An Investigation on Fracture Surfaces of Shot Blasted and As Forged Components in Constant and Variable Loading Fatigue.

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Abstract. *The fatigue properties of two series of truck forged components in as forged and surface shot blasted condition were studied. The tests were performed in full components in a specially designed rig for such purpose. Both series of components were tested in constant and variable amplitude loading conditions. Constant amplitude fatigue loading was performed at amplitude 40, 45 and 50 kN on shot blasted and at 25, 29 and 32 kN on as forged components. A specific spectrum was employed to test both series of specimens in variable loading condition, providing identical order of load cycles in all tests. However the maximum load level was varied between different tests. The maximum load was set to be 50, 55 and 70 kN for shot blasted components and 45, 50 and 55 kN for as forged components. The shot blasted components generally showed a longer life time in both constant and variable amplitude loading. A thorough investigation on the fracture surfaces was done. The crack initiation and propagation as well as the final fracture zones in both series were studied. A systematic different between crack initiation points was detected. The fatigue part of the fracture surface was also investigated and the results were compared.*

INTRODUCTION

Almost all truck components experience cyclic loading. To improve the design and manufacturing process a deep understanding of the fatigue properties of each component is required.

In order to remove the oxide scales developed during hot forging and to provide a better surface for painting, some manufacturers shot blast the components after forging. Shot blasting is performed in a rotating tumbler where the hard small shots repeatedly hit the components. The shots not only remove the scales but also plastically deform the surface. Such plastic deformation causes compressive residual stresses and some work hardening to a certain depth from the surface.

Specially designed rigs are employed for full component testing. The component should be subjected to similar type of loading as in the vehicle. The loading spectrum is then extracted from the matrix of loads. As a result of such tests, stress-life curves (Wöhler curves) can be plotted.

There is a vast amount of literature on fatigue of materials but the majority of it is focused on specimen testing. Fatigue testing machines have been developed for various modes of loading and therefore special configuration of the test specimen. Not only the geometry but also the surface condition of theses specimens is well defined providing a very precise testing condition and limited scatter in the results.

Due to several reasons such a precise stress-life curve cannot be developed in full component testing. Both the tested component and the loading conditions are not as well defined as for small specimen testing. Stress concentrators such as scratches, surface roughness, geometrical changes and softer material phases are all highly possible in the component. The load distribution is sometimes three dimensional and more complicated. The only predefined values in the load spectra are often the maximum and mean values of the load. The load sequence is random, meaning that higher loads can show up at any time of the loading history. This can affect the time for crack initiation and of course the life time.

As mentioned before, some components are shot blasted leading to a very thin layer of a compressive residual stress at the surface. According to literature [1],[2],[3], shot peening has a positive influence on fatigue behaviour. However it depends on many factors such as peening condition, the material and microstructure, surface roughness and of course the kind of loading [4]. The positive influence of compressive residual stresses depends on their stability. The stability of the residual stresses is correlated with the stability of the dislocation configuration. During fatigue loading, back and forth movement of dislocations develops new configurations leading to relaxation of residual stresses. Higher loads can relax the residual stresses faster than lower loads and increasing number of cycles can have the same effect [5].

The aim of this study was to compare the fatigue properties of forged components in both shot blasted and as forged conditions. The components were tested under constant and variable loading conditions. The influence of shot blasting on life time, crack initiation and crack propagation was investigated. In a parallel larger programme the fatigue behaviour of shot peened test bars from the same kind of material is investigated much more in detail; these results will be reported elsewhere.

MATERIAL AND MANUFACTURING METHOD

The components were made of a micro alloyed (precipitation hardening) steel and the chemical composition is presented in Table 1. The yield and ultimate tensile strengths are 600 and 900-1050 MPa. The components were forged from 50-85 mm round bars at a temperature of 1300 °C, followed by air cooling down to room temperature.

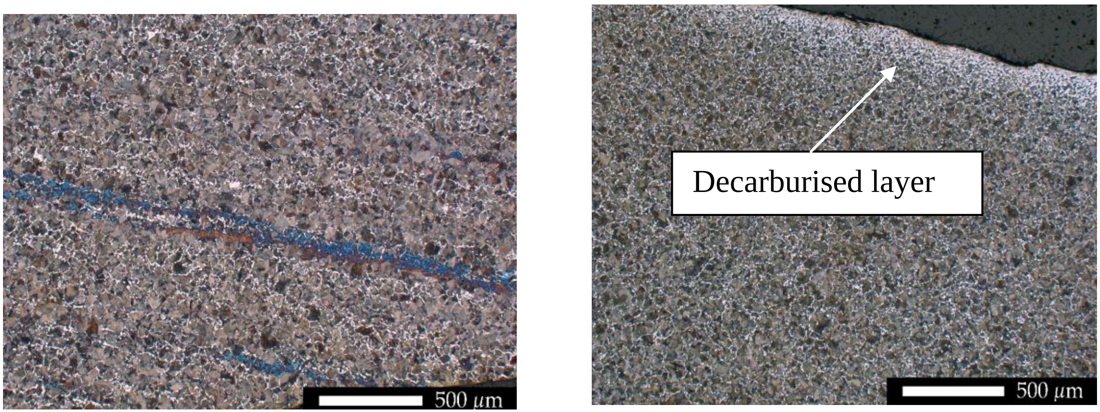
Table 1: The chemical composition of Steel (wt-%)

	C	Si	Mn	P	S	Cr	V	N	Ti	H(ppm)
wt%	0.39	0.63	1.39	0.008	0.027	0.22	0.08	0.017	0.026	1.5

The resulting microstructure is pearlitic-ferritic with some small patches of bainite. There is a slightly decarburised layer at the surface; the depth of this layer is 0.2-0.3mm (Figure 1). Macro hardness testing with 10 Kgf load was made and the global hardness measured as 266-275 HV.

The next manufacturing step was the blast tumbling. One hundred of components were shot blasted for 17 minutes which is corresponding to 0.4 mm Almen intensity and 100% coverage.

Figure 2, shows the result of residual stress measurement by X Ray Diffraction technique (XRD); the measurement took place from the surface to 250 µm depth.



a

b

Figure 1: a) Pearlitic-ferritic microstructure in longitudinal direction with slight bands of bainite present, b) Decarburised layer at the surface covered by a thin oxide layer (dark grey).

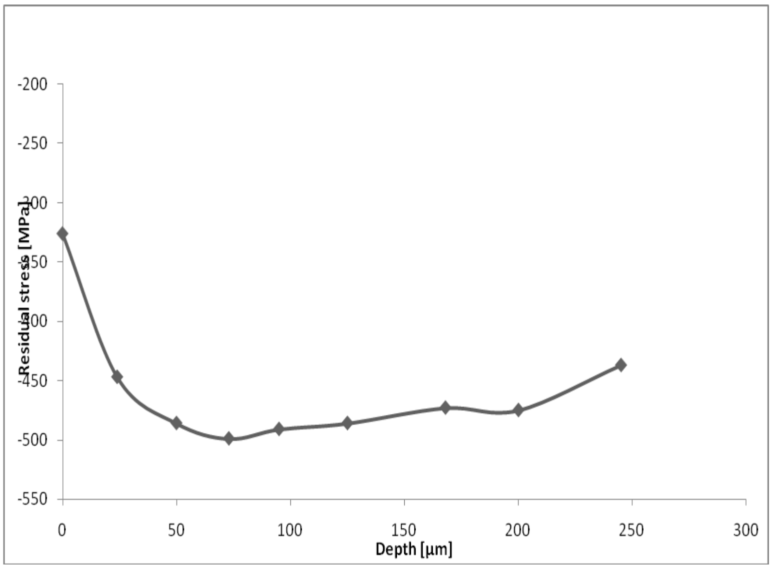


Figure 2: Residual stress distribution from surface to 250 µm depth.

RESULTS AND DISCUSSION

Fatigue Results

Forty components, all manufactured from the same batch of material, were chosen. They were divided into two groups, one of which was shot blasted. Both groups were then tested in constant and variable amplitude loading conditions according to Table 1.

Table 2: The test groups and load levels.

As forged		Shot blasted	
Constant loading (Load amplitude, kN)	Variable loading (Maximum load amplitude, kN)	Constant loading (Load amplitude, kN)	Variable loading (Maximum load amplitude, kN)
25	45	24	50
29	50	29	55
32	55	32	70
-	-	40	-
-	-	45	-
-	-	50	-

The components were tested in a specially designed rig to resemble the truck loading condition.

The constant amplitude loading wave form was sinusoidal with mean load value of zero.

The wave form in spectrum loading condition was much more complicated. In general the maximum load was chosen and other loads were randomly picked out from the matrix respectively. In this study a specific spectrum was employed to test both series of specimens, using identical sequences of loads in all tests. However the maximum load level was varied between the different tests. This method decreases the complications and provides a better possibility for comparison. Figure 3 shows a part of the test spectrum with maximum load of 50 kN which was increased or decreased in different tests leading to expansion or shrinkage of the height of the spectrum respectively.

The range pair method was used to define and count the number of cycles [6]. Figure 4 illustrates the maximum load range vs. number of cycles to failure.

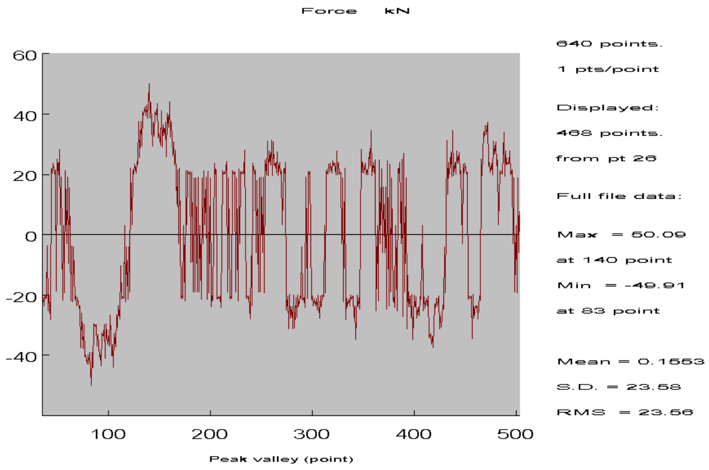


Figure 3: A part of test spectrum, maximum load = 50 kN

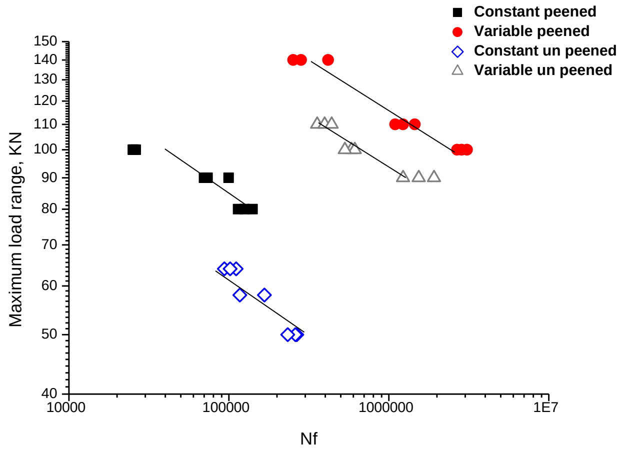


Figure 4: Load range vs. number of cycles to failure

The shot blasted components showed a markedly better performance compared to the forged components for both constant and variable loading conditions. If the equivalent load (the load level which causes the same lifetime as the variable history if applied for the same number of cycles[7]) is then calculated:

$$F_{range} = \left[\frac{Capacity}{N}\right]^{\frac{1}{k}} \qquad (1)$$

$$Capacity = \sum_{i=1}^{m} (F_{range})_i^k * n_i \qquad (2)$$

F_{range} = Equivalent load
N= Total number of cycles
n_i = Number of cycles for level i
m=Number of range pair levels
$F_{range\ i}$=The force range (peak-valley) for level i
k= the reciprocal of the slope of the F vs. N plot

Figure 5, shows the calculated equivalent load ranges plotted vs. number of cycles to failure. The data from both constant and variable amplitude loading tests were plotted in the same graph. The life time for shot blasted components is between 3 times to one order of magnitude longer than as forged components. The smaller is the equivalent load range level, the more pronounced is the effect of shot blasting.

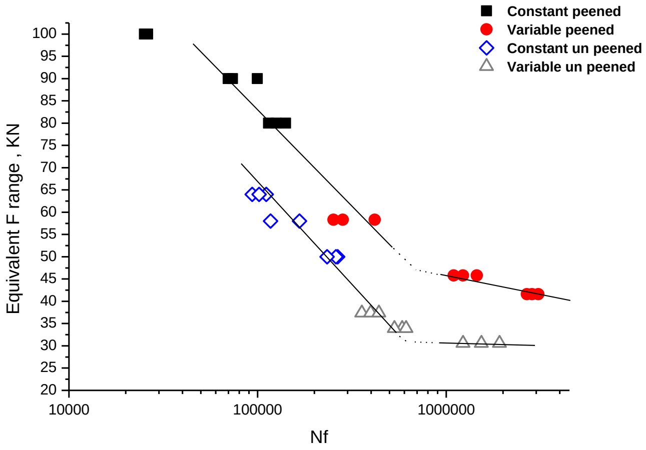


Figure 5: Equivalent load range vs. number of cycles to failure

Fracture Surfaces

The fracture surfaces were investigated after the fatigue tests. The number of crack initiation points and the depth of fatigue crack propagation were measured. In order to compare the depth of crack propagations in different cases, the projected area of the fatigue fracture surfaces was measured in each case. By equating this with a rectangle with the same width as that of the component itself, an equivalent depth a_{eq} could be estimated for each fracture. Figure 6 shows the measurement method on a sample fracture surface.

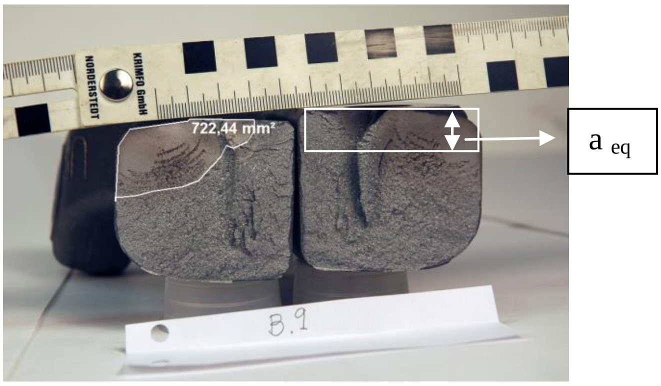


Figure 6: A sample fracture surface and measurement of mean crack propagation depth.

As it is shown in Figure 7, there are two stress concentrators in the component; one is the hole, where the bolt sits and the other one is the geometrical change.

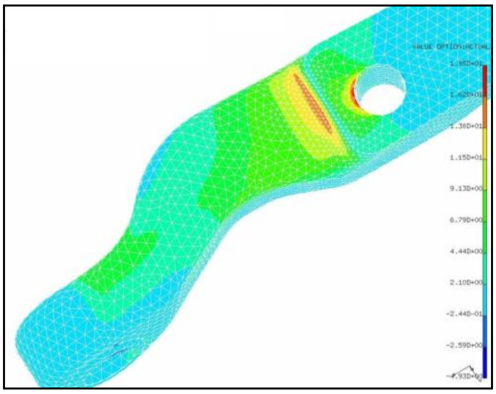


Figure 7: A finite element model of the component in static loading, the dimensional change and stress concentration are observed.

The rig set up is based on fracture at the dimensional change zone; however in constant amplitude testing of the shot blasted components at lower loads (24, 29 and 32 kN), the fracture took place at the hole. Since the hole is supported by the bolt and the steel frame, the fracture at the hole is considered to be a set up failure and will not be discussed as an approved test here.

Figure 8 and Figure 9 show some of the fracture surfaces from constant amplitude and variable amplitude loading respectively.

Crack initiation

The crack initiations took place at the very surface in all components. The number of crack initiations is increasing with increasing load level. Figure 10 demonstrates the number of crack initiation points at different load levels for both shot blasted and as forged components. Totally 36 fracture surfaces were studied. Figure 10a shows that the number of crack initiation points is smaller in shot blasted specimens compared to as forged specimens despite the increase of the load. Crack initiation mainly took place at the corners. This is due to the fact that the loading condition is a combination of bending and torsion. In Figure 11 the number of crack initiation points is shown as a function of maximum load. At identical maximum load levels, there are more crack initiation points in as forged components than the shot blasted ones. Yet Figure 10b shows that even in lower equivalent load levels as forged components develop more crack initiation points than the shot blasted ones. On the other hand there is a clear increase in number of crack initiation points by increasing the load level in shot blasted components. However as forged components do not show such a trend.

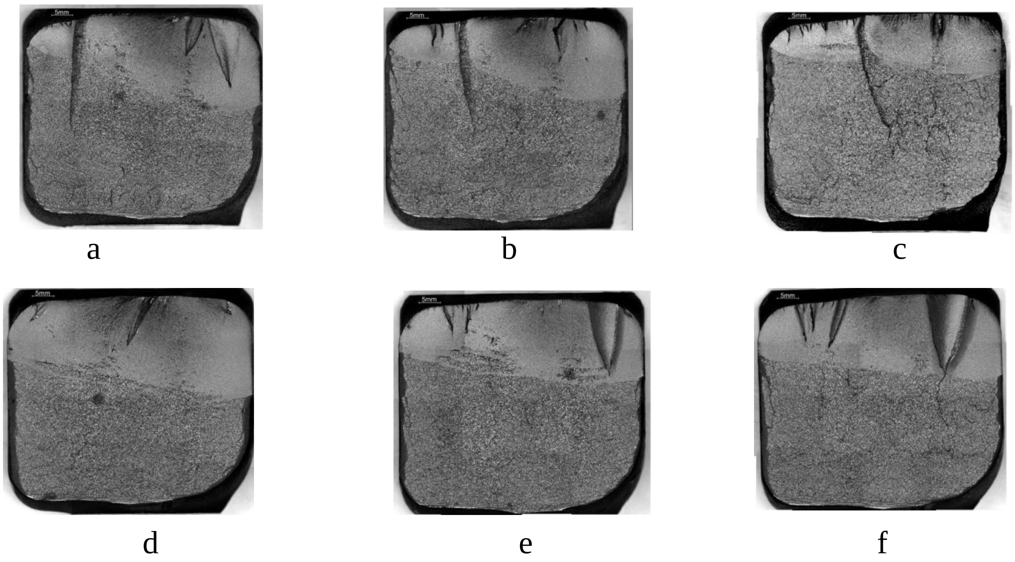


Figure 8: Constant loading fracture surfaces; shot blasted and tested at a) 40 kN, b) 45 kN, c) 50 kN and as forged, tested at d) 25 kN, e) 29 kN and f) 32 kN.

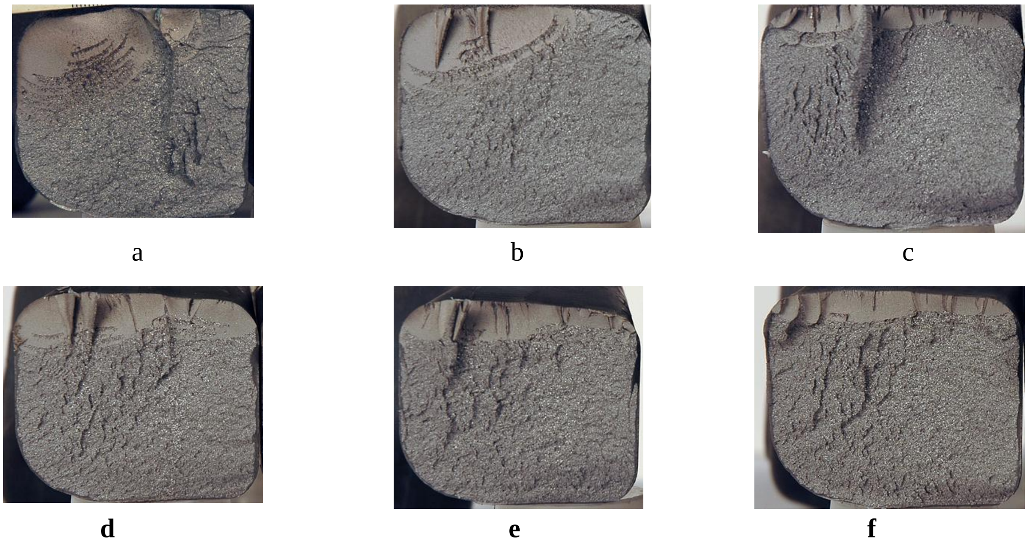
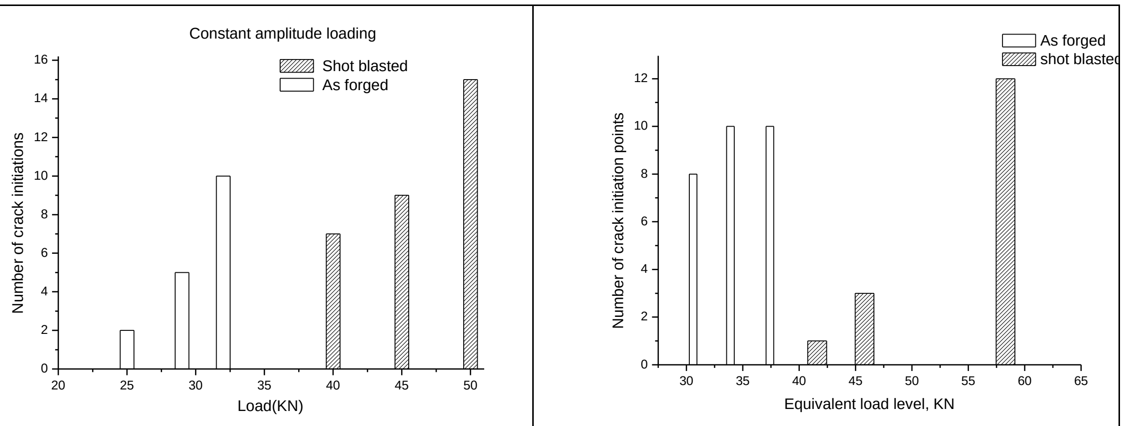


Figure 9: Variable loading fracture surfaces; Shot blasted and tested at maximum load a) 50 kN, b) 55 kN, c) 70 kN and as forged, tested at maximum load d) 45 kN, e) 50 kN and f) 55 kN.



a) Constant amplitude loading

b) Variable amplitude loading

Figure 10: Number of crack initiation points vs. maximum load.

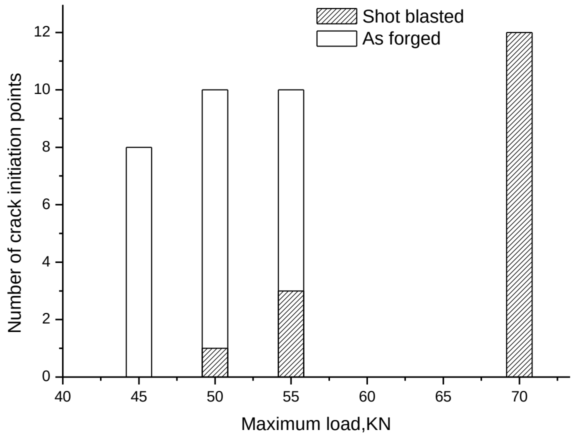


Figure 11: Number of crack initiations vs. maximum load in variable amplitude loading tests

Crack propagation

The depth of fatigue crack propagation in all cases (as it is shown in Figure 8 and 9) decreases with increasing load level. The beach marks can be seen in variable amplitude specimens tested in lower loads but they gradually disappear by increasing the maximum load. Figure 12 shows that for both shot blasted and as forged components the depth of fatigue crack propagation decreases with increased maximum load. This trend is, however, more pronounced in shot blasted specimens. Figure 12b shows the same trend but for variable amplitude loading condition.

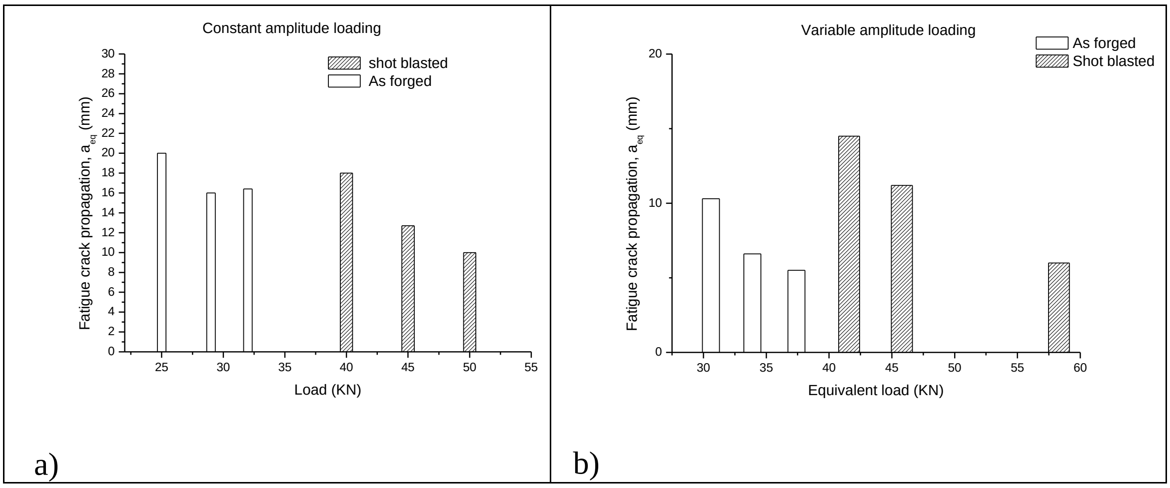


Figure 12: Equivalent fatigue crack propagation depth vs. load for a) constant and b) variable load condition

Both series of components are made of the same batch of material, with the same microstructure and mechanical properties, the compressive residual stresses created by shot blasting are limited to less than 300 µm depth from the surface and tensile residual stresses inside the components are very small and negligible. Therefore considering the long crack propagations both shot blasted and as forged components are in identical states. Both series of specimens were tested with identical spectrum meaning that the load sequence was kept but the range was varied. Therefore consistent depths of fatigue crack propagation are expected in both cases. However Figure 12a, shows a different behaviour. There is a sudden shift in depth of fatigue crack propagation in shot blasted components, despite the increase in load level. Such an increase seems quite difficult to explain.

Comparing the Wöhler curves in Figure 5, the shot blasted specimens showed a longer life time. Since the fatigue tests were designed based on final failure and not the crack initiation, it is not evident when in the life time crack initiation took place. Therefore it is difficult to judge if the longer life time of the shot blasted components is just due to delay in crack initiation or if the propagation also was determining.

There are many steps of crack retardation and possible acceleration involve during variable amplitude loading; on the other hand the equivalent loads were not identical for as forged and shot blasted components. These two factors might be correlated to the difference in depth of fatigue part of fracture surfaces.

CONCLUDING REMARKS AND THE FUTURE WORKS

It is evident that shot blasting has positive influence on fatigue life time of the components.

Number of crack initiations is higher in as forged components in both constant and variable amplitude loading tests.

It seems as the number of crack initiations in as forged components subjected to variable loading tests is not as sensitive to the load level as it is for shot blasted ones.

There is a systematic decrease in depth of fatigue part of fracture surface in shot blasted and as forged components independently. No such consistency is observed when as forged and shot blasted components are compared.

In order to study the influence of crack initiation and propagation on life time, further tests designed based on crack initiation are needed.

In order to study the reasons for such difference in fatigue part of fracture surfaces, a thorough investigation on small fatigue specimens tested in similar condition with full component test is in progress.

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