Effect of Pre- and Post-Processing upon Shot-Peening Residual Stresses

T. Rasul

Dr A. Q. Khan Research Laboratories
Rawalpindi
Pakistan

ABSTRACT

The process of shot-peening finds extended 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.

The following work is the result of an extended investigation into the effect of pre- and post-processing upon shot-peening residual stresses.

Specimens were subjected to controlled turning to produce four different surfaces 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. The material investigated was an aircraft alloy 817M40.

INTRODUCTION

The presence of residual stresses is difficult if not impossible to avoid, no matter what the method of manufacture may have been. 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, e.g., see (1-2) and the references mentioned therein. The shot-peening process in which small spherical steel shots / 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.

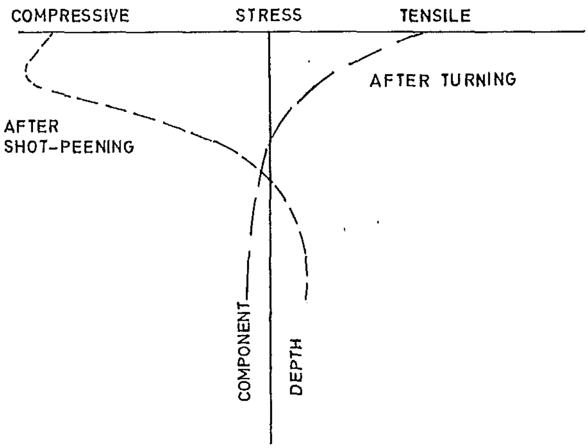

Figure 1. Effect of Shot-Peening on Typical Turning Residual Stresses

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, e.g.,see reference (3) and the references mentioned therein. Since the peening residual stresses are superimposed on whatever residual stress field the component has, the stress distribution before shot-peening plays as important a role 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. The results presented in this study were obtained during a detailed analysis carried out by the author (4).

MATERIALS AND METHODS

The material investigated steel 817M40 is a typical aircraft alloy and finds extensive use in industry. Components made from this alloy are also frequently shot-peened to enhance the fatigue fracture life. For steel, both the pre- and post-processing aspects were looked into. The material was selected on the basis of (i) its 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 rosette, (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 a damaged surface were discarded. The specimen details are provided in Figure 2, while the material composition and properties are given in Tables 1 and 2.

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.

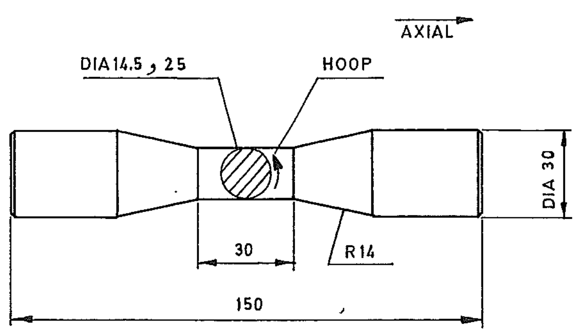

Figure 2. Specimen Dimensions

TABLE 1
Chemical Composition of Test Material

Element	Maximum/Minium
Carbon	0.45/0.35
Silicon	0.35/0.10
Manganese	0.70/0.45
Nickle	1.80/1/30
Chromium	1.40/0.90
Molybdenum	0.35/0.20
Sulphur	0.05/----
Phosphorus	0.05/----

TABLE 2
Mechanical Properties of Test Material

Property	Steel 817M40
Young's Modulus	207 GPa
Ultimate Tensile Strength	1 GPa
Proof Strength 0.1 %	770 MPa
Poissons Ratio	0.28
Hardness	300 Hv

The hole drilling method is well documented e.g. see references (5-7), and the details of the modification are given in reference (4).

RESULTS

Pre-Processing

Steel specimens were produced to four different surface roughnesses varying from a fine 1.2 µm Ra to a rough 6.6 µm Ra. Residual stress measurements were carried out on these and the results for the two extreme roughnesses are presented in Figure 3.

The results have been normalized in both X and the Y directions by dividing the residual stresses with the material yield strength and the hole depth with the specimen thickness. 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 residual stresses within the same specimen, as well as between two specimens subjected to the same stress producing process e.g., two specimens similary produced and subjected to the same shot-peening parameters,(see chapter 6 of (4)).

As shown in Figure 3 the residual stress distribution for the fine specimen is significantly different to that for the rough specimen, with the rougher specimen having greater

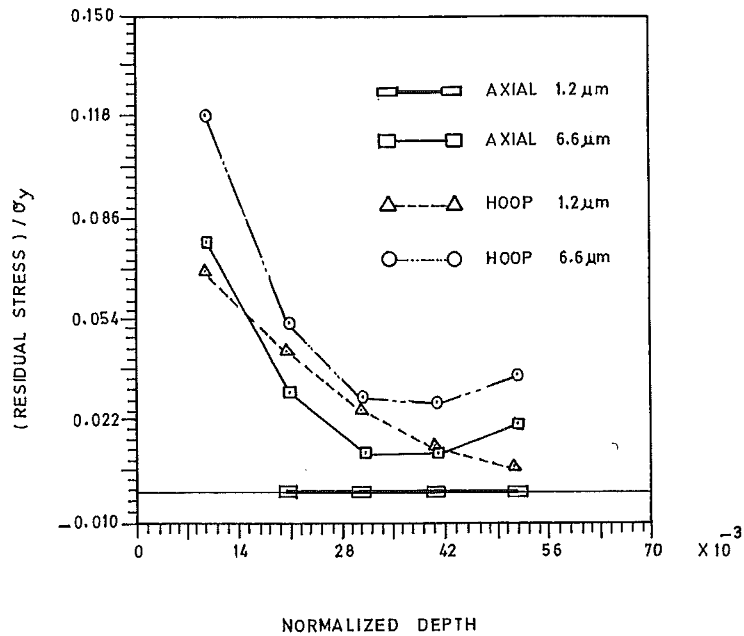

Figure 3. Turning Residual Stresses for Extreme Roughnesses for Steel

tensile residual stresses in general. Figure 4 Shows these stresses together with those for the two specimens of 3.2 and 4.5 µm Ra.

The stresses are the surface stresses normalized by the yield stress and are plotted with the X-axis representing the surface roughness of the specimen. A trend of increasing tensile surface residual stress with increasing surface roughness can be seen in the plot.

The residual stress distribution of these specimens after shot-peening is given in Figure 5. Only the axial stress distribution is given here, the hoop residual stress distribution being omitted; due to shot-peening the residual stresses in both directions become more or less similar in distribution with only slight variations in quantity. It is obvious from the graph that shot-peening has induced compressive residual stresses in the surface and the near surface layers of all four surface roughnesses investigated. The magnitude of the residual stresses is however lower in the very rough surfaces as compared to that for the fine surface.

Post-Peening

For the effect of post-processing controlled grinding was selected and the residual stresses were measured in a

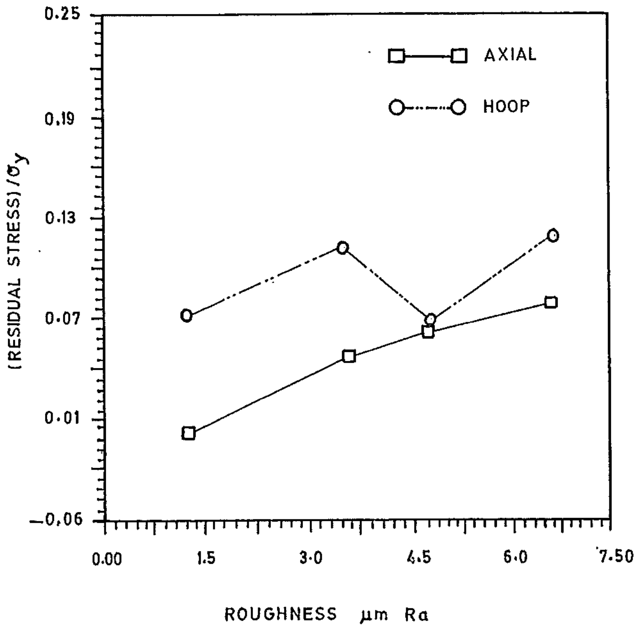

Figure 4. Turning Residual Stresses for Steel

shot-peened component. Residual stresses were then again measured in a component shot-peened and then post-processed to different surface finish by grinding. These results are given in Figure 6.

The stress distribution for lapping is considerably different to that for grinding and could be an experimental error as the result for lapping was available for a single specimen. However the process of lapping as performed could have possibly caused excessive heat to be trapped and hence caused the distribution to vary significantly from that of grinding. This aspect needs further investigation before meaningful conclusions can be drawn. 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, it was then ground finished and the stresses measured again. Greater and greater depth was successively removed from the specimen and the stresses measured at each stage. The results are represented in Figure 7.

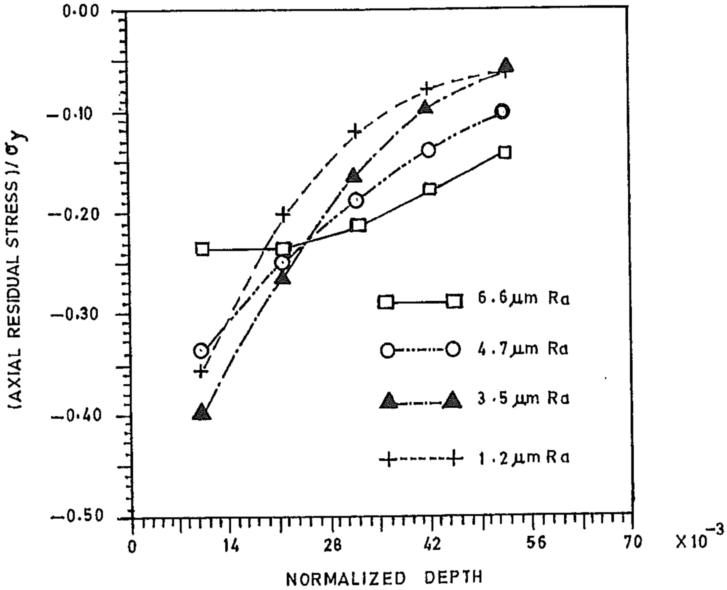

Figure 5. Turning Residual Stresses after Shot-Peening

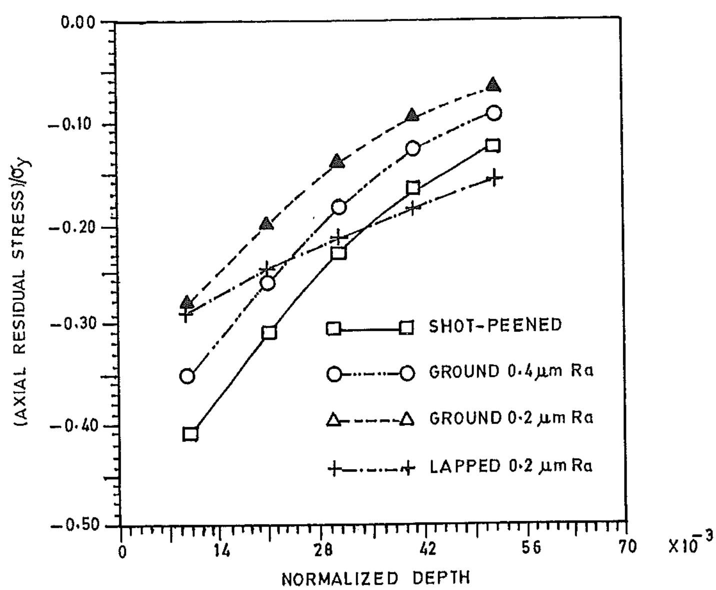

Figure 6. Axial Residual Stress Distribution for Post-Processing (Comparison of different specimen)

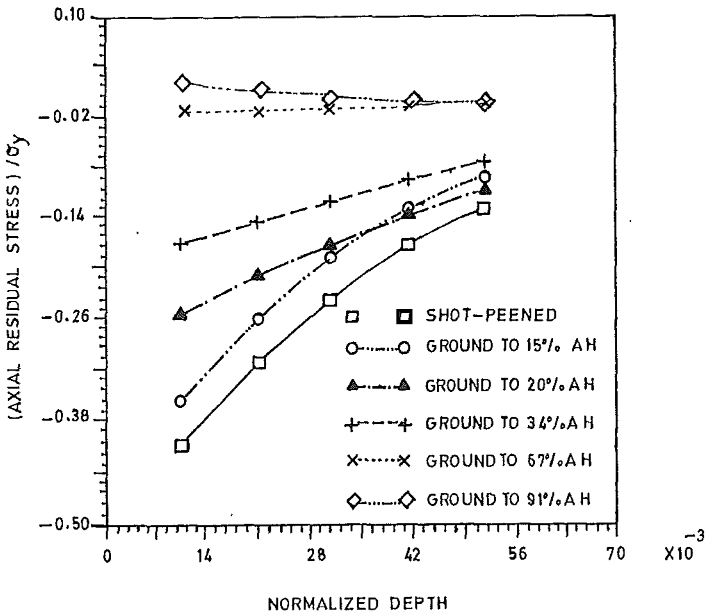

Figure 7. Residual Stress Distribution Versus Arc-Height Removed (Same specimen)

DISCUSSION

Pre-Processing

From Figure 5 it can be clearly seen that despite the initial rather large variation in surface roughness i.e., from 1.2 µm Ra to 6.6 µm Ra, 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 Ra 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 surface is also not significantly lower (0.27 times σ_y as opposed to 0.43 times σ_y) to that of the 1.2 µm Ra surface. As a matter of fact a surface as rough as 6.6 µm Ra would never be shot-peened with an intensity of 12 A, and the surface stresses of 0.27 σ_y can be increased by shot-peening a rough surface with a higher intensity. Since the cost of producing rough surfaces increases exponentially with a reduction in Ra surface roughness, it is always advantageous to produce rougher surfaces rather than fine if the component is to be shot-peened before use. When the turning residual stresses are subtracted from the shot-peening residual stresses and plotted against the surface roughness, the plot of Figure 8 results.

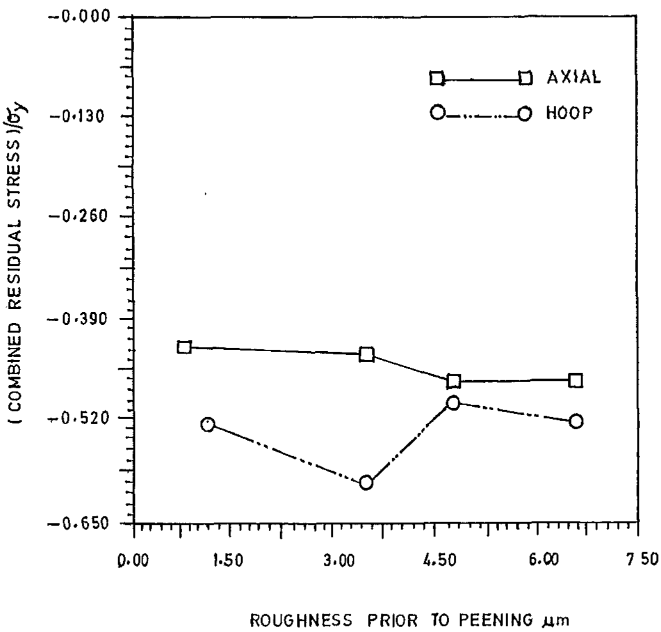

Figure 8. Combined Surface Residual Stresses

The more or less horizontal nature of this plot (it must be emphasized here that no smoothening action has been applied to the data points on the plot) signifies that the lower amount of compressive residual stresses in the rougher surfaces is a consequence of the higher initial tensile residual stresses. Thus, it is important to specify the limit of residual stresses in a component that is to be shot-peened, if repeatable results after shot-peening are essential.

The Ra roughness values before and after shot-peening for a number of different specimens are plotted in Figure 9.

It shows that although the initial roughness of the turned surfaces varied considerably, it was not so with the shot-peened surfaces. It also shows that while fine surfaces are made rougher, rough surfaces are made smoother, and that the effect of the initial turned surface, is in general, carried through the process of peening. Since the turned

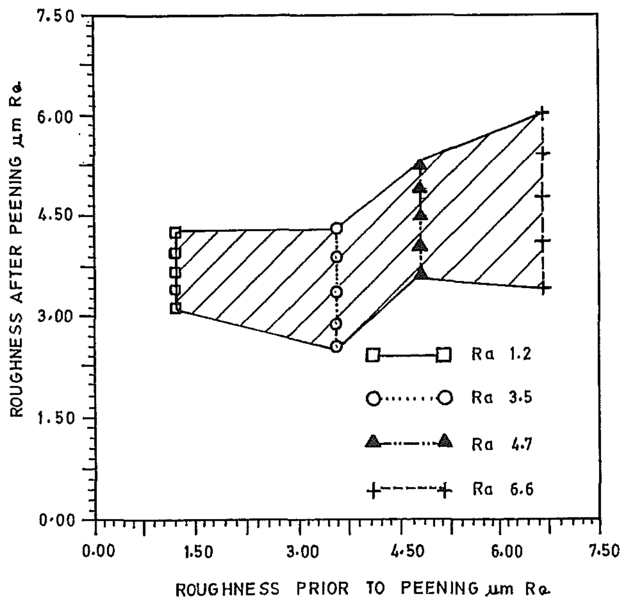

Figure 9. Scatter Band for Roughness after Shot-peening

surfaces of 1.2 µm Ra to 6.6 µm Ra are within 2.5 µm to 6 µm Ra after peening, components for general shot-peening practice need not be produced outside this scatter band.

Post-Processing

As long as the post-processing method is able to produce an acceptable surface finish, and does not induce tensile residual stresses due to the finishing operation, 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 very 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 6 shows the effect of grinding after shot-peening; a reduction in the compressive stress magnitude. This is straightforward 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 greater loss of the compressive residual stresses induced by shot-peening.

Figure 7 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 visualize the residual stress diminishing effect Figure 10, showing the surface residual stresses against the arc-height has been produced. The graph shows an almost linear variation with depth.

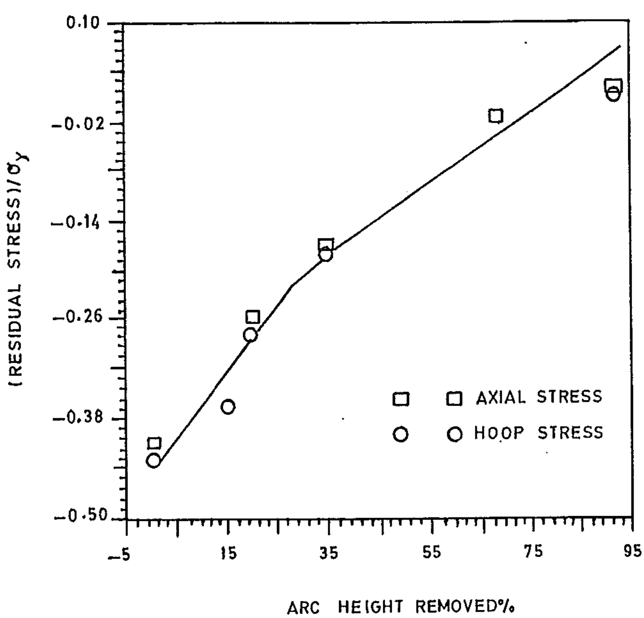

Figure 10. Surface Residual Stresses Versus Arc-Height Removed (Same Specimen)

This variation can however be better represented by two straight lines; the first being 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 use in mind.

CONCLUSIONS

The conclusions presented here relate to controlled turning which was used as a pre-process and controlled grinding which was used as a post-process for this study.

Pre-Processing

By keeping all factors constant and varying the feed rate only, surfaces having different roughness were produced for the 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 Ra nor shot-peen such surfaces with an intensity of 12 A, it was indicated that shot-peening induced considerable stresses in the roughest surface examined. This result is of considerable importance as the cost of producing components increases dramatically with lower Ra 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 Ra, and vice versa, there is no advantage in producing surfaces better than 3.5 µm Ra 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 a redistribution of the residual stress field. This reduction in stresses was rapid during the initial layers and reduced with deeper layers. The reduction of residual stresses with the 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.

Crossover Point In Shot-Peened Specimens

When measurements were carried out on shot-peened specimens, the residual stresses were found to be compressive up to a depth of 0.75 mm. Since such stresses are expected to change from compressive to tensile in the first 1 mm of depth, the possibility of a measurement error was suspected and considered.

An experiment was performed in which residual stresses in a shot-peened Almen strip (6 C) were measured by the same method. The results clearly indicated, that the measurement technique, as being used, was capable of picking up the crossover point, as accurately as any other technique, if not better. These results were also compared with those measured by electro-etching, and the depth of the crossover point agreed to within 0.15 mm while the maximum residual stress distribution for the strip is given in Figure 11.

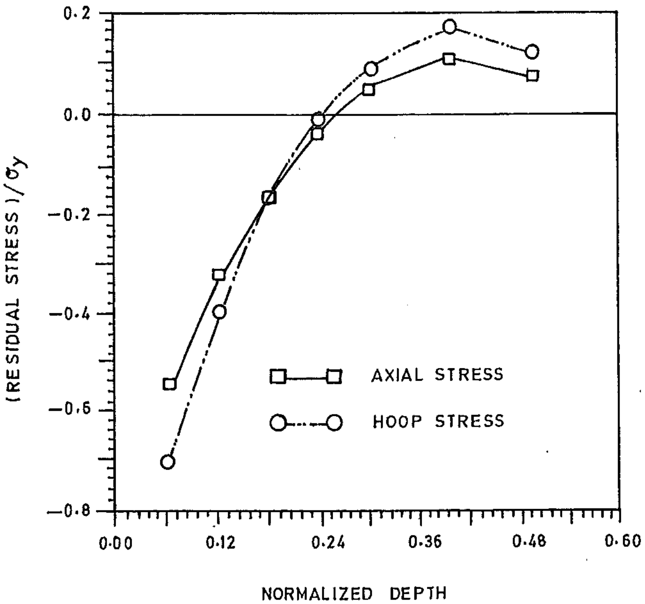

Figure 11. Shot-Peening Residual Stresses in an Almen Strip

It must, however be noted, that the presence of a crossover point in the Almen strip, does not necessarily mean, that there is not one within the range of the hole drilled in the actual specimen. Whilst the depth of the compressed layer is of the same order as compared to the depth of tensile stresses in the 2.4 mm thick Almen strip, it is not so in the 14.5 mm specimens. For the test specimens the compressive stress layer is a much smaller percentage of the tensile stress layer. The hole-drilling technique is primarily an averaging technique, and despite the modification discussed herein, remains an averaging technique. Thus, in very thick specimens it is not possible to accurately obtain the crossover point.

Accuracy Repeatability and Overall Error.

Any set of experiments however well planned and executed, shall not produce results that can be relied upon unless a few words are mentioned about the accuracy and repeatability of the setup. A number of different experiments were performed to check the validity of the results obtained. These pertained to four distinct parts of the study, i.e., mounting of strain gauges, location of specimens in the experimental jig, measurement of hole diameter and hole depth, and the measurement of residual stresses, (for details see chapter 4 of (4)).

During the extensive residual stress measurements using the modified hole-drilling method a careful account of the various errors (as above) involved was made. It is logical that these errors are not directly additive and the overall error cannot be a simple sum of these. Besides, these errors are the maximum observed, and the average values are considerably below those stated. When these maximum errors are added a total overall error of 8.6 percent maximum is obtained. The comparison of the modified hole-drilling technique with other popular methods has also established that the results agree to within 10 percent.

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Notation

μm	Micrometer
Ra	Average Roughness Parameter
Oy	Yield Stress
Hv	Vickers Hardness Number
MPa	Mega Pascals
GPa	Giga Pascals
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 (4).
12 A	Deflection of 0.012 inch in an 'A' strip.

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