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Effect of pre- and post-processing upon shot-peening residual stresses

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ABSTRACT

The process of shot-peening finds extensive use in industry to combat fatigue fracture in engineering components. The introduction of compressive residual stresses increases the fatigue life considerably and forms an integral part of the design process. Although the benefits of the shot-peening process are well established, all investigations overlook the history of the component being treated. This increases the scatter in the results and makes them unreliable. Also, although researchers are aware that post-processes performed on treated components reduce and redistribute the peening compressive residual stresses, no experimental confirmation exists.

Specimens of an aircraft alloy 817M40 were subjected to controlled turning to produce four different surface roughnesses, and the residual stress fields for each were established by a modified centre hole drilling technique. The different specimens were then exposed to the same shot-peening parameters and the resulting residual stress distribution again investigated. A comparison of the two revealed that rough turned surfaces had lower compressive residual stresses after shot-peening and the reason was the initially higher tensile residual stress associated with the rougher surfaces. It was also shown that the maximum amount of residual stress was induced when the surface roughness before and after shot-peening were similar.

For the post-processing effect controlled grinding was studied and the results indicated a straight line reduction in the maximum compressive residual stress as well as a redistribution of the stress field. It was also shown that even after a layer removal equivalent to 50% of the arc-height, the compressive stress still remained compressive.

INTRODUCTION

The presence of residual stresses is difficult if not impossible to avoid, irrespective of the production method. There are many studies which show that surface tensile residual stresses are detrimental to the fatigue life of engineering components while surface compressive residual stresses are beneficial, [1-2]. The shot-peening process in which small steel shots or glass beads are bombarded under air pressure onto the surface of the component, is the most widely used industrial method of imparting beneficial compressive residual stresses in the surface and near surface layers of a prospective component. A typical residual stress distribution of a component before and after shot-peening is given in Figure 1.

Although many studies have shown both theoretically and experimentally that the shot-peening process helps to convert the detrimental surface tensile residual stresses into beneficial compressive residual stresses, all such work has ignored the history of the component that is to be treated [3]. Since the peening residual stresses are superimposed on the components initial residual stress field, the stress distribution before shot-peening plays a role as important as the shot-peening residual stresses. Thus, to obtain meaningful and reliable results, attention must be focused on the effect of different residual stress fields prior to peening being subjected to the same shot-peening parameters.

MATERIALS AND METHODS

Components made from alloy steel 817M40, which finds extensive use in industry, are also frequently shot-peened to enhance the fatigue fracture life. The material was selected on the basis of (i) it being an aerospace application material, (ii) its behaviour not having been previously studied, and (iii) its availability.

A close watch was kept on the specimens which for pre- and post-processing effects were produced on a centre lathe. The factors considered in the selection of the specimen geometry were (i) ease of residual stress measurements, (ii) freedom from distortion on loading, (iii) to permit use of strain gauge rosettes, (iv) ease of uniform peening, and (v) economics of production.

All specimens were critically inspected regarding the geometrical form and any falling outside limits or having even minor surface damage were discarded.

Residual stress measurements were carried out by the well known centre hole-drilling strain gauge method albeit in a modified form to enable the stress gradient to be measured. The hole drilling method is well documented, [4-6], and the details of the modification are given in reference [7].

RESULTS

Pre-Processing

Steel specimens were produced to four different surface roughnesses varying from a fine 1.2 μm R_a to a rough 6.6 μm R_a. Residual stress measurements were carried out on these and the results for the two extreme roughnesses are presented in Figure 2.

The results have been normalized in both the X and Y directions by dividing the residual stresses with the material tensile strength, and the hole depth with the specimen diameter. Each point on the graph represents a residual stress measurement point some distance from the surface. Due to time and cost limitations, only three specimens for each type were investigated for residual stresses, and only if the three readings were more than 10% apart a further confirming measurement was performed. Besides, a series of experiments were also carried out to throw light on the scatter in the residual stress measurements within the same specimen, as well as between two specimens subjected to the same stress producing process, e.g., two specimens similarly produced and subjected to the same shot-peening parameters, (see chapter 6 of [7]).

As shown in Figure 2 the residual stress distribution for the fine specimen is significantly different to that for the rough specimen, with the rough specimen having greater tensile residual stresses in general.

The residual stress distribution of these specimens after shot-peening is given in Figure 3. Only the axial stress distribution is given here, the hoop residual stress distribution being omitted; due to shot-peening, the stresses in both directions become more or less similar in distribution with a slight variation in magnitude. It is obvious from the graph that shot-peening has induced compressive residual stresses in the surface and near surface

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layers of all four surface roughnesses investigated. The magnitude of residual stresses is however lower in the very rough surfaces as compared to that for the fine surface.

Post-Processing

For the effect of post-processing controlled grinding was selected and the residual stresses were measured first in a shot-peened component, and then in a specimen shot-peened and post-processed to different surface finish by grinding. These results are presented in Figure 4.

Although it was established that the scatter in residual stress results from specimen to specimen was of the order of 5%, residual stresses were measured on the same one specimen to establish the variation of residual stresses with arc-height. This specimen was shot-peened and the residual stresses measured, and then ground finished and the stresses measured again. Greater and greater depth was successively removed from this specimen and the stresses measured at each stage. These results are presented in Figure 5.

DISCUSSION

Pre-Processing

From Figure 3 it can be seen that despite the initial rather large variation in surface roughness, i.e., from 1.2 to 6.6 μm R_a, shot-peening of the same parameters has induced compressive residual stresses in all specimens. This, on the one hand shows that it is possible to induce compressive residual stresses in surfaces which are in excess of 6 μm R_a rough, and on the other that considerable latitude with regard to surface finish is available in producing surfaces that need to be shot-peened. The near surface compressive residual stresses in the 6.6 μm Ra specimen is also not significantly lower (0.27 times σ as opposed to 0.43 times σ) to that of the 1.2 μm R_a specimen. As a matter of fact a surface as rough 6.6 μm R_a would never be peened with an intensity of 12 A, and the surface stresses of 0.27 σ can be increased by shot-peening a rough surface with a higher intensity. Since the cost of producing surfaces increases exponentially with a reduction in R_a surface roughness, it is always advantageous to produce a rough surface rather than a fine one if the component is to be shot-peened before use.

Post-Processing

As long as the post-processing method is able to produce an acceptable surface finish, and does not induce tensile residual stresses any available technique may be used. Fine turning has been shown to produce near zero stresses and could be used as an economical post-processing method, but the increase in surface hardness due to shot-peening must be kept in mind. Grinding, boring and lapping are all finishing processes, and by the nature of their being finishing processes the material removal rate is small and hence the influence on the residual stress field is also small. The reduction in residual stresses due to grinding is because of two reasons; the induction of tensile residual stresses due to grinding and the removal of the shot-peened compressed layer. However, it is the effect of the latter which is dominant.

Figure 4 shows the effect of grinding after shot-peening; a reduction in the compressive stress magnitude. This is straight forward as the plastically deformed layer which is responsible for the compressive stresses, is being removed. Thus, the compressive stresses are reduced to less compressive or in extreme cases even to tensile stresses. The production of a fine surface means loss of the compressive residual stresses induced by shot-peening.

Figure 5 shows the reduction in residual stresses as different thickness layers were successively removed from the same specimen; the specimen being finished to the same characteristic roughness each time and in the same manner. A single specimen though considerably time consuming as far as handling was concerned, was opted for to get rid of all possible extraneous factors. The figure shows that the compressive stresses are being reduced and changed to tensile. As this happens the bulk of the specimen becomes stress-free. The reason is that at the end when all the plastic layer has been removed, it is only the residual stresses induced by the grinding process that become dominant. These are mildly tensile at the surface whilst the rest of the specimen is essentially stress-free. To better visualize the residual stress diminishing effect, Figure 6, showing the surface residual stresses against the arc-height has been produced. The graph shows an almost linear variation with depth. This variation can however be better represented by two straight lines; the first of a greater gradient than the second. This is due to the fact that the initial layers have higher stresses, and the removal of these affects the overall distribution more than the removal of layers some distance from the surface. It is worth noting that even after 50% of the arc-height has been removed, the stresses have not changed to tensile, although they are almost zero.

Thus, considerable latitude is available to ensure that the rough surface is converted to a smooth enough surface, proper for the intended use.

CONCLUSIONS

These relate to controlled turning as a pre-process and controlled grinding as a post-process.

Pre-Processing

By keeping all factors constant and varying the feed rate only, surfaces having different roughnesses were produced for examination. These surfaces were subsequently shot-peened and the compressive residual stresses thus induced, measured. All components had compressive residual stresses; however those that had higher initial tensile residual stresses to start with, had lower compressive stresses after shot-peening. It is indicated that the cause of lower compressive residual stresses in rough specimens is the initial higher tensile stress.

Although one would neither use critical surfaces as rough as 6 μm R_a nor shot-peen such surfaces with an intensity 12 A, it was indicated that shot-peening induced considerable stresses in the roughest surface examined. This result is of great importance as the cost of producing components increases dramatically with lower R_a values. Thus, general use components could be produced towards the higher roughness limits studied here, and shot-peened with intensities in excess of 12 A, quite economically.

Also since the shot-peening process reduces the roughness of surfaces in excess of 3.5 μm R_a (will vary according to shot size; the size for this study is 0.6 to 0.8 mm), and vice versa, there is no advantage in producing surfaces better than 3.5 μm R_a, unless it is a consequence of the production method used. This, again, is important as the results have indicated that the maximum lift towards compression in residual stresses, is obtained when the surfaces before and after shot-peening are equally rough.

Post-processing

The process of controlled grinding was used as a post-processing operation and shot-peened specimens had various thickness layers removed. The resulting residual stress field was measured, and it was clearly indicated that any form of post-surface treatment resulted in a reduction in the compressive stresses as well as redistribution of the residual stress field. This reduction in stresses was rapid during the

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initial layers and reduced with deeper layers. The reduction of residual stresses with arc-height removed can be represented by two straight lines of different gradients; the first having a sharper gradient than the second. It was also indicated that even after 50% of the arc-height had been removed the stresses were still compressive.

During the detailed study carried out by the author certain experiments were also performed to increase the confidence in the results (see chapter 4 of [7]). The overall error in residual stress measurements was found to be less than 10%.

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NOTATION

R_a	Average Roughness Parameter
σ	Ultimate tensile strength
Arc-Height	Deflection in thousandths of an inch of a standard metallic strip (Almen strip) when subjected to shot-peening. Used to compare shot-peening intensities [7]
12 A	Deflection of 0.012 inch in an 'A' strip

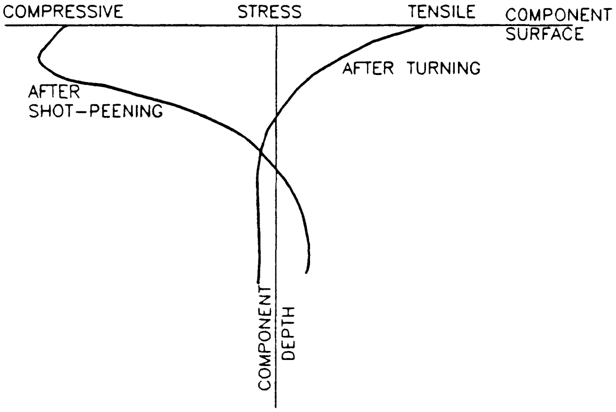

Fig.1 Effect of Shot-Peening on Typical Turning Residual Stresses

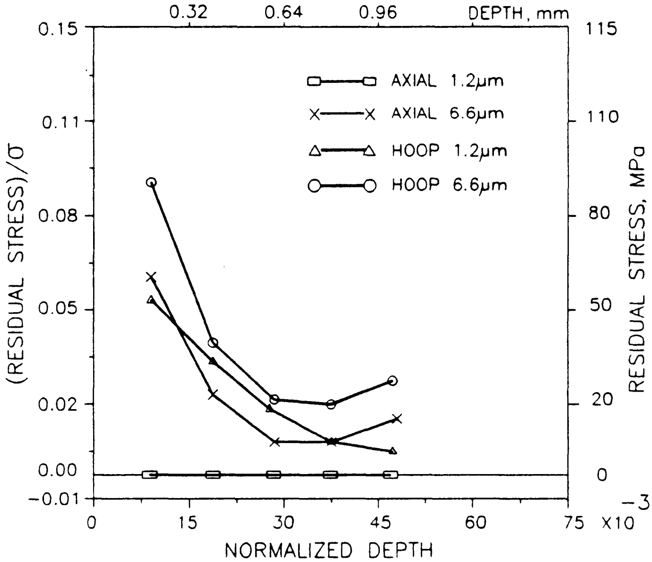

Fig.2 Turning Residual Stresses for Extreme Roughnesses for Steel 817M40

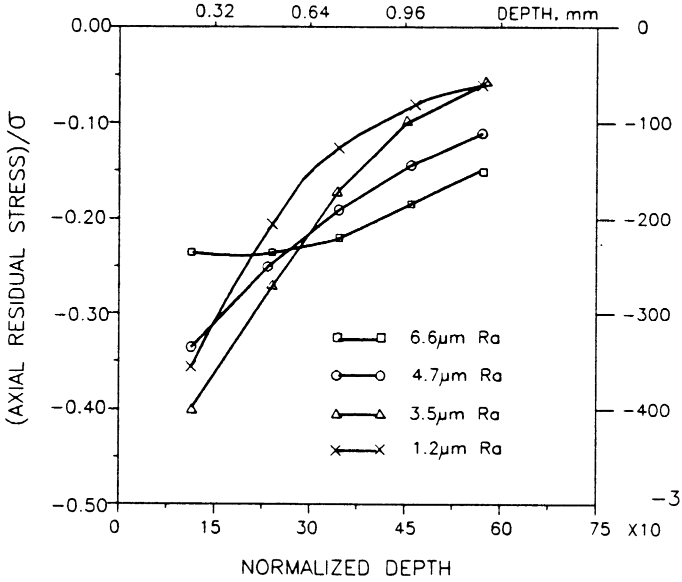

Fig.3 Turning Residual Stresses after Shot-Peening

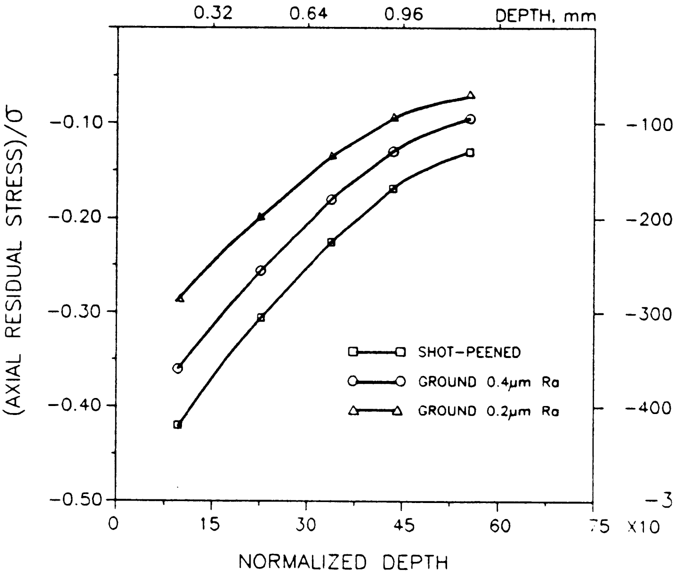

Fig.4 Axial Residual Stress Distribution for Post-Processing (Comparison of different specimen)

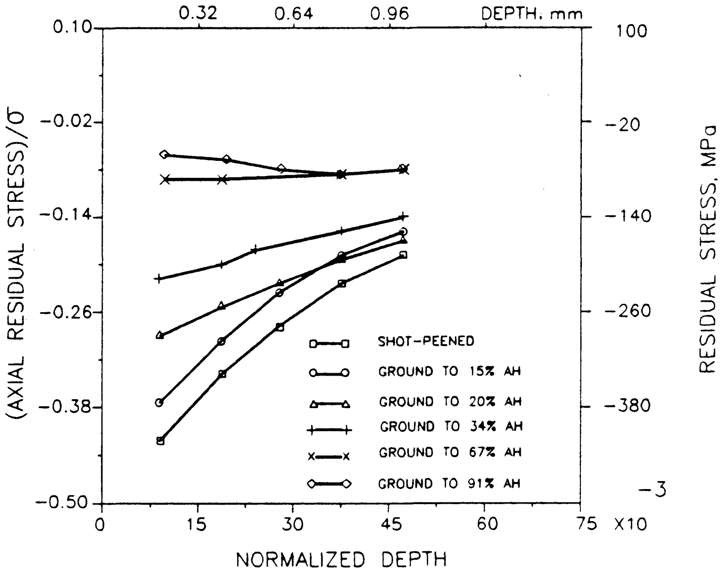

Fig.5 Residual Stress Distribution for Various Arc-Height Removed (Same specimen)

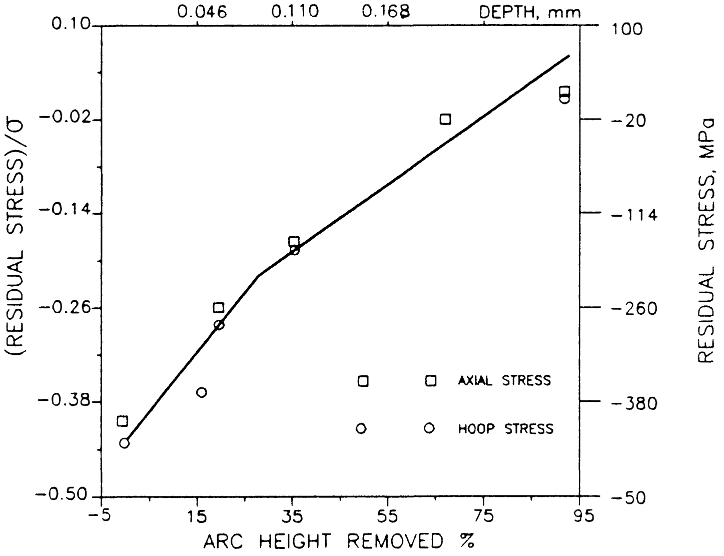

Fig.6 Surface Residual Stresses versus Arc-Height Removed (Same Specimen)