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Experimental Analysis of Near-Surface Residual Stresses and their Effects on Retardation of Short Fatigue Cracks in an Aircraft Al-Alloy after Shot Peening

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Abstract: The paper contains results of an experimental investigation of surface and near sub-surface residual stresses induced by shot peening with two groups of parameters of both sides near edges of fairly thin plated sheets of a V-95 aircraft Al-alloy. Residual stresses were evaluated using two very different methods: (i) by strain gauge measurement of gradual surface stress relaxation during grinding the opposite surface off and (ii) by X-ray diffraction method performed directly on the specimen surface and in the near sub-surface area after etching the surface layer off. Though the methods were very different, they both confirmed that longitudinal residual stresses in the subsurface location were as expected of the compressive type, but surprisingly low, no more than several tens of MPa. This result was rather unexpected because particularly one group of the peening parameters was quite severe. Nevertheless the shot peening effect on initiation and growth of physically short fatigue crack was significant. Before the shot peening, physically short fatigue cracks of the length from 0.2 mm to more than 3 mm, most of them between 0.8 – 1.5 mm, were prepared under high cycle fatigue loading of a constant nominal stress amplitude ±160 MPa. Development of crack growth after shot peening was measured and compared with crack growth in specimens without shot peening. Retardation of crack growth was significant particularly for cracks shorter than 2 mm. For the specific stress amplitude, evaluated results enabled to estimate threshold length of defects, which after the application of the shot peening will be reliably arrested. The results are discussed considering the evaluated compressive residual stresses.

Keywords: Residual stresses; Shot peening; Fatigue crack growth; Fatigue life; Aircraft 7075 Al-alloy.

1. Introduction

It is well known that surface and near sub-surface compressive residual stresses, when orientated in the direction of the main loading, can significantly increase fatigue life of metallic materials and components. One of the surface treatment operations, which usually induces surface compressive residual stresses is

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shot peening. This operation is being applied to various metallic materials either separately or in a combination with other, usually subsequent surface treatments like plating, hard anodising etc., in order to locally improve the performance of mechanical components under fatigue loads or to reduce possible negative effects of the subsequent surface operations on fatigue strength like coating, plating or hard anodising [1,2]. In order to perform an effective and reliable design, it is not namely adequate to consider only the in-service stress of the component. Unexpected cracking of components could occur due to the fact that tensile residual stresses, which can originate from various manufacture processes at different production stages, added to the in service stress decrease the component life.

The final effect of shot peening on fatigue resistance depends on numerous parameters and material which the technology is applied to. If the technology parameters are not optimised for a specific material and for its basic structural and mechanical properties, shot peening may not be beneficial, fatigue resistance can even be deteriorated [3,4]. Recent advanced approaches are based on the hypothesis that compressive residual stresses are able to slow down or stop cracks propagation instead to prevent their formation, and therefore there are based on main concepts of fracture mechanics.

The paper contains results and analyses of an extensive experimental programme aimed at an evaluation of effects of shot peening applied to clad V-95 Al-alloy (similar to a 7075 Al-alloy) sheets on growth and retardation of existing short fatigue cracks. The aim was to investigate, weather shot peening also has some potential to retard or arrest small crack-type defects already existing in the clad 7075 Al alloy prior to the shot peening operation.

2. Experimental material

The work was addressed to potential use in aircraft industry with the aim to investigate conditions of retardation of small cracks or crack-like defects using shot peening. Therefore, a V-95 Al-alloy, clad with Al-Zn1 (7072 Al-alloy) surface layers was selected as the experimental material. Typical values of basic mechanical properties of this material at heat-treated conditions are: strength up to 550 MPa and yield stress up to 480 MPa.

The V-95 alloy was available in the form of sheets of the total thickness 2.4 mm including both cladding layers (both surfaces) of the thickness 0.07 mm each in Aeronautical Research and Test Institute in Prague, where specimens also were manufactured. It could be mentioned that the sheet including the clad layers was a typical material industrially widely used for a manufacture of small aircrafts and their wings, whereas the clad layers have an important anticorrosive role. The sheet is usually manufactured by cold rolling followed by recrystallisation process.

3. Experimental programme

The experimental programme contained the following steps:

- preparation of series of a sufficient, representative number of specimens with physically short fatigue cracks of different lengths from 0.35 mm to 3.6 mm,
- shot peening of the specimens with short cracks, using two groups of parameters,
- evaluation of residual stresses using two independent methods,
- evaluation of residual fatigue life of the shot peened specimens with pre-existing short fatigue cracks,
- evaluation of residual fatigue life of specimens with pre-existing short fatigue cracks, but without peening.

Using the adapted and verified methodology of short crack measurement by DCPD method [5], fatigue cracks of different length between 0.35 mm and 3.6 mm were prepared in 17 specimens, whereas the length of most of the cracks was between 0.87 mm and 1.49 mm (9 specimens). The work programme was performed on the resonance SCHENCK PVQA machine. The loading was of sinusoidal repeated type (load asymmetry R = 0) of the constant nominal stress range 160 MPa, load frequency around 17 Hz. Artificial microscopic notches of dimensions less then 0.05 mm were made on the specimen edges to accelerate the microscopic crack initiation period.

After pre-cracking, the specimens were divided into two groups, each of them containing a similar spectrum of cracks lengths so that the groups could be compared to each other. Shot peening of two different parameters was applied at Technometra Radotín a.s. to the first and second group, respectively. Parameters of the shot peening were: Balottini sizes 0.43 – 0.7 mm and 0.21 – 0.32 mm for the first group and second group, respectively, Almen intensity A = 0.25 mm and A = 0.14 mm for the first and second group respectively. Shot peening angle was 60^{o} and coverage 200% for both the groups. Both edges in the central area of specimens were shot peened from both sides to the distance of 4 – 4.5 mm from the edge. Shot peening area can be seen in Figs. 1a,b.

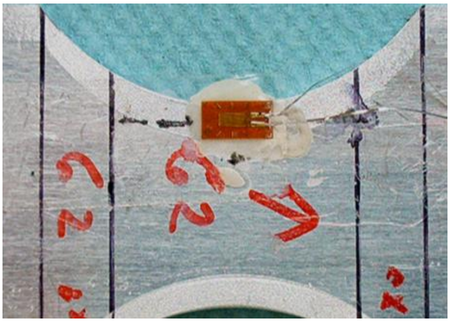

Fig. 1a. Strain gauge for residual stress measurement glued longitudinally at the centre of the shot peened area

Fig. 1b. Position of strain gauge on the specimen shot peened with the more severe parameters

Residual fatigue life of specimens containing the physically short fatigue cracks either after shot peening or without the shot peening was evaluated using the same loading conditions as those used for the precracking – ±160 MPa.

3.1. Evaluation of residual stresses

The method of the residual stress evaluation using strain gauges has to be described more in detail. Firstly, only specimens after fatigue tests were available, whereas all the specimens peened with the first, more severe parameters were cracked in the central area. The selected specimen peened with the second, less severe parameters was equipped with one strain gauge glued in the centre of the shot peened area in the longitudinal direction – Fig. 1a, i.e. in the direction perpendicular to fatigue cracking. Unlike this optimum position, strain gauge on the specimen peened with the more severe parameters had to be glued at the distance of 14-15 mm from the specimen centre and was inclined by 15^o from the longitudinal specimen axis – Fig. 1b.

After connecting the strain gauge device, the strain value was set to zero. The opposite surface of the specimen, which also contained the shot peened area, was then gradually ground off with steps of approximately 0.2 mm followed by strain recording. It should be pointed out that the grinding was of a low deformation type, very gentle. It was performed using an automatic STRUERS metallographic grinding machine with a minimum pressure force to minimise possible residual stresses introduced by the grinding procedure itself. It could be therefore assumed that residual stresses introduced by grinding were insignificant in comparison with those induced by shot peening and they only were localised just in a very thin surface layer. The remaining thickness of the material at the last step only was between 0.15 – 0.2 mm. It could be therefore anticipated that original surface stresses were almost completely released. It should be noted that the complex residual stress state near the edge, which was shot peened at both surfaces, was very complicated and could not be fully evaluated using the described simplified strain measurement. However, the measurement provided at least some qualitative and partially quantitative results in terms of longitudinal residual stresses, most important from the viewpoint of fatigue crack initiation and early stages of growth.

An alternative method, very different from the strain gauge one was used for the evaluation of residual stresses, namely X-ray method, performed at the Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering. The measurement was carried out with the use of θ-θ goniometer *X´Pert PRO MPD* from the *PANalytical* company. The anode was of the Cr-type. The diffraction line {222} Al was analysed. Residual stress values were calculated from experimentally evaluated dependencies of the diffraction angle $2\theta(\sin^2\psi)$ on the assumption of two-axes state of the residual stresses, where ψ is the angle between the specimen surface and diffractive atomic lattice planes. The dependence $2\theta^{222}(\sin^2\psi)$ was measured just in the longitudinal direction in both the specimens. The diffraction angle $2\theta^{222}$ was determined as the centre of gravity of the diffracted doublet CrKα in the lattice planes {222} Al. For the evaluation of the stresses, macroscopic elastic constants s_1 = -4,99 · 10^{-6} MPa^{-1} and $\frac{1}{2}s_2$ = 19,25 · 10^{-6} MPa^{-1} were used.

It should be pointed out that the X-ray measurements were performed in the central area of both the specimens peened with the different parameters. The measurement points corresponded to the position of the strain gauge in Fig. 1a (not Fig. 1b), in both the specimens. The depth of the measurement corresponded to 0.15 mm, the surface layer was removed off by electropolishing using the STRUERS Movipol-3 device.

4. Results and discussion

4.1. Residual stresses

The diagram of strain values recorded using the strain gauges as a dependence on the specimen remaining thickness, when the material was ground off from the surface opposite to that with the strain gauge, is in Fig. 2. There are some important results. Firstly, the character of the curves is different, as expected. However, higher values of strain, more than twice as much when approximately one half of the specimen thickness was ground off, is rather surprising. It should be noted that the measured deformations represent not only axial surface relaxation, but also some bending of the remaining material layer after grinding the opposite layers off. It is important that eventually, both the curves tend to come together to similar values, between 300 and 400 μm/m. One could expect that the more severe treatment will result in higher strain values. Some explanation could be found in the fact that the more severe shot peening resulted in higher number of deeper surface microcracks, which might cause some stress release. On the other hand, the more uniform growth of the curve connected with the more severe treatment could be linked to more homogeneous and deeper effects. Note that through thickness residual stress distribution does not depend only on Almen intensity, but on different combination of shot peening parameters [6].

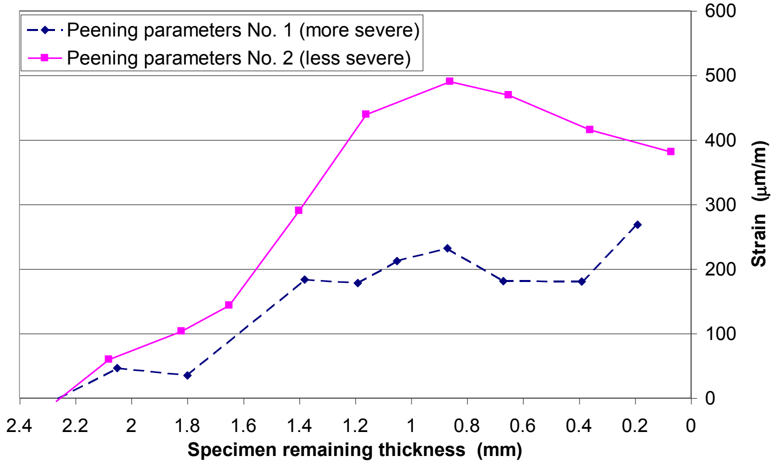

Fig. 2. Strain values recorded as a dependence on specimen remaining thickness during grinding material off

As regards the strain values after the material relaxation (stress release) at the final step, when the residual thickness only was approximately 0.2 mm, namely 270 and 380 μm/m, respectively, considering the E-modulus 72 GPa, the strain values would correspond to stresses of 19 and 27 MPa, respectively, if the simplified conditions are accepted. It is not too much on one hand. On the other hand, considering the fact that the applied maximum stress of 160 MPa was quite close to the material fatigue limit [7], even small changes of surfaces residual stresses to negative values resulting eventually in a reduction of the overall maximum stress can affect fatigue life quite significantly, particularly in terms of retardation or arrest of short fatigue cracks.

Concerning the measurements carried out at the Faculty of Nuclear Sciences and Physical Engineering, the values of the macroscopic longitudinal residual stress, corresponding to the mean value of effective infiltration depth T^e of the used CrKα radiation ($T^e \approx$11 μm for the Al-alloys) were -73±18 MPa and -58±18 MPa for the specimens peened with more and less severe parameters, respectively. Particularly in the latter case, when the positions of the strain gauge and X-ray measurement were equal as in Fig. 3a, the agreement of the results obtained by the two different methods can be considered as surprisingly good.

4.2. Residual fatigue life

Survey of residual fatigue life of the pre-cracked specimens after application of shot peening in comparison with untreated specimens is shown in Fig. 3. As regards the fatigue life of specimens without shot peening, the experimental points of these three specimens namely correspond to the crack growth stage starting with the length 0.2 mm.

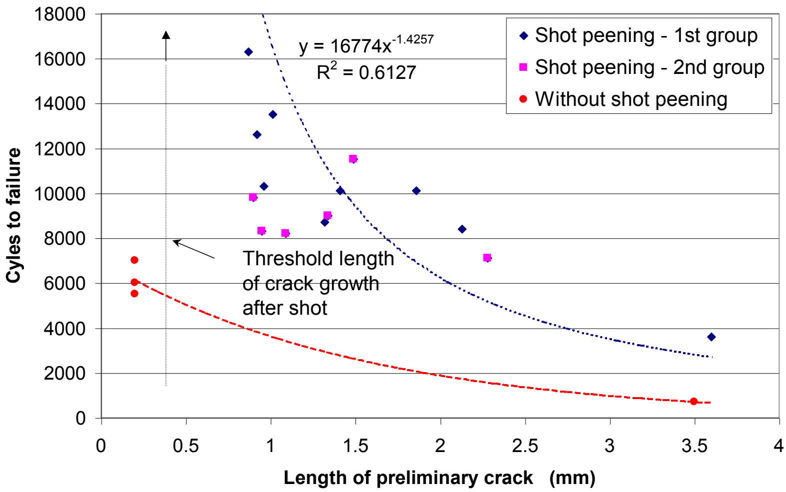

Fig. 3. Survey of residual fatigue life of pre-cracked specimens after shot peening in comparison with untreated specimens

It follows from Fig. 3 that the retardation effect resulting from shot peening was quite significant. In the region of crack length around 1 mm, the estimated increase of fatigue life is at least between 2- and 3-times, the effect being slightly stronger for the first group of shot peening parameters (more severe). However, even for cracks longer than 2 mm, some retardation effect is evident. The slightly higher retardation effect of the more severe shot peening particularly on short crack of length less than 1.5 mm (around 1.0 mm) can be attributed to the more homogeneous distribution of the compressive residual stresses indicated in Fig. 2. It can be noted that similar effects of quite a strong retardation of short fatigue cracks in the field of compressive residual stresses was observed in [8].

Results in Fig. 3 enabled to estimate the threshold length of the total crack arrest. The estimation was made on the basis of extrapolating the regression line for the shot peened specimen groups, the estimated value being approximately 0.35 mm.

5. Conclusions

An experimental investigation of an effect of shot peening with two different groups of parameters on subsequent retardation and further growth of physically short fatigue cracks to failure in 2.4 mm thick aircraft V-95 Al-alloy sheets (a type of a 7075 alloy), clad with a 7072 Al-alloy (Al-Zn1) was carried out. Measurement of surface and subsurface residual stresses using two different methods, strain gauging during grinding the material off and X-ray diffraction was carried out, too. The main conclusions can be summarised as follows:

- Crack growth after shot peening was measured and compared with crack growth in specimens without shot peening. Retardation of crack growth was significant particularly for cracks shorter than 2 mm. Some minor differences between the two groups of shot peening parameters were ascertained.
- The residual stress measurement indicated significant differences in the through thickness residual stress relief between specimens peened with the two different parameters. A presence of surface compressive residual stresses was confirmed. An agreement of the results obtained using the strain gauge and X-ray methods, respectively, can be considered as very good.
- Evaluated results enabled to estimate for the specific stress amplitude threshold length of defects corresponding to the total crack arrest. This estimated crack length was approximately 0.35 mm.

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