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Life Enhancement of Aero Engine Components by Shot Peening: Opportunities and Risks

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1 Abstract

In service, aero engine parts are subject to high temperatures and extreme cyclic loads. As a consequence, the initiation and propagation of surface fatigue cracks is life-limiting for many components. The application of surface treatments, such as shot peening, can cause a shift of the crack initiation site from surface to subsurface and concomitantly, a significant increase in the cyclic life. However, in practice, the actual improvement achieved by shot peening is sometimes found to be less than expected. One reason is that residual stresses produced by shot peening are not stable against high temperatures and non-elastic deformation induced by service loads. Another reason is that defects (intrinsic defects of the material, surface defects caused by handling as well as surface damage caused by peening itself) may also reduce the benefit of shot peening. The following paper discusses the possibilities to exploit the benefits of shot peening for life enhancement of aero engine components and the requirements that must be fulfilled to take full advantage of shot peening.

2 Introduction

Shot peening is a very common method for increasing the fatigue strength and has frequently been used for aero engine applications for many years. Aero engine components are characterized by high-strength materials (titanium and nickel base materials), high cyclic loads (often locally exceeding the yield strength) and high service temperatures (in the region of time-dependent material behavior). In the past, shot peening has been used for safety-critical parts mainly as a measure to increase safety margins rather than for extending service lives. However, with increasing understanding of the mechanisms of shot peening and increasing predictive capabilities, the opportunities of increasing service lives by shot peening or other surface treatments are expected to grow in the future.

3 Life Enhancement by Shot Peening

The experience from laboratory tests, component tests as well as failure analysis clearly indicates that the large majority of fatigue cracks initiate from the surface. The crack origin is either directly at the surface or slightly subsurface within a distance of less than about 25 microns to the surface. As an example, Figure 1 shows the result of a component test performed on a titanium compressor disk (simulating 36000 start/stop cycles). After this test, cracks were found in the disk bore and in the cooling holes as well as in the lobes (blade fixtures). The fractographic evaluation showed that all these cracks had their origin directly at the surface. There are several reasons for the surface to be the preferred location of fatigue crack initiation: For most situations, there is a negative stress gradient at the surface (Figure 2). The reduction in stress below the surface (say at a distance of 0.1 mm) is not very important for unnotched features (such as the bore) but is far from negligible for notched features. Furthermore, surfaces are prone to specific defects produced by machining (e. g. wear or ductility exhaustion) or handling (e. g. scratches). Another important aspect is that the fatigue resistance of the bulk material is generally higher compared with that of the surface (Figure 3): there are two distinct stress-life curves for surface and for internal initiation. From this diagram it is obvious that life benefits are to be expected from any surface treatment capable of shifting the crack initiation site from surface to subsurface and that the maximum possible life benefit is limited by the internal initiation curve.

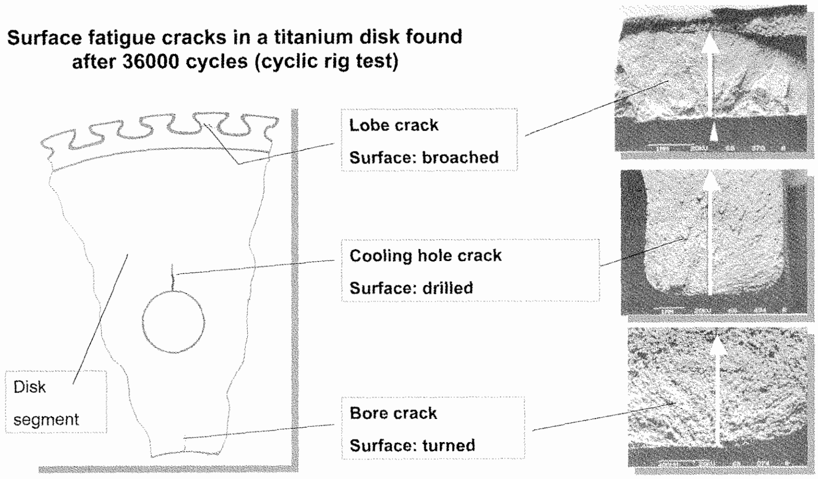


Figure 1: Example of surface crack initiation at various locations of a compressor disk

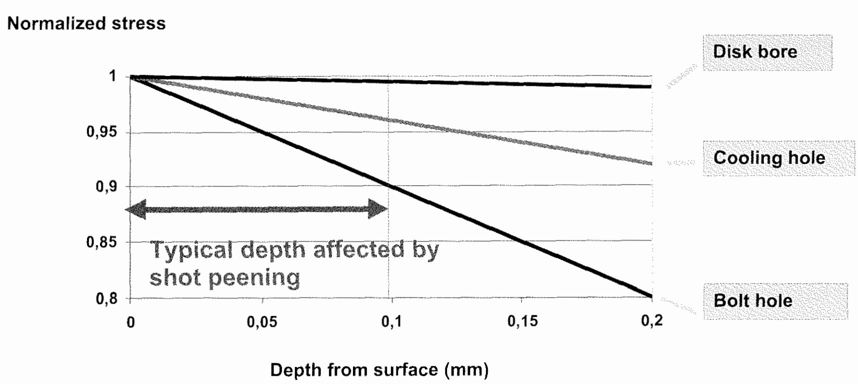


Figure 2: Stress gradient below the surface for various disk features (bore, cooling and bolt hole)

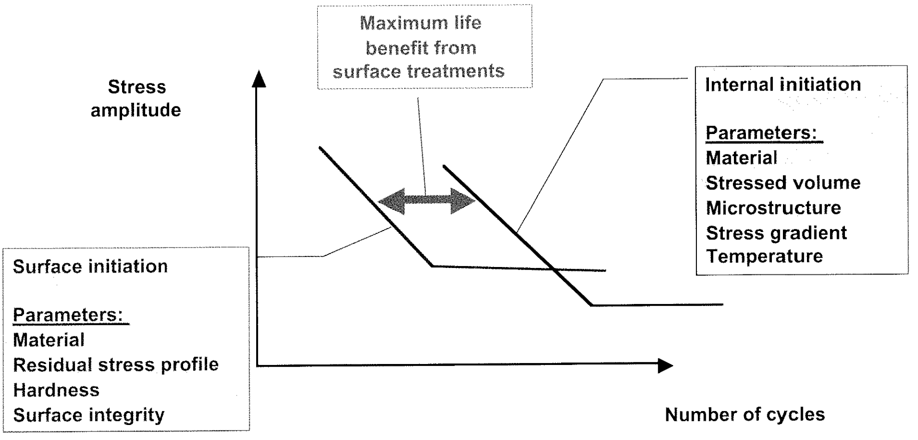


Figure 3: Surface crack initiation vs. internal crack initiation

The capability of shot peening to suppress surface crack initiation is mainly due to two effects: The impact of the shot leads to heavy work hardening in the surface layer with a concomitant increase in fatigue strength (Figure 4). Furthermore, shot peening produces compressive residual stresses in the surface layer. Typically, the amount and depth of these compressive stresses (an example is shown in Figure 14) are significantly higher than those produced by standard manufacturing methods such as turning, drilling or broaching. The enhancement of fatigue lives through compressive residual stresses relates both to crack initiation and propagation. Crack initiation life modeling considers the lowering of the mean stress and the resulting increase in fatigue lives: Figure 5. The prediction of crack propagation life (based on fracture mechanics) assumes crack-like surface defects. Indeed, fractographic observations support the

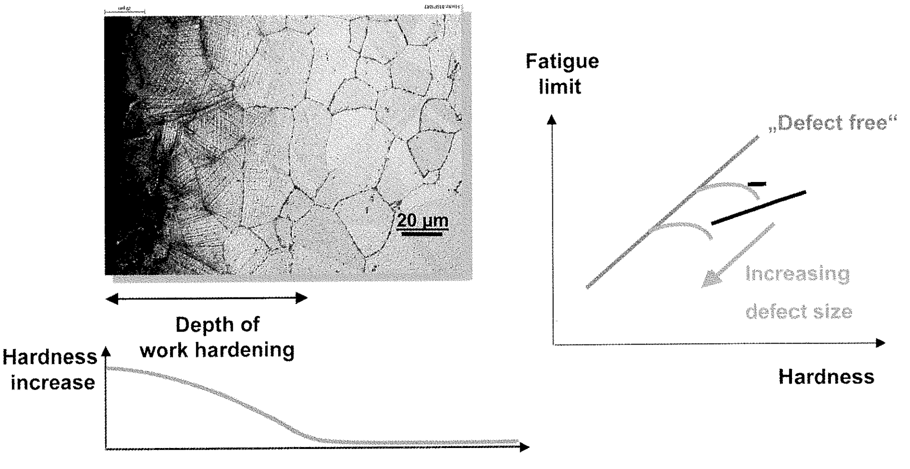


Figure 4: Fatigue strength increases with hardness; defects disturb this relationship

existence of crack-like defects (e. g. scratches or metallurgical defects) at the origin of engineering surface cracks (Figure 6). According to fracture mechanics estimations, compressive residual stresses may cause arrest (of small cracks) or retardation of crack growth (Figure 7). For large cracks even an acceleration is possible, caused by tensile stresses (which balance the compressive stresses).

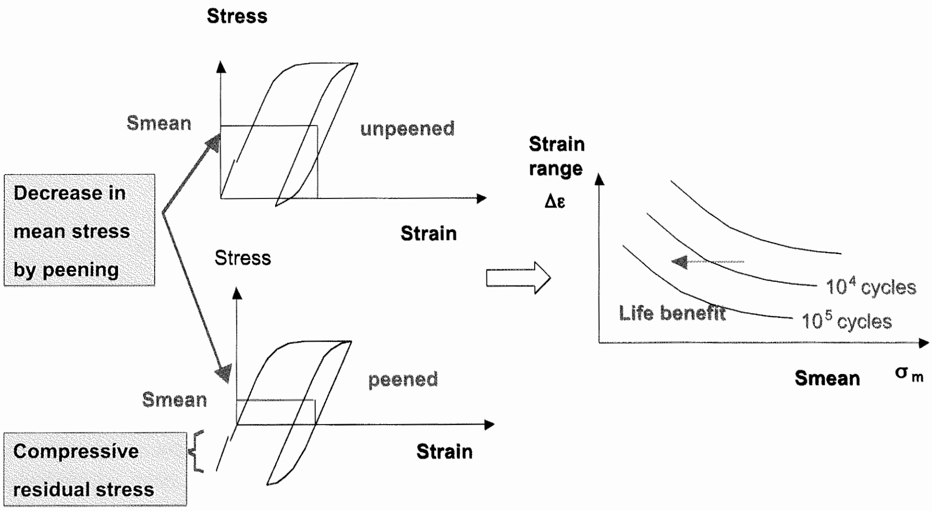


Figure 5: Model to predict the benefit of compressive residual stresses on fatigue life caused by a reduction of the mean stress Smean

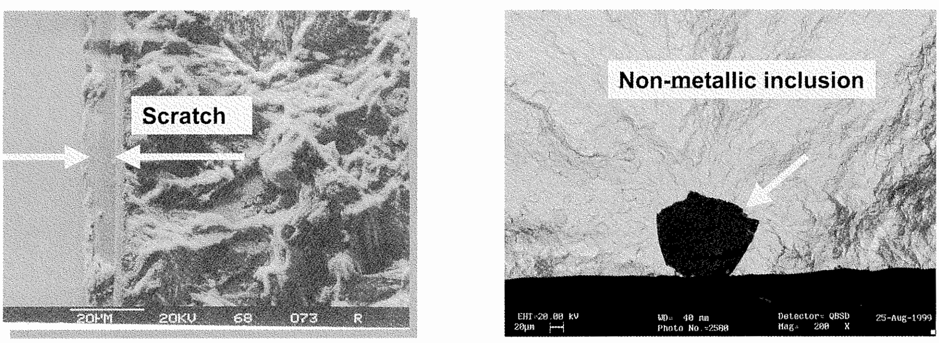


Figure 6: Examples of crack-like surface defects found at the origin of fatigue cracks Scratch produced by handling - Non-metallic inclusion (nickel base alloy)

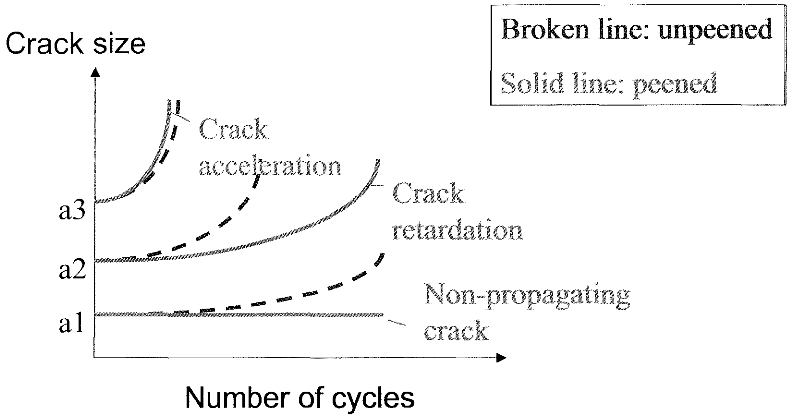


Figure 7: Effect of shot peening on the propagation behavior of surface cracks

4 Factors Reducing or Preventing Life Improvements by Shot Peening

Numerous specimen and component tests verify the capability of shot peening to improve fatigue life (Figure 8) as well as to shift the crack initiation from surface to subsurface (Figure 9). However, there is also ample evidence of shot peening resulting in life debits rather than benefits (Figure 8). Therefore, the exploitation of shot peening benefits requires detailed knowledge about the mechanisms and relevant parameters. These are addressed in the following discussion.

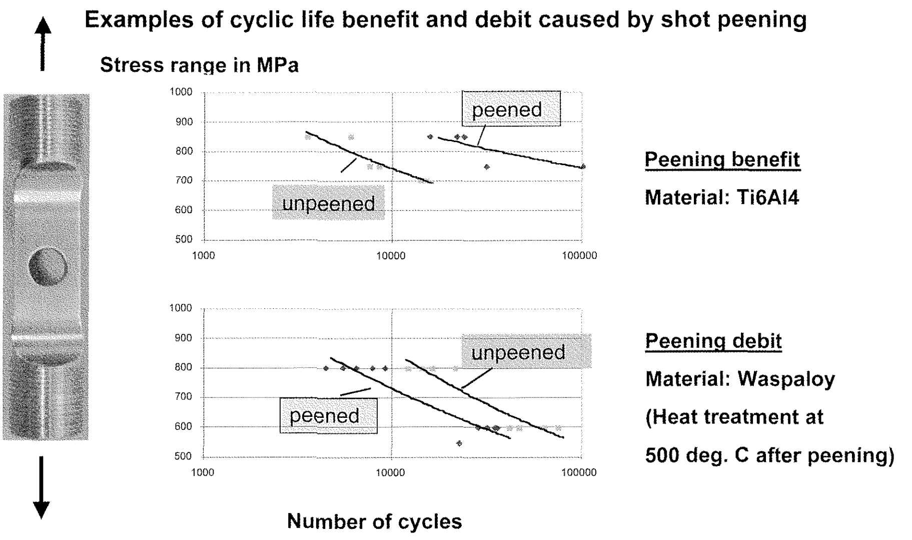


Figure 8: Examples of benefit and debit of fatigue lives produced by shot peening

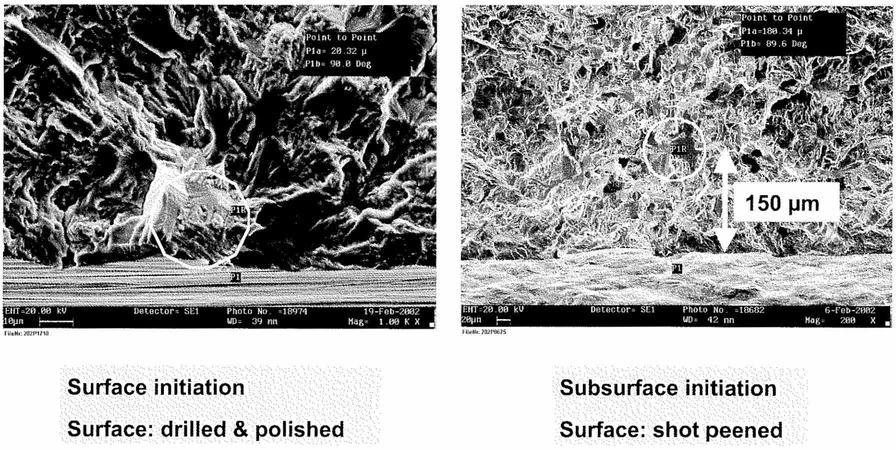


Figure 9: Examples for the shift of the crack initiation site caused by shot peening Notched specimen; titanium alloy

4.1 Local Variations of Residual Stresses

The process of shot peening of engineering components is subject to considerable statistical scatter including local variations of the number of impacts, the size and mass of individual shot particles, their angles of impingement etc. As a result, residual stresses are subject to considerable statistical variations, too. Figure 10 shows residual stress measurements (X-ray measurements at the surface) at various identical locations on a titanium disk. Evidently, increasing the coverage from 100 to 200 percent increases the mean value of the compressive stress and redu-

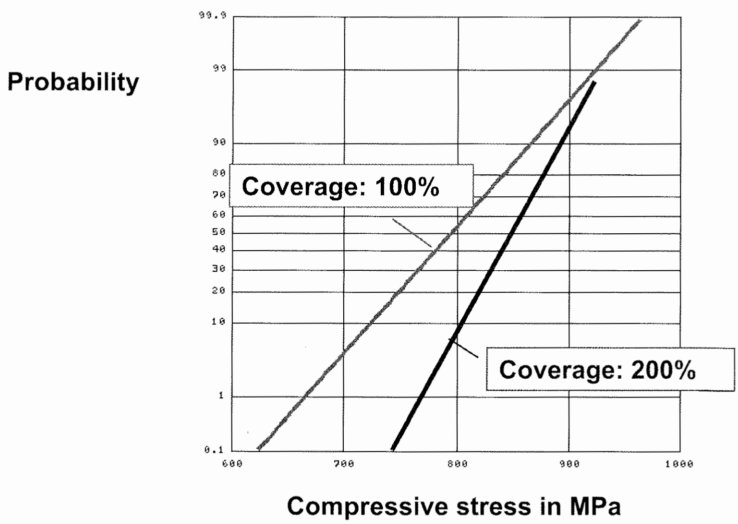


Figure 10: Influence of coverage on mean values and scatter of residual stresses

ces the scatter. In order to ascertain a specified minimum level of residual stresses, a high coverage is desirable. But this conflicts with another effect of shot peening: the damage in the surface (see below) also increases with increasing coverage. Therefore, the process has to be optimized such that sufficient values of residual stresses are ensured while keeping the peening damage low.

4.2 Residual Stress Shake-Down Caused by Thermal Exposure and Plastic Strain

After shot peening, residual stresses are typically close to the compressive yield stress of the material. However, these compressive stresses are not stable under the temperature and plastic deformation imposed under service conditions. The mere exposure to service temperatures may already reduce residual stresses by 50% or more (see Figure 11). The underlying mechanism is very similar to the well-known stress relaxation observed for creep under constant strain. In addition, further reduction of residual stresses is experienced through monotonic loading (such as that occurring in the first half of a fatigue cycle). This behavior is a consequence of the flat slope of the typical stress-strain curve for a high-strength material. Compressive residual stresses are reduced with increasing tensile strain and tend to disappear completely (Figure 11). Similarly to monotonic plastic deformation, cyclic strains may also lead to further reductions of residual stresses with increasing number of cycles. This effect is well established by specimen tests. However, for many applications, the cyclic amplitudes are low enough such that this effect is negligible compared to thermal and monotonic relaxation.

Monotonic and cyclic relaxation are the reasons why residual stresses are not effective at high cyclic loads. This is illustrated in Figure 12 comparing test results of peened and unpeened specimens of a nickel base alloy. At low amplitudes, crack initiation is observed to be subsurface both for the peened and unpeened conditions, whereby peening has no effect on fatigue life. At high amplitudes, relaxation effects remove the residual stresses initially produced by shot

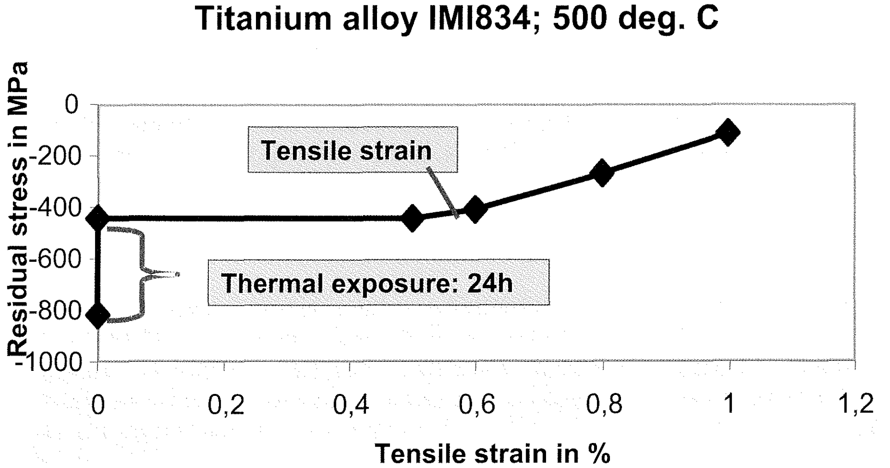


Figure 11: Modeling of residual stress shake-down caused by thermal exposure and subsequent tensile strain at 500 deg. C

peening such that the behavior of peened and unpeened specimens becomes very similar (with surface crack initiation in both cases). Only at intermediate strain amplitudes is there a significant difference between peened and unpeened specimens: The unpeened specimens show initiation at the surface while the compressive residual stresses of the peened specimens shift the initiation location to subsurface, leading to longer fatigue lives.

This example shows that there is no general life enhancement to be expected from shot peening. Benefits are limited to "windows" of loading parameters. Of course, these windows are very much dependent on parameters such as material, surface conditions, temperature, loading conditions etc. The reliable prediction of these effects is a continuous challenge for testing as well as for modeling of the material behavior.

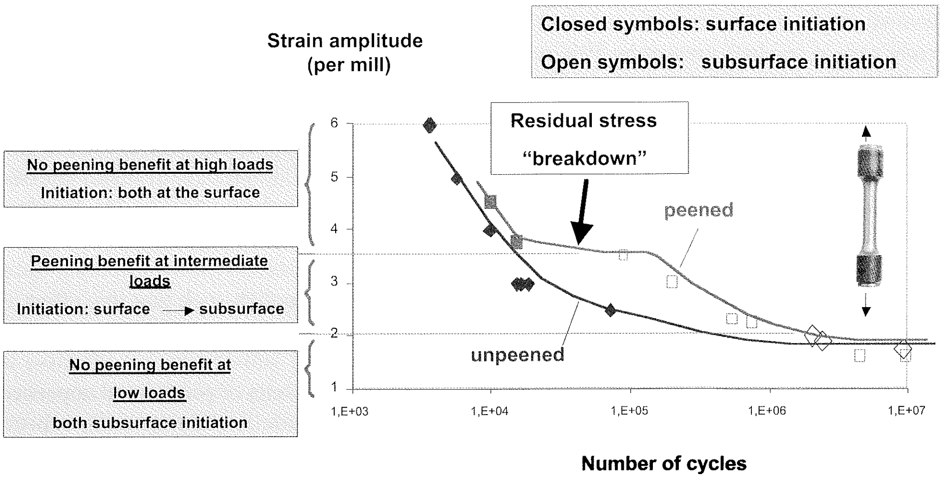


Figure 12: Effect of peening on LCF life (nickel base alloy)

4.3 Defects in the Material and in the Surface

The fatigue strength of a structure is determined by its weakest element. Therefore, the minimum life is often related to the behavior of defects. In the following, the role of defects on the shot peening effects is considered.

4.3.1 Volume Defects

As shown in Figure 3, the fatigue life of a subsurface volume element is longer than that of an equivalent element at the surface. In principle, this is also true in the presence of defects: A given defect is less detrimental in the volume than at the surface. However, there is a marked difference with regard to defect sizes between surface and subsurface because of the statistical size effect: The density of large defects is much lower than that of small defects (Figure 13). For an unnotched feature, the volume of the surface layer typically represents less than 1% of the highly stressed volume. Therefore, the worst defects that can be found in the volume tend to be larger than those in the surface layer. In the situation of very large internal defects these may become the life-limiting feature and surface treatments are no longer of any benefit (this effect can be quantified on the basis of probabilistic life models). To avoid this situation, it is necessary to control defect densities by choosing appropriate materials and manufacturing routes. In addition to the statistical size effect, technological size effects also have to be considered (e. g. local degradation of material properties due to unfavorable conditions of forging or heat treatment).

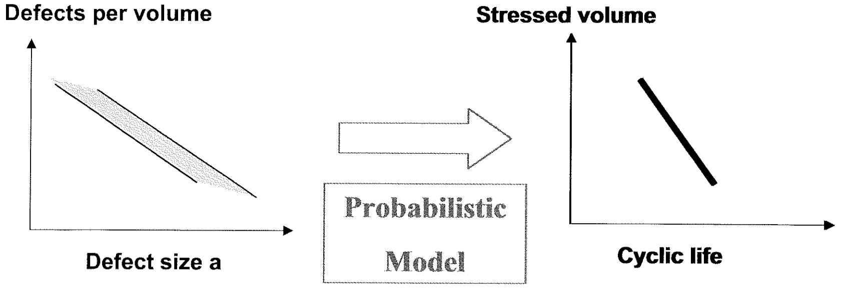


Figure 13: Volume-dependent cyclic life due to the statistical size effect

4.3.2 Surface Defects

The increased hardness of a peened surface improves the resistance against handling damage. But the main advantage of shot peening is the capability to reduce the harmfulness of surface defects. Crack initiation from defects can become suppressed and crack propagation stopped or delayed (see Figure 7). Therefore, shot peening is a very effective means of enhancing minimum lives. This is even true considering the fact that considerable surface damage is produced by the process of shot peening itself. An illustration of such behavior is the increase in surface roughness or the smearing of material (Figure 15). However, in most cases, the life benefit outweighs the debit due to additional surface damage. But there is an important limitation: The defect depth must not exceed the depth of the compressive residual stress profile. Figure 14 shows

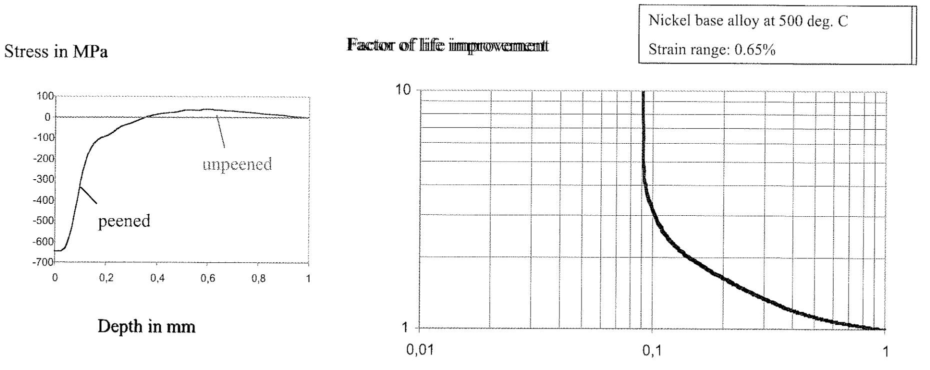
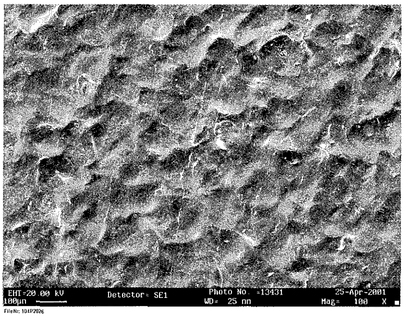
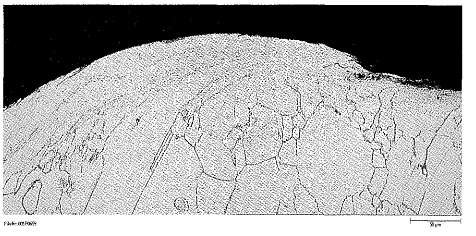


Figure 14: Decreasing life benefit with increasing defect size Residual stress depth profile (left) Fracture mechanics calculation for a semi-circular surface defect (right)

that the factor of life improvements dramatically decreases with increasing defect depth. Similarly, the fatigue strength benefit due to surface hardening is also reduced by defects (Figure 4). Again, there exists a "window" of defect sizes where shot peening is effective. Benefits can only be achieved when surface defects are kept below a size determined by the residual stress profile.



Increase in surface roughness
due to steel-wire shot peening



Smearing caused by
Non-optimized peening of a corner

Figure 15: Examples of surface damage produced by shot peening

5 Summary and Conclusions

Shot peening is an effective means to enhance fatigue life of aero engine components operated at severe loading conditions. The life benefits are restricted to "windows" of boundary conditions with key elements including loading parameters, residual stress profiles, work hardening and inelastic material behavior as well as the size, location and density of defects.

Important aspects of shot peening effects can be predicted on the basis of elasto-plastic material models and fracture mechanics as well as specially-designed specimen tests.

Further progress in life enhancement can be obtained by development of surface treatments with the following properties:

- Capability to produce deep profiles of compressive stresses and work hardening
- High stability of residual stresses and work hardening with regard to thermal exposure as well as inelastic deformation
- Minimizing surface damage caused by the surface treatments
- Good reproducibility of surface properties
- Suitability for different geometric requirements