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FATIGUE PROPERTIES OF COLD WORKED HOLES

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INDUSTRIAL SUMMARY

The introduction of holes in a body would inevitably raise the stress locally around the holes. This stress concentration would in turn affect the performance of the body under static and fatigue loading conditions. The aim of the present paper is to investigate how three cold working processes, namely, shot peening, wet blasting and ballising would affect the fatigue lives of holes. Fatigue tests on 3mm thick tensile specimens of Assab 760 steel showed that ballising with interference between 1 and 3.3% enhanced the fatigue lives of the holes by about 60 to 220%. For shot peening with pressure from 138 to 414 kPa, the enhancement was about 30 to 100%, while for wet blasting at pressure between 69 and 690 kPa, 10 to 50%. The residual stresses around the holes as a result of the cold working processes were evaluated using a fracture mechanics approach. It was found that all the three processes studied induced compressive residual stress field at the surfaces of the holes. The compressive stress decreased and became tensile as the distance from the surface of the hole increased. The compressive stress was observed to increase with pressure in the shot peened and wet blasted holes and with interference in the ballised holes. Within the range of pressure and interference investigated, residual stress measurements revealed that ballising induced the greatest amount of compressive residual stress while wet blasting, the lowest. This is well manifested in the fatigue lives of the holes.

1. INTRODUCTION

Most engineering assemblies are joined by inserting mechanical fasteners through holes. Holes are necessary features in almost all engineering structures. However, the fatigue performance of a component is reduced by the presence of a hole because of the increase in stress concentrations around the hole. As most hole manufacturing processes like drilling and boring also introduce flaws and defects on the surfaces of the holes, the fatigue lives of components are further decreased due to the presence of holes. For applications where fatigue loadings are encountered, it is therefore important to ensure that the decrease in fatigue life is minimal. One proven way to compensate for the decrease in fatigue life of a component is by the introduction of beneficial compressive residual stresses at the surface of the hole using cold working. The residual stresses counteract the applied tensile stress responsible for crack initiation and growth. Processes like cold-expansion of holes [1-6], interference-fit [6], a combination of interference-fit and cold-expansion [7], and stress coining [8] have been employed to improve the fatigue lives of holes in structures.

The purpose of the present study is to compare three manufacturing processes that are able to introduce compressive residual stresses on hole surfaces. The comparison was based on the magnitude of the residual stress induced as well as fatigue life under cyclic tensile loading. The processes investigated are: wet blasting, shot peening and ballising.

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The wet blasting process is a metal cleaning treatment which, apart from its surface roughening effect, is used primarily in the removal of burrs from machined parts, heavy rust and scales as well as grease oil and other contaminations. The process involves directing a stream of abrasive in a liquid medium at high velocity from a nozzle onto the hole surfaces. The kinetic energy of the high speed particles induces a change of state on the surface of the metal. The residual stress induced depends upon the size, shape and hardness of the particles employed. Much the same as wet blasting, shot peening makes use of steel shots (ball bearings) in a stream of air to create overlapping indentation on the surface of a machine component. This process causes a non-uniform deformation through the thickness of the part, hence imparting compressive residual stress on the surface to improve fatigue performance [9]. Shot peening is being applied extensively on shafts, gears, springs, oil-well and jet engine parts such as turbine and compressor blades.

Ballising, as shown in Fig. 1, is a technique that involves forcing a precision ground ball of a prescribed diameter through a slightly smaller pre-machined hole. It is basically a metal working cum finishing process in which no material is removed. It has a burnishing action (except virtually no rotation of the ball is involved) that refines the surface structure of the hole leaving a plastically deformed hole surface. As the ball is pushed through, protrusions generated by the initial hole drilling or boring process are pushed down plastically to fill up depressions. This results in improvements in surface finish, roundness and dimensional tolerance of the holes [10,11]. The improvement in surface finish, together with the compressive residual stresses on the surface due to cold-working, is believed to enhance the fatigue life of the ballised hole.

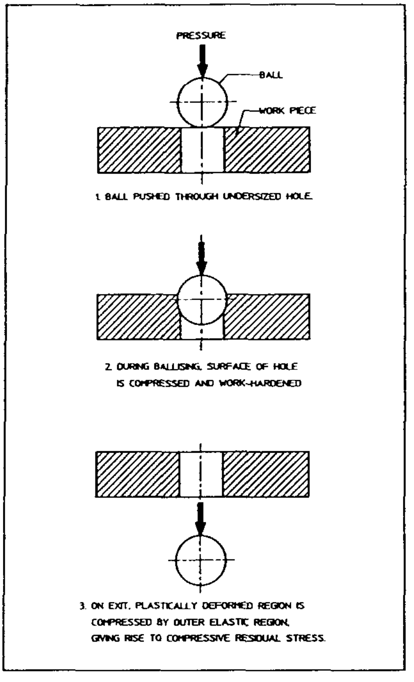

Fig. 1 The ballising process.

2. EXPERIMENTAL PROCEDURES

The material used in the present investigation was Assab 760 steel with typical chemical composition of: 0.50%C, 0.3%Si, 0.6%Mn, and 0.04%S (nearest equivalent: AISI 1050 or En 43). With a tensile strength of 640 MPa and a 0.2% proof stress of 340 MPa, the material was utilised in the as-received unannealed condition with an approximate hardness of 200 HB.

Tensile fatigue test specimens of 10x60x 210mm, as shown in Fig. 2, were obtained from a flat stock of 10mm thickness plate. The 60mm gauge length section of the specimen was machined down to a thickness of 3mm to reduce the applied load needed for the test. After centre marking, a pilot hole of 4mm diameter was drilled. The pilot hole was later carefully enlarged on a lathe with a carbide insert boring bar to the desired diameter. For ballising, the final diameters

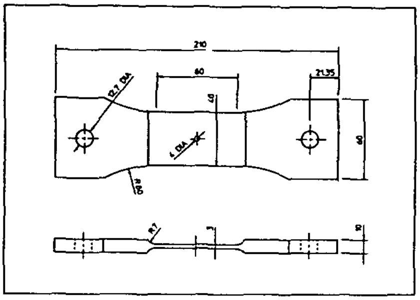

Fig. 2 Dimensions of tensile fatigue test specimen.

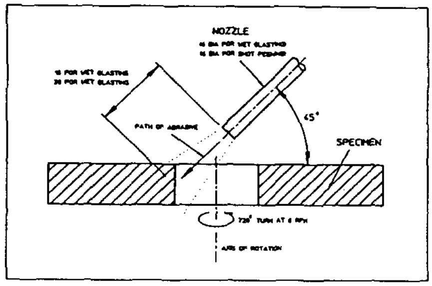

Fig. 3 Setup of the wet blasting process.

were closely controlled so that a range of interferences between the hole and the ball could be obtained. Care was taken to ensure that the surface of hole was well finished and surface roughness maintained uniform between test specimens.

Wet blasting of the specimens was carried out using the Vaqua 'Kompact' wet blasting machine. The machine consisted of a rotating table on which the specimen was placed centrally and a blasting gun mounted on an adjustable support. Specimens were wet blasted as shown in Fig. 3 with two different types of abrasives, namely, pink alumina of grade 90/100 and a finer white alumina of grade 180/220. The wet medium applied was water with the addition of rust inhibitors. A range of pressures from 441kPa to 690kPa was employed for the pink alumina while for the white, 690kPa was used. An average blasting time of 22 seconds was set. This corresponded to a 720 ° turn of the specimen. Instead of alumina, steel shots of grade 230 (average diameter 0.7mm) was used in the shot peening process. Air pressures commonly used for most industrial applications of between 138kPa and 414kPa were employed in the present work also. Except for the distance between the nozzle and the hole surface of 20mm instead of 18mm, the shot peening procedure was parallel to that of wet blasting.

Ballising of the holes was done on an automatic AUTO-multi function press set with single stroke one-way operation. A 19.046mm diameter tungsten carbide ball of grade AFMA 25 was used in the ballising process without the application of lubricant.

Fatigue tests were conducted on a 100kN capacity Instron electromagnetic resonance machine with a mean load of 20kN, peak load of 7.5kN and natural frequency of about 122Hz. In order to compare the fatigue lives of specimens with different blasting and shot peening pressures and different degrees of interferences, all specimens were subjected to the same load levels. ASTM standard E466-82 was adhered to as far as possible. When the mean load dropped by 1kN, which had been found to give rise to macrocrack observable with the naked eyes, the fatigue test was terminated and the corresponding fatigue life was recorded.

3. RESIDUAL STRESS MEASUREMENT

The residual stress distribution around a hole that has been subjected to the three fatigue enhancement processes was evaluated using a fracture mechanics approach [12] which has been fully described in Ref. [13]. In this approach, the relationship between the residual stress, stress intensity factor and displacement associated with the released residual stress by the introduction of a crack at the edge of a hole was developed. The displacements as the cracks were extended incrementally, were used to calculate the residual stress field around the hole. The present study made use of rectangular specimens of 40x104 mm machined from the same stock of material as the tensile fatigue test samples. Specimen preparation procedures were identical to those for the fatigue test earlier described. After the holes had been prepared, a crack in the form of a saw cut in the direction transverse to the long axis of the plate was then introduced at two diagonally opposite edges of the hole as shown in Fig. 4. The displacement between points C and C' was measured to an accuracy of 0.5μm using a travelling microscope. The two cracks were extended simultaneously in a step-wise manner with increments of 2mm until the crack length reached 14mm. Residual stress beyond 14mm crack length was not investigated as it had been found to be small in magnitude.

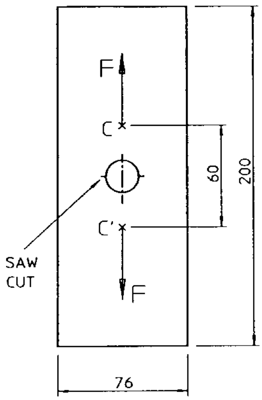

Fig. 4 Specimen for residual stress measurement.

4. RESULTS AND DISCUSSION

Fig. 5 shows the effects of wet blasting and shot peening on the fatigue lives of holes. The lives of the original unprocessed holes can be found on the vertical axis where the pressure is zero. An average life of about 77,000 cycles has been obtained for the unprocessed specimens. Despite some scattering of the results which may be due to slight variation in surface roughness of the holes, it can be clearly observed that fatigue lives of the processed holes are longer than those for the untreated ones and that generally, fatigue life increases with increasing applied pressure. At a shot peening pressure of 400 kPa for example, the increase in fatigue life is about two times that of the unprocessed counterparts indicating the benefits of the presence of compressive residual stress.

It is also evident that the increase in fatigue life is dependent upon the processed employed. Fig. 5 depicts that shot peening is more effective in increasing fatigue life than wet blasting,

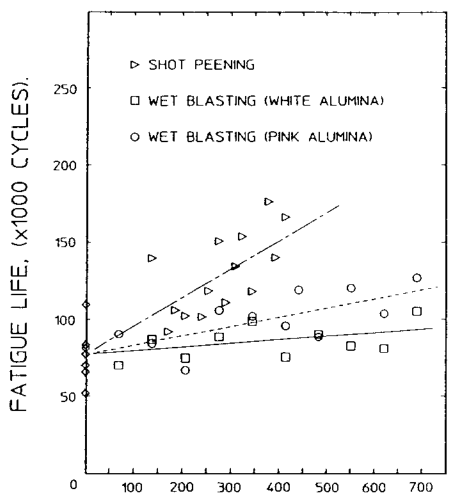

Fig. 5 Fatigue lives of shot peened and wet blasted holes.

irrespective of whether pink or white aluminas are being used in the wet blasting process. At lower pressures, however, both shot peening and wet blasting produced about identical fatigue lives. The difference between using pink or white aluminas is small although pink alumina consistently manifested a slightly longer life.

Effect of degree of interference on the fatigue lives of ballised holes is shown in Fig. 6. Similar to that observed in Fig. 5 for shot peening and wet blasting, it can also be discerned that fatigue lives of the ballised holes increased with the increase in interference. At an interference of 3.5%, the increase in fatigue life is at least two times that of the unballised holes. This finding is consistent with the unpublished results of Panchal [14] who, using stainless steel tension specimens in his work, obtained an approximately three-fold increase in fatigue life.

Comparison between fatigue lives of the ballised holes and those that have been shot peened and wet blasted could not be directly made since the former was done in terms of percentage interference while the latter two processes, in pressure in kPa. Fig. 7 was in stead plotted to show the relative spread of fatigue lives for the three processes employed. Although a large overlapped in fatigue life occurred between shot peening and ballising, the longer fatigue lives

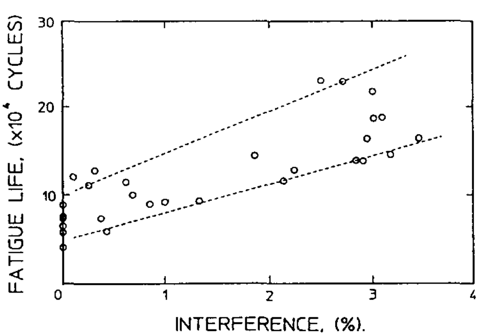

Fig. 6 Fatigue lives of ballised holes.

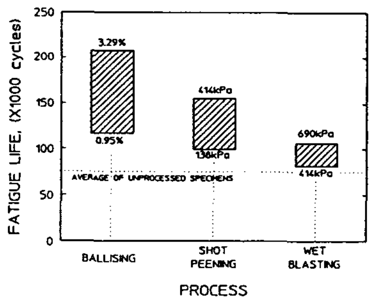

Fig. 7 Comparison of fatigue lives from the three processes used.

from the ballising process at larger interferences of about 3% can clearly be observed. At lower interferences, the two processes resulted in approximately similar lives.

Residual stress distributions around a shot peened holes at shot peening pressures of 138, 207, 276 and 414kPa are shown in Fig. 8. It can be seen that the region immediately adjacent to the surface of the hole exhibits a residual stress that is compressive. The magnitude of this compressive stress decreases until it reaches a maximum tensile stress at a distance about 3.5 mm from the surface of the hole. The tensile residual stress gradually decreases thereafter to approximately zero towards the edge of the plate. Increasing the applied shot peening pressure effectively increases the magnitude of the residual stress as can be seen from the figure. The residual stress that tapers off away from the edge of the hole tends to reach about the same values, implying that it is independent of the pressure. The features depicted in Fig. 7 are similar to those observed in cold-expanded fastener holes [15] although the magnitude of the stresses may be different due to the severity of the deformation induced on the surface of the hole.

Although the residual stress distribution in Fig. 8 has been obtained for the shot peened holes, identical distributions are also observed for holes that have been wet blasted and ballised. The only

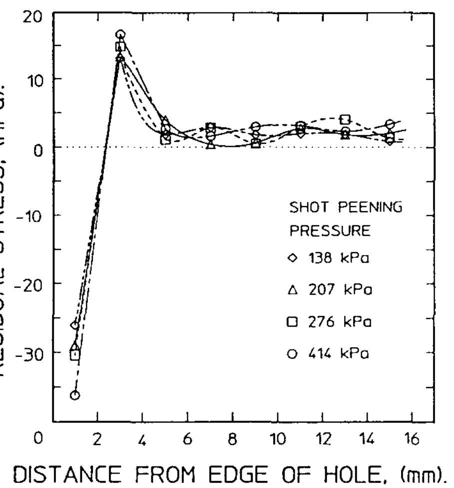

Fig. 8 Residual stress distribution around a shot peened hole.

difference between them is the magnitude. This is summarised in Fig. 9. where the maximum measured compressive residual stresses at 1mm from the edge of the hole are provided. It is obvious that ballising has induced the greatest amount of residual stress on the holes while wet blasting, the least.

Compressive residual stress has generally been recognised to be favourable to fatigue resistance since fatigue cracks find it more difficult to propagate through a compressive stress field [16]. The beneficial effects of compressive residual stress on the fatigue life of structures containing residual stresses have been widely reported [15, 17-20]. To render crack initiation and fatigue crack propagation from the surface of a hole that has been ballised, shot peened or wet blasted, a tensile stress of sufficiently high magnitude has to be applied to offset the compressive residual stress that surrounds the hole. This means that either a longer fatigue life is achieved for holes that are moderately loaded or a higher load is required to fail a hole within a moderate fatigue life.

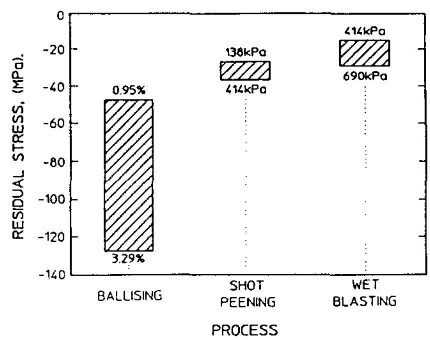

Fig. 9 Comparison of residual stress induced by fatigue life enhancement processes.

From the results of the present study, it is evident that the recommended hole finishing process is ballising. The shot peening process, although it has not resulted in residual stress as high as ballising, has fatigue performance as good as holes that have been ballised with smaller interferences. Within the range of pressure employed in industry, shot peening appears therefore to be a good process. However, while the process is cumbersome and time consuming in its application to holes, shot peening cannot be carried out when the hole is too deep or too small. It is also difficult to obtain good surface finish on the hole. Ballising, on the other hand, is reputed to be fast and economical as it requires simple and inexpensive tooling, especially when only a few specific hole sizes are desired. In addition, with the application of hydraulic pressure it is possible to ballise very small and deep holes [21]. Studies have shown that the ballising process is able to improve the surface finish of the hole five-folds [22]. An average surface roughness value of as low as 0.04 to 0.05æm can be achieved if the ballising process is repeatedly carried out on the same hole [23].

5. CONCLUSIONS

From the results of the present investigation, the following conclusions can be made:

1. Fatigue lives of holes that have been wet blasted, shot peened or ballised were found to increase with the increase in pressure or interference. Compared to the unprocessed holes, ballising with interference between 1 and 3.3% enhanced the fatigue lives by about 60 to 220%. For shot peening with pressure from 138 to 414 kPa, the enhancement was about 30 to 100%, while for wet blasting at pressure between 69 and 690 kPa, 10 to 50%.

2. Irrespective of the finishing process applied, the residual stress at the surface of a hole was found to be compressive at the immediate hole surface. This compressive residual stress decreased in magnitude until it reached maximum tensile at a distance some 3.5mm from the surface of the hole. Thereafter, the tensile stress gradually decreased to zero towards the edge of the specimen.

3. Although shot peening was able to enhance the fatigue performance of a hole satisfactorily, ballising is a better process not only due to its simplicity and efficiency, but also its ability to produce good surface finish and applicability to deep and small holes.

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