

Interaction between Short Surface Cracks and Residual Stress Field in Shot Peened Titanium Samples

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Abstract: To enhance the fatigue life of metal components, frequently compressive stress is introduced to the surface layer. Although procedures such as shot peening have been practiced for many decades in other industries, an improved understanding of the fundamental mechanics that leads to the improved performance is desired. From a continuum mechanical point of view, the interaction between the crack and the stress intensity field is the factor determining whether the crack will propagate. Of special interest for fatigue performance is the propagation behavior of microstructurally short cracks, where the energy release rate, ΔG , is smaller than the threshold value, ΔG^{th} . For this presentation Abaqus/Standard has been used to calculate J-integral values for different ratios of crack length and compressive residual stress depth, as well as different residual stress magnitudes.

1. Introduction

Implantable medical devices are in general exposed to cyclic loading originating from physiological processes and patient activities. For example, in cardio-vascular applications dilatation of blood vessels due to the change from systolic to diastolic pressure or the motion of the heart due to its beating results in 10^8 to 10^9 cycles over the life time of a device. In addition, patient activities, such as arm motion or walking, lead to 10^4 to 10^5 cycles at higher load levels. In many cases both loading conditions are superimposed which makes accurate longevity predictions difficult. On one hand, activity levels vary from patient to patient, and the very specific implant location and orientation, and patient anatomy define the resulting stress and strain levels. On the other hand, variations in material properties and residual stresses from manufacturing determine the resistance of a component against fatigue failure. Finally the resistance of a material against corrosion and other forms of material degradation plays an important role in the prediction of the longevity of a medical device, but is not considered in this paper.

In addition to biostability/biocompatibility, manufacturability and affordability, stiffness and fatigue strength are important material properties for the selection of metal alloys used in implantable medical devices. Especially for non-bioactive implants, the use of high strength material is desirable as it also reduces the invasiveness of a procedure and improves patient comfort, as it allows for a reduction of the load carrying cross section of the implant. Besides stainless steels, both ferritic and austenitic, and cobalt-chrome alloys, titanium alloys are most commonly used. Especially for orthopedic implants, Ti-6Al4V is very often the preferred choice. Tight control of surface roughness and residual stress management are two common methods to improve fatigue life of metal components. Introduction of compressive residual stresses by shot peening has been practiced for axles of rail road cars and leaf springs for over a century. The application of such methods is not commonly practiced for medical implants yet. One reason may be that the development of a suitable shot peening process for small components with complex shapes is difficult. The other may be that the improved fatigue life can only be utilized, if the longevity predictions are accurate enough not to potentially harm patients.

Components in some medical devices are heavily loaded with residual stress due to the manufacturing process or implantation process. The coiling process of cobalt-chrome lead wires leads to significant tensile stress on the inner diameter of the coil and compressive stress on the outer diameter of the coil. Addition of an annealing step is not possible as the much desired effect of cold work on fatigue life would be eliminated. Another example is the crimping and deployment of stents where the struts are repeatedly deformed. In these cases the options for residual stress management are limited.

The most common method to introduce residual stress to the surface layer of a metal component is shot peening. Small, more or less spherical media, with sufficient density, i.e. steel or WC-Co, is accelerated and shot at the rotating component. This leaves in addition to residual stress plastic deformation of the surface layer behind. As a result, the material is locally cold worked and therefore the yield limit increased. The increased yield strength is another possible mechanism that improves fatigue life, as surface flaws such as extrusions and intrusions caused by persistent slip bands may be harder to generate.

2. Model description

2.1 Generation of the residual stress field

The residual stress field was induced by an artificial thermal expansion, which simulates the effect of shot peening, on the back face of the cracked specimen (Figure 1a). The temperature change is only imposed on a small area of the geometry so that remaining material acts as confinement. The built-in Abaqus function “predefined field” in combination with “analytical field” has been used to generate a negative temperature field for compression areas, and a positive temperature field for tension. A realistic coefficient of thermal expansion for titanium, i.e. 10^{-5} K^{-1} , was utilized, and the magnitude multiplier for the temperature field was adjusted to obtain realistic stress levels. It can be assumed that the maximum compressive stress of the shot peened material will be approximately its yield strength. Further, the compressive stress level at the surface will be fairly small. For reasons of force equilibrium, the compressive section has to be followed by a tensile section that slowly decays. The two separate functions used to describe the complex shape

of the curve are shown in Figure 1b. The functions have been chosen in a way that the transition from compressive to tensile residual stress is located a distance, $d = 0.2$ mm beneath the surface. Elastic and plastic properties for Ti-6Al4V in annealed condition were taken from the ASM Handbook and converted to the required format. Young's modulus and Poisson's ratio are 113800 MPa and 0.42, respectively, and the plastic properties are given in Table 1.

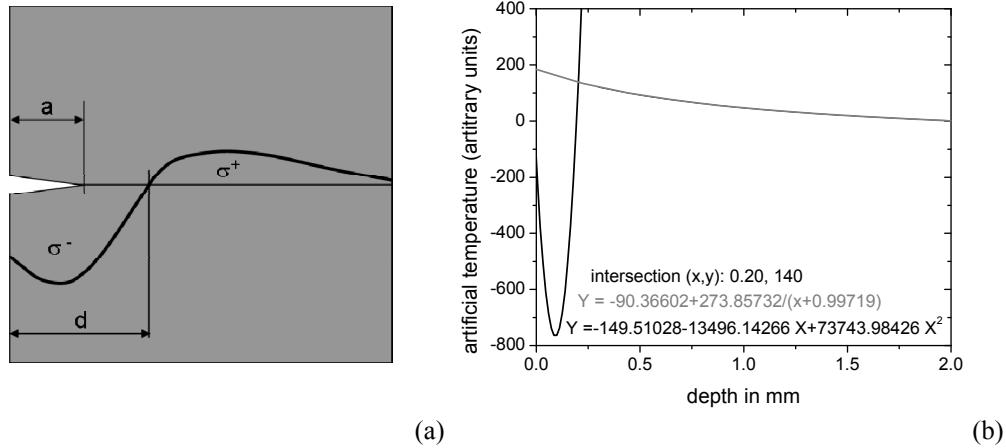


Figure 1. Schematic of the crack and the imposed stress field used in the simulations (a). Temperature vs. depth function used for the analytical function in the prescribed field. (b)

Table 1. Plastic properties of Ti-6AL4V used in the model.

true plastic strain, ϵ_{in}^{pl}	0	$7.7 \cdot 10^{-4}$	$7.3 \cdot 10^{-3}$	0.0111	0.0207	0.302	0.0526	0.0978
true stress, σ_{true} (MPa)	693	932	981	992	1020	1035	1060	1085

2.2 Model and analysis method

A 2D plain strain analysis was carried out in Abaqus/Standard on a 10 by 10 mm² big part that was partitioned several times to impose the temperature field and contained at sharp crack. Three different cracks with lengths $a = 0.1$, 0.3, and 0.5 mm were generated, accordingly meshed and seven contour integrals were requested as output. In fracture mechanics analysis, the crack length is typically not reported in absolute values, but as ratio of crack length, a , over sample length, l (a/l). Therefore the ratios for the cracks with $a = 0.1$, 0.3, and 0.5 mm are 0.01, 0.03, and 0.05, respectively. The simulations are conducted in the framework of continuums mechanics, but in the

real specimen they would be considered microstructurally small, since typical grain sizes for such a material are between 20 and 200 μm . Since no contact conditions were defined for the crack flanks, no crack closing effects are considered in the simulation. The overall geometry, with the partitions (a), the part mesh (b), and close-ups of the mesh in the proximity of the crack (c, d) are shown in Figure 2. The first ring of elements at the crack tip was meshed with reduced integration quadratic quadrilateral elements that have one collapsed side. The following rings of the crack domain and the remainder of the geometry were meshed with reduced integration quadratic quadrilateral elements (CPE8R).

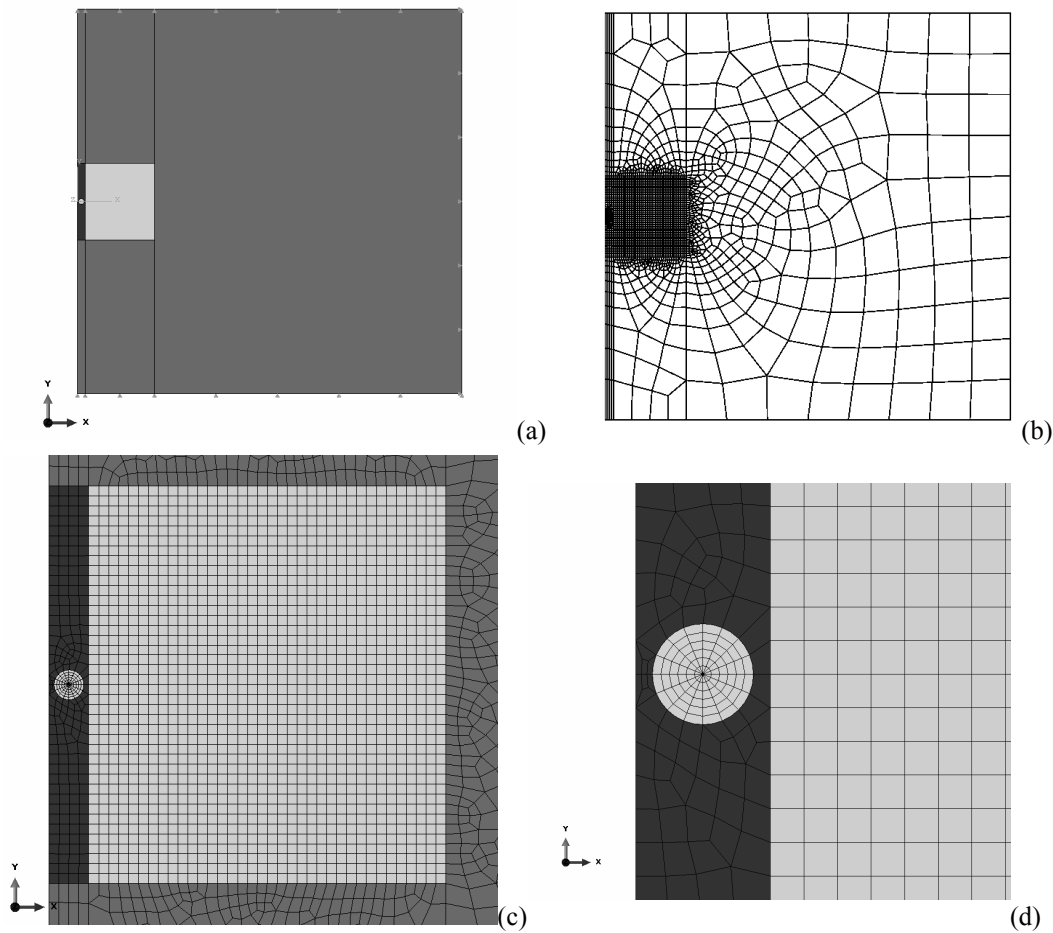


Figure 2. Overall geometry (a), mesh (b), and mesh details (c, d). In (c) the dark and the bright section represent the areas of compressive and tensile residual stress, respectively.

The simulation has been carried out in two steps. Initially, boundary conditions that restrict vertical motion are defined for the top and bottom surface, and a third one that prevents lateral motion is imposed on the right side of the part. In the first step, the temperature is imposed, and in the second step, the top boundary condition is removed followed by the application of a distributed load of 1000 MPa on the top edge causing a mode I stress field at the crack tip.

3. Modeling Results

3.1 Thermally induced stresses in the uncracked part

To verify that the imposed temperature field results in a meaningful residual stress field, a simulation without a crack was carried out. Temperature and stress contour plots are shown in Figure 3 and 4. Stresses S22 and S33 range from -500 to 1000 MPa, S11 is close to unity in the whole part, as it is unconstrained in that direction.

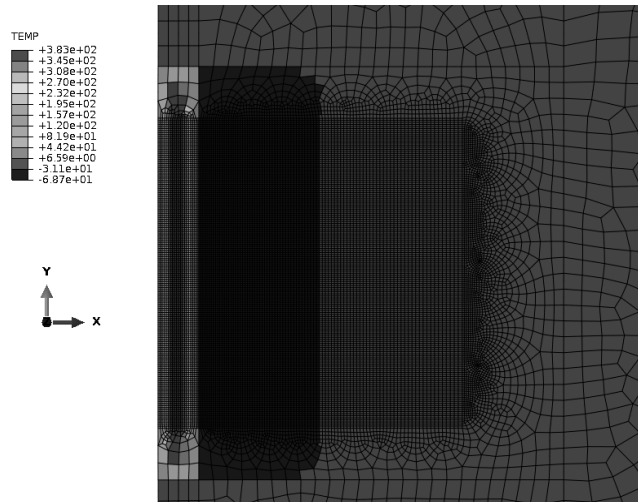


Figure 3. Temperature distribution for the residual stress generation.

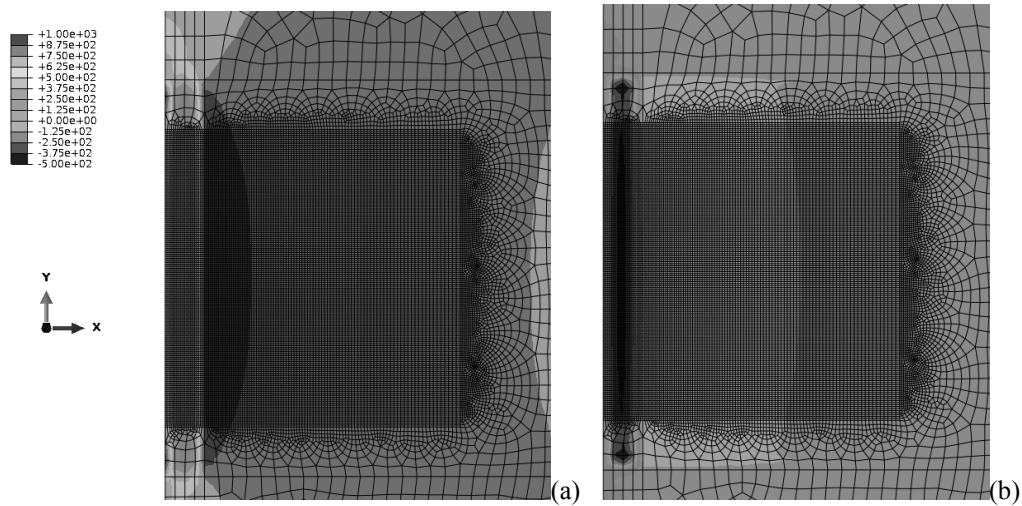


Figure 4. Resulting S22 (a) and S33 (b) caused by the temperature field.

3.2 Results of parts with cracks

In the first case, the crack length $a = 0.1$ mm ($a/l = 0.01$), and therefore the crack tip is located in the compressive stress field. Figure 5 shows vertical stresses, S22 just due to the residual stress field (a) and with superimposed mode I loading. Detailed contour plots are showing the effect of the residual stress only (a) and the superimposed loading (b) are presented in Figure 6. In (a) the crack tip is under compression, whereas in (b) the crack tip is in tension.

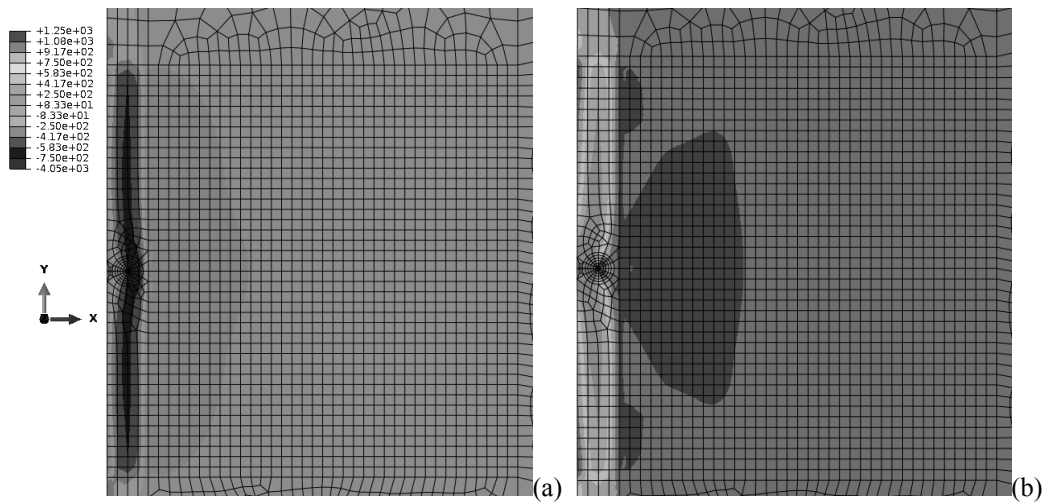


Figure 5. S22 in a part with crack ($a = 0.1$ mm, $a/l = 0.01$) due to residual stress (a) and superimposed tensile far field stress (b)

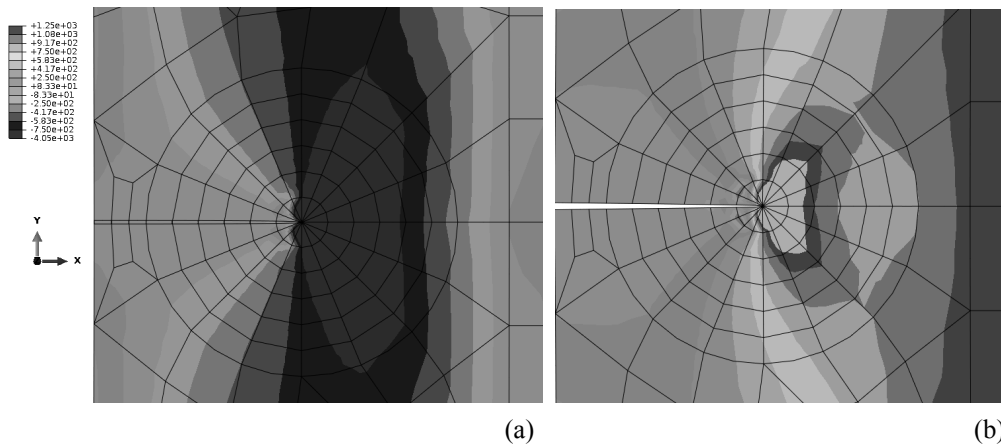


Figure 6. S22 stress: The residual stress results in compressive stress (a) and superimposed load to a tensile stress ahead of the crack tip (b).

As expected, in the case where no residual stress was imposed to the surface layer, the tensile stress ahead of the crack tip is higher (Figure 7).

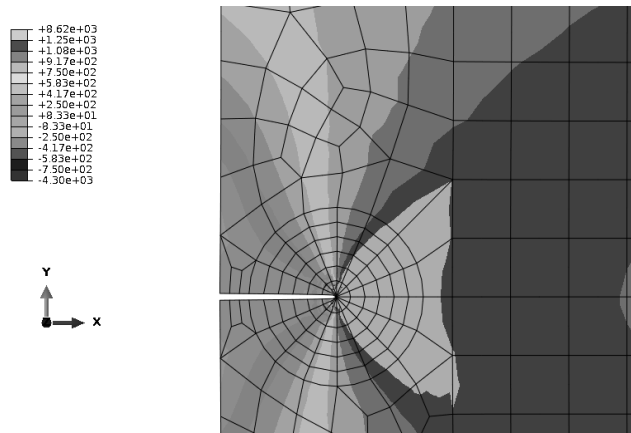


Figure 7. S22 stress field: The area exceeding the upper contour limit of 1250 MPa is significantly larger than in the case with residual stress field.

The Abaqus built in functionality to evaluate the contour integral has been applied to determine the energy release rate, G or J (Rice, 1968). The way the contours are defined, only G_{tip} (or J_{tip}) can be evaluated, but not the far field values of G . Figure 8 clearly shows the effect of the residual stress field, the energy release rate at the maximum load reduced from ≈ 4 to ≈ 1 mJ/mm². In the plot a step time < 1 represents STEP 1, where the thermal gradient is imposed, and step time > 1 indicates the STEP where the mechanical load is applied. For the case with the residual stress, G is non-zero even before the external stress is applied due to the compressive stress field. This observation is discussed in Section 4

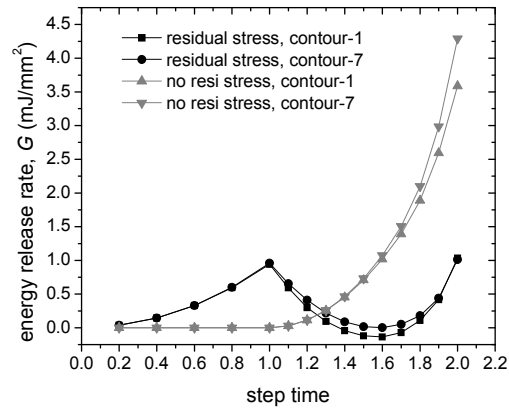


Figure 8. Energy release rate for the case with and without compressive residual stress at the crack tip ($a = 0.1$ mm, $a/l = 0.01$). The thermal loading is from step time 0 to 1.0 and the mechanical loading is beyond step time 1.0.

In the next simulation, where the crack length $a = 0.3$ mm, the crack tip is located in the area of tensile residual stress. Imposing the residual stress leads only to a very minor stress in the proximity of the crack (Figure 9a). After loading, the area of high stress around the crack tip is very similar for both the case with (Figure 9b) and without (Figure 10) the residual stress field, respectively.

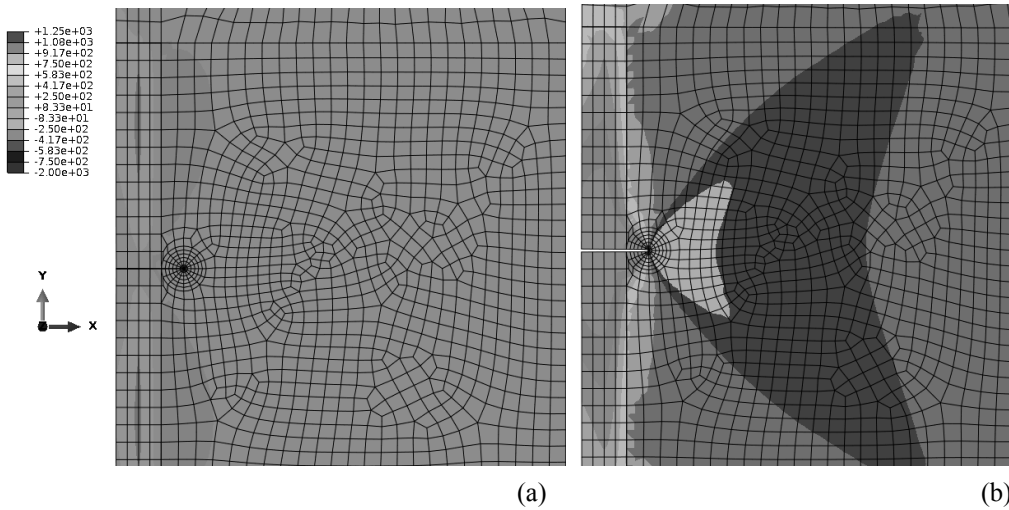


Figure 9. S22 in a part with crack ($a = 0.3$ mm, $a/l = 0.03$) due to residual stress (a) and superimposed tensile far field stress (b)

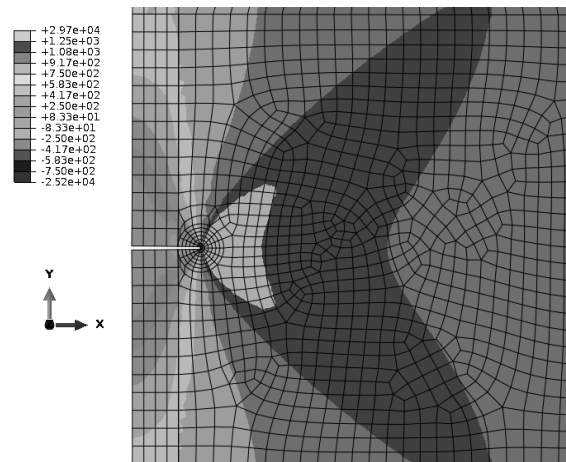


Figure 10. S22 in a part with crack ($a = 0.3$ mm, $a/l = .03$) but no residual stress shows considerably higher crack tip stresses

The comparison of the energy release rates, G , (Figure 11) shows that the overall value has increased because of the crack length, but there is no significant difference for the two cases. The influence of the size of the contour interval has become larger compared the influence of the residual stress.

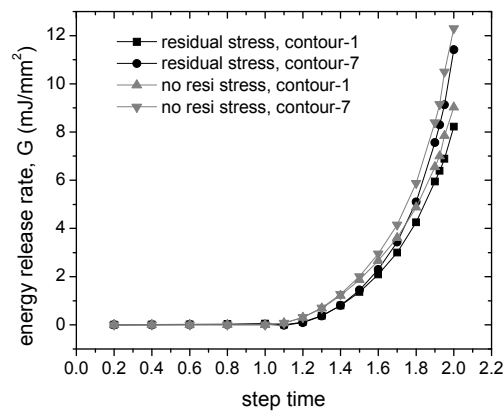


Figure 11. Energy release rate for the case with and without compressive residual stress at the crack tip ($a = 0.3$ mm, $a/l = 0.03$).

Finally the influence of the residual stress field is analyzed for a case, where the crack ($a = 0.5$ mm, $a/l = 0.05$) is significantly longer than compressive region of the residual stress field. Figure 12 shows that there is again hardly any influence of the residual stress on the stress field in the proximity of the crack, and the same is reflected by the energy release rate plot (Figure 13). The overall value of G has increased further due to the increased crack length.

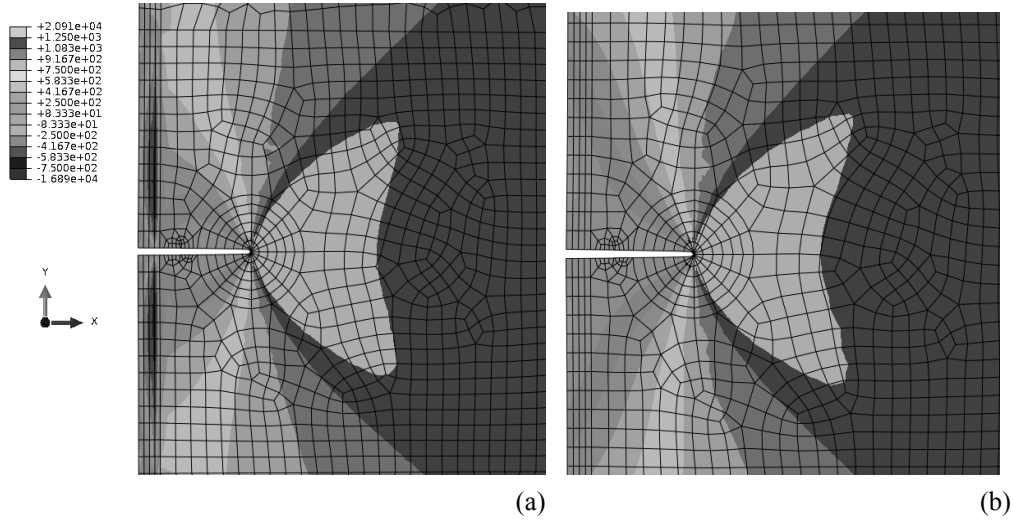


Figure 12. S22 in a part with crack ($a = 0.5$ mm, $a/l = 0.05$) due to residual stress and loading (a) and loading only (b)

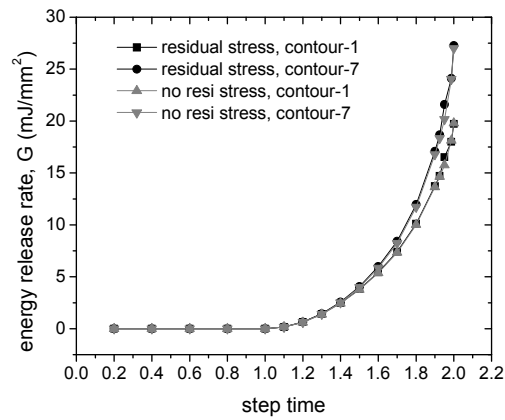


Figure 13. Energy release rate for the case with and without compressive residual stress at the crack tip ($a = 0.5$ mm, 0.05).

4. Discussion

The goal of this study was to understand the influence of residual stresses, like due to shot peening, on the crack driving force. Residual stresses were introduced on the back face of cracked specimens by using a fictitious temperature distribution. Three crack lengths were considered so that the crack tip was in the region with compressive residual stresses ($a = 0.1$ mm, $a/l = 0.01$), tensile residual stresses ($a = 0.3$ mm, $a/l = 0.03$) and no residual stresses ($a = 0.5$ mm, $a/l = 0.05$; *i.e.*, residual stresses in the wake). The J-integral was taken as the measure of the crack driving force and the difference in the value of the J-integral with and without the residual stress field was found. For crack length $a = 0.1$ mm ($a/l = 0.01$), with compressive residual stresses at the crack tip, residual stresses decreased the J_{tip} , defined as by about 75% at maximum applied nominal load; the corresponding values are 7% for $a = 0.3$ mm ($a/l = 0.03$) and negligible for $a = 0.5$ mm ($a/l = 0.05$).

The J-integral on contour 7 was typically larger than that on contour 1, for all three crack lengths. This was not an artifact due to the residual stresses, since it was found also for the cases where the cracked specimen did not have any residual stresses. The J-integral is known to increase in this manner in other cases as well, *e.g.* when the large deformation option is used (Brocks, 2003).

The J-integral values do not monotonically increase with applied loading for the smallest crack ($a = 0.1$ mm, $a/l = 0.01$) when residual stresses are present. The J-integral is positive during the development of the residual stresses; the crack tip stresses are compressive and the strains are also compressive, so this is numerically consistent that the J-integral is positive. However the physical interpretation is unclear as this may be due to the lack of any contact condition imposed on the crack faces. Although in the study by Rakin (2009), positive J_{tip} values were also found for cracks near a bimaterial interface where residual stresses had developed due to thermal mismatch but at zero mechanical loads. We are currently evaluating this possibility and will report alternate methods of introducing residual stresses in the final version of this paper.

Also, in the final version of the paper:

- we will report crack-tip opening displacements (CTOD) and relate that to the crack driving force for the growth of small cracks under fatigue loading as in (Kolednik, 2010).
- Simha *et al.* (2003, 2005) have developed a post-processor that implements the configurational forces approach (Maugin, 1995, Gurtin, 1996), which provides the nodal distributions of the configurational or material forces. The sum total of these nodal forces in the cracked body provides the influence of inhomogeneous material properties, eigenstrains, residual stresses, etc. They have applied this to cracks in incrementally elastic-plastic materials (Simha, 2008) and to examine the influence of residual stresses at bimaterial interfaces (Rankin, 2005, Simha, 2005). That approach will be applied in this context to validate the J-integral values that have been evaluated by using the standard contour integral.

Further study is planned to reconcile numerical results with experimental observations of the influence of shot peening on fatigue crack growth in thin titanium sheet specimens.

Apparently, stresses larger than the endurance limit of Ti-6Al4V are necessary for tensile stresses to appear at the crack tip for the smallest crack length ($a = 0.1$ mm, $a/l = 0.01$; 600 MPa at step time 1.6 in Figure 7). At stress levels relevant for high cycle fatigue (*i.e.* lower than the endurance

limit), it is consistent to expect negligible CTOD. However, the current results show that the CTOD is negligible even for stresses significantly higher than the endurance limit. We will explore this discrepancy as well. Lastly, in the context of transformation toughening in zirconia ceramics, Budiansky (1983) showed that compressive stresses in front of a crack tip would lead to crack tip anti-shielding (i.e. $J_{tip} > J_{far}$), whereas compressive stresses in the wake of a long crack would lead to crack tip shielding ($J_{tip} < J_{far}$). Our results show that for the mid-size crack ($a = 0.3$ mm, $a = 0.03$) residual stresses have a small shielding effect and for the largest crack ($a = 0.5$ mm, $a = 0.05$) residual stresses have a negligibly small shielding effect. For both these crack lengths there is compressive residual stress in the wake. So the shielding effect due to compressive residual stresses in the wake appears to decrease with crack length here, unlike in the zirconia ceramics case. It is unclear if the difference in the geometry of the residual stress zone (adjacent to crack in zirconia ceramics, but at the back specimen face here) is the cause of this discrepancy or whether the discrepancy is because Budiansky (1983) considers long cracks under self-similar growth, whereas the cracks considered here are on the scale of the residual stress field. Further study is necessary to clarify these aspects.

Comment:

- A new functionality is being released in Abaqus Release 6.11 (May 2011) to include residual stress terms directly in contour integral calculations. Prior to 6.11, contour integral calculations did not include these terms so, in the presence of residual stresses, contour integral results were not path independent.

5. References

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6. Acknowledgement

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