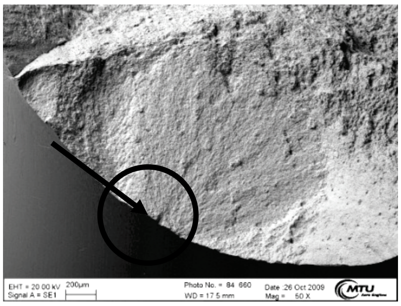

**Figure 10:** as-machined

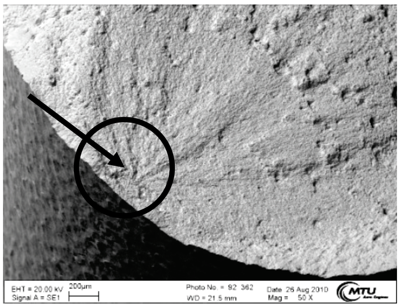

**Figure 11:** shot peened, medium Almen intensity

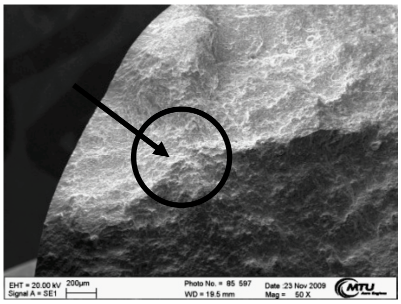

**Figure 12:** deep rolled, medium ball size

S-N curves from rotating bending testing of the various conditions are shown in **Figure 13**. Compared to axial testing, there is no significant difference between the three deep rolled conditions (compare **Figure 13** with **Figure 9**). The rotating bending results are within a fairly narrow scatter band. At the highest stress amplitude of 1150 MPa, there is no difference in the fatigue lives between shot peened and deep rolled specimens. However, there is a marked improvement in life compared to the as-machined baseline condition.

In the low stress-HCF region, more specimens need to be tested in order to derive a ranking between the low and

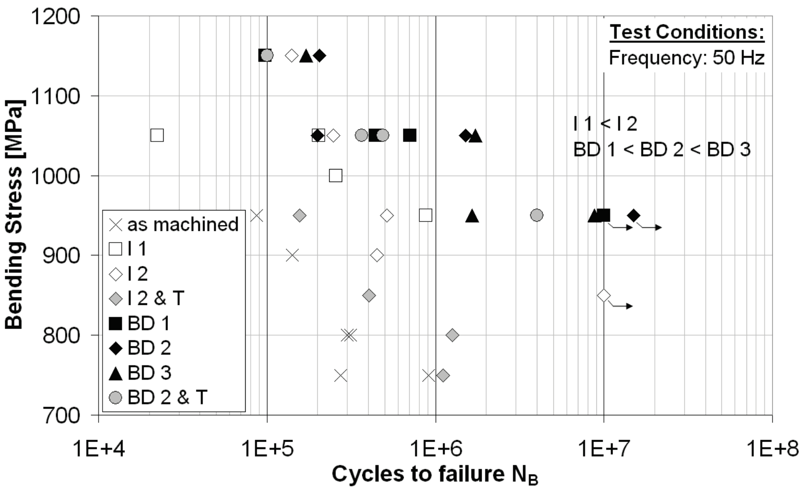


**Figure 13:** Fatigue results for rotating bending testing

medium intensity shot peened conditions. However, it is evident that deep rolling is more beneficial regarding fatigue life enhancements than shot peening (**Figure 13**). This can be explained by the penetration depth of residual compressive stresses being much greater than that after shot peening. Therefore, fatigue crack propagation is retarded up to greater depths. In addition, the smooth surface condition after deep rolling as opposed to the rough surface after shot peening is also beneficial with regard to the resistance to fatigue crack nucleation. Prior exposure at elevated temperature affects the rotating bending results similar as already seen in axial fatigue testing (**Figure 9**).
The Fatigue performance of deep rolled specimens is hardly affected by the prior exposure at elevated temperature. In contrast, the fatigue performance of shot peened specimens after prior exposure at elevated temperature ranges only barely above the as machined reference condition (**Figure 13**).
**Figures 14 to 16** illustrate typical crack nucleation sites of the various conditions tested in rotating bending loading. Subsurface fatigue crack nucleation sites after deep rolling were observed only for the maximum ball diameter. Deep rolling with small and medium sized ball diameters resulted in fatigue crack nucleation at the surface often observed as multiple cracking (**Figure 16**).

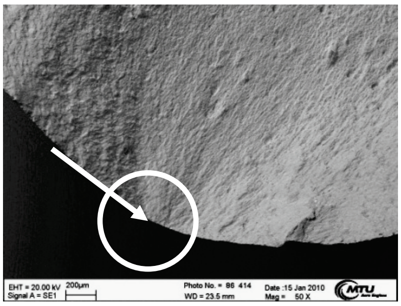

**Figure 14:** as-machined

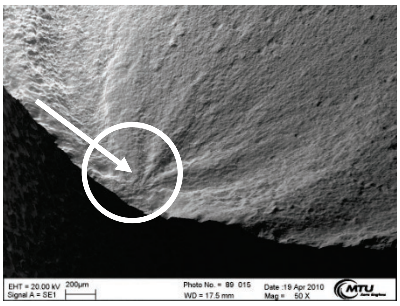

**Figure 15:** shot peened, high Almen intensity

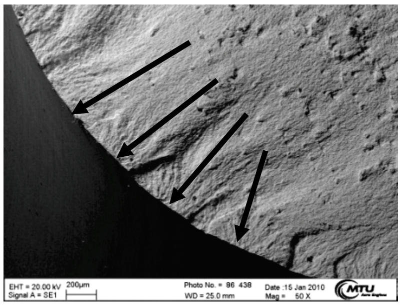

**Figure 16:** deep rolled, medium ball size

## Conclusion

Fatigue life for the Ni-base superalloy DA718 can significantly be improved by mechanical surface strengthening methods such as shot peening and deep rolling. In rotating bending loading, the fatigue performance after deep rolling is essentially independent of the process parameters even though slight differences in the location of crack nucleation sites can be seen. Additionally, fatigue life of deep rolled specimens in the low stress - HCF region is clearly superior to that of shot peened specimens.
Furthermore, elevated temperature exposure is seen to detrimentally affect the fatigue performance of shot peened conditions for rotating bending as well as for axial testing. For the deep rolled condition hardly any negative effect is observed for rotating bending, whereas for axial testing a smaller loss in fatigue life than for the shot peened condition can be noted.

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