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Residual Stresses and Retained Austenite in Shot Peened Steels

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IN THIS ISSUE:

And much, much more!

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ABSTRACT

X-ray diffractometry has been used to examine the variation of residual stress across shot peened surfaces, the transformation of austenite to martensite on peening and the decay of surface residual stress during fatigue testing of peened specimens. It is shown that masking gives rise to tensile surface residual stresses adjacent to the peened area. Peening of austenitic stainless steel produces surface martensite in amounts that depend upon the composition of the steel. Transformation of retained austenite on peening of carburised steel is found to give a substantial improvement in the surface and sub-surface residual stresses. Shot peened austenitic stainless steel is found to lose its compressive surface residual stress on fatigue testing at high levels of applied alternating stress. The fatigue and corrosion fatigue properties of the shot peened stainless steel are then found to be inferior to those of as-polished steel but are superior at lower stress levels.

KEYWORDS
X-ray diffractometry; shot peening; residual stress; austenite transformation; corrosion-fatigue; steels

INTRODUCTION

Shot peening is primarily used to induce a compressively-stressed, work-hardened surface layer into a component. This layer is useful because it may improve service performance in a number of ways: wear, stress-corrosion, fatigue and corrosion-fatigue resistance. It also involves a bending moment that can be used either to form or to straighten components. Plastic deformation, apart from cold-working the surface, may effect changes in the microstructure. These changes may be either beneficial or harmful.

This paper shows how x-ray diffractometry can be used to obtain valuable information on the changes in residual stress and structure that are brought about by the shot peening of steel surfaces. X-ray diffractometry is particularly useful because it can allow the measurement of variations of residual stress across surfaces and the changes in phase composition within the shot peened layer.

EXPERIMENTAL

Residual stress measurements reported in this paper were all made using a standard two-exposure, X-ray diffractometer method (Hilley, 1971; Kirk. 1971). The area of irradiation was restricted to appropriate dimensions by using two pairs of divergence slits at right angles to each other. The method involved the use of re-focusing and statistical control of each measurement precision (Kirk and Caulfield, 1977). Retained austenite measurements were made using a direct-comparison x-ray diffractometer technique. Sub-surface examinations were made after removal of surface layers using a chemical polishing technique.

Fatigue and corrosion-fatigue tests were carried out on the as-polished and selectively peened specimens shown in Fig.1. Alternating stresses were applied by a Mand servo-hydraulic machine. A cell was used to surround specimens with fluid pumped peristaltically from a heated reservoir.

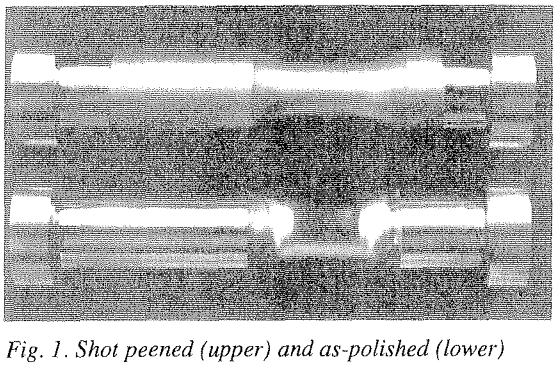

Fig. 1. Shot peened (upper) and as-polished (lower) specimens.

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Each of the austenitic stainless steel specimens of the type shown had a gauge length diameter of 12.75 mm. The specimens were either selectively peened as shown or had the gauge length and fillets polished mechanically to a 600-grade of finish. Shot peening was to an Almen intensity (A2) of 0.25 mm using S280 shot and an air pressure of 140 kPa. Glass bead peening was applied after shot peening.

SURFACE RESIDUAL STRESS DISTRIBUTIONS

Engineering components may be either shot peened overall or may have the peening confined to certain areas of the component. Overall shot peening will give a compressive residual stress over the whole surface although there will be some variation in the magnitude of the compressive stress. The uniformity of surface residual stress distribution will then depend on variations in the material and on the geometry of the component together with variations in the peening process.

A standard commercial practice is to mask off areas that are not to be shot peened using protective adhesive tapes. This results in a clearly-defined boundary between peened and unpeened areas of the component. Masking was used for the specimens shown in Fig. 1. Figure 2 shows the results of surface residual stress measurements made on a line across steel plates, 120 mm wide and 3 mm thick, with and without the use of masking. The steel had a composition of 0.1%C, 0.7%Mn, 1.0%Mo and 2.25%Cr. One plate had masking to restrict peening to a central band 30 mm wide. The other plate had no masking but the peening head was made to traverse the central area with the same motion as for the masked plate. In both cases, the direction of residual stress measurement was parallel to the plate surface and perpendicular to the straight edge of the masking tape. For the plate with the masked boundary, there is a sharp transition between compressive residual stress over the peened area to tensile residual stress underneath the masking tape.

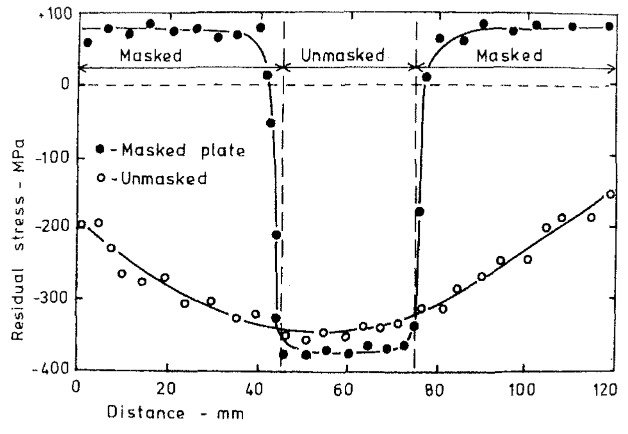

Fig. 2. Effect of masking on residual stress distribution.

This transition occurs in a distance of about 2 mm. The results for the unmasked plate show that there is compressive residual stress over the whole of the plate surface. The greater level of compressive stress in the central region compared to the plate edge regions is due to the relatively high peening intensity in that area. The advantage of masking is that it protects some areas from the roughening effect of shot peening. If masking is essential then it would be possible to reduce the severity of the stress gradient by using multilayer masking tape with 'steps' of decreasing thickness leading down to the fully-peened area.

Strip No.	Position			Mean
	Centre	Midway	Edge	
1	- 428	- 378	- 367	- 391
2	- 489.	- 578	- 350	- 472
3	- 488	- 350	- 490	- 443

Figures are for residual stress in MPa.

Table 1. Surface residual stresses at different positions on Almen strips

Although the level of surface compressive residual stress is generally uniform for overall peened flat surfaces surprising variations are sometimes seen. Such a variation is illustrated by the measurements given in Table 1. These results are of stress measured at three positions along the major axis of the peened face of Almen strips. All three strips were peened to the same Almen Arc Height at the same time. The measured residual stresses were corrected for the relaxation of stress, caused by bending of the strip on release from its clamping block, by means of Timoshenko's plate formula.

MICROSTRUCTURAL CHANGES

The most important microstructural changes introduced by shot peening are work hardening and phase transformations. Two important cases can be identified that illustrate these effects. One is the case of carburised steels in which retained austenite is a characteristic feature of the carburised layer. The other is the case of steels, such as the 18/8 stainless steels, that are essentially austenitic prior to shot peening. In both cases, the austenite is prone to transformation to martensite by cold working.

The retained austenite in the surface layer of carburised steels is readily transformed by shot peening. Retained austenite is a characteristic feature of the surface layer because the high carbon content reduces the Mf temperature often to well below room temperature. If some of the retained austenite can be transformed to martensite, it confers a number of advantages. Dimensional stability is improved, the level of residual compressive stress near to the surface is increased and wear rates are generally reduced. The dramatic improvement in surface and sub-surface residual stress pattern that is possible is illustrated by the results given in Fig. 3 (see page six).

The as-carburised SAE 4320 steel transforms on cooling to give a tensile residual stress of 60 MPa at the extreme surface giving way gradually to compressive stress below the surface. The retained austenite content of 22% at the surface also falls progressively with distance from the surface. A carburised case depth of 2.0 mm had been applied to the steel. Shot peening has reduced the surface retained austenite content to 3% by transformation to martensite. The volume expansion that accompanies this transformation has induced a compressive surface residual stress of - 410 MPa. Even larger values of compressive stress are present just below the extreme surface reaching a maximum value of - 560 MPa.

Austenitic stainless steels are useful not only because of their intrinsic corrosion resistance but also because they are non-magnetic. Austenite can, however, be transformed in these steels by plastic deformation at temperatures below a certain value. Shot peening is therefore liable to produce not only a work-hardened, compressively-stressed surface but also a

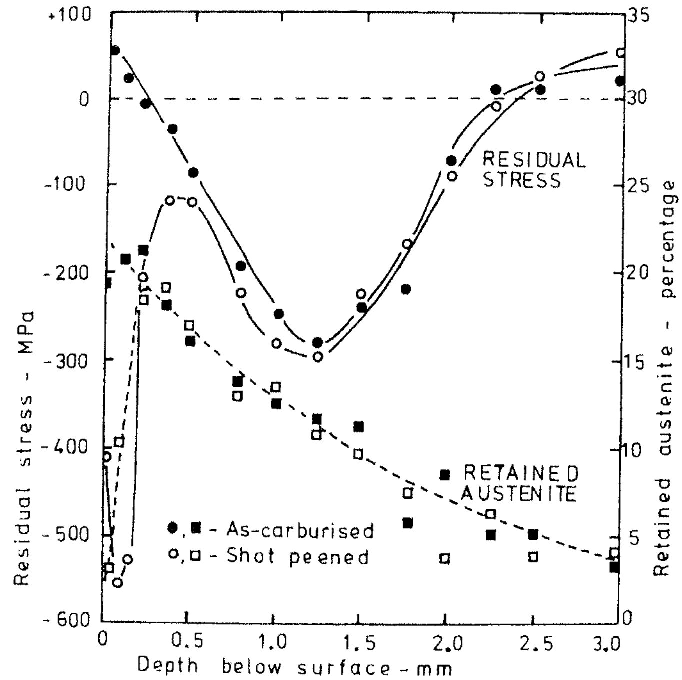

Fig. 3. Residual stress and retained austenite distributions in as-carburised and shot peened carburised steel.

two-phase structure. A two-phase austenite-martensite surface corrodes much more readily than an austenitic surface and is magnetic. The intrinsic advantages of shot peening can therefore be reduced or even lost by this transformation.

Composition plays an important part in the susceptibility of the 18/8 type steels to mechanically-induced transformation. The results given in Table 2 are for surface martensite present in two typical steels after identical peening treatments have been applied. No martensite was detected in either steel before peening. Nishiyama (1978) has given a description of the transformation mechanisms involved and of the effects of composition.

Composition	Martensite - %
18.0%Cr, 8.0%Ni	less than 1
17.9%Cr, 11.3%Ni, 3.3%Mo, 1.5%Mn	30.6

Table 2. Martensite contents in shot peened stainless steels

CORROSION FATIGUE

The general advantages of shot peening in improving stress-corrosion, fatigue and corrosion fatigue properties are well known. It is not so generally publicised that shot peening can be harmful to both fatigue and corrosion fatigue properties if high cyclic stresses are applied. The results described in this section relate to preliminary studies aimed at establishing the conditions under which the compressive residual stress imparted by peening is reduced, or removed, during fatigue cycling.

Shot peened and as-polished test specimens of the type shown in Fig. 1 were subjected to different stress ranges alternating above and below zero stress. Tests were carried out on 18/8 stainless steel in air, in distilled water and in a solution of 3%NaCl in distilled water. The tests in distilled water and in the sodium chloride solution were carried out at 37°C in order to simulate cooling-pipe conditions. Residual stress measurements were made on the gauge length in an axial direction for each peened specimen. The results are given in Table 3. The residual stress measurements on the untested specimens show that shot

Stress Range - MPa	Test Medium	Surface Treatment	Cycles to Failure	Residual Stress - MPa
321	Air	SP*	-	-
		AP*	1,080	-
	H_2O	SP	2,760	+90
		AP	7,700	-
	3%NaCl	SP	2,910	+77
		AP	4,210	-
270	Air	SP	3,120	+70
		AP	9,150	-
	H_2O	SP	18,200	+33
		AP	35,370	-
	3%NaCl	SP	19,980	-70
		AP	9,770	-
247	Air	SP	13,170	+62
		AP	25,250	-
	H_2O	SP	68,960	+37
		AP	61,020	-
	3%NaCl	SP	21,640	-70
		AP	33,670	-
233	Air	SP	108,390	-57
		AP	147,090	-
	H_2O	SP	347,570**	-53
		AP	65,250	-
	3%NaCl	SP	328,730**	-76
		AP	44,620	-
Untested	-	SP	-	-246
	-	AP	-	-140

* Shot peened and As-polished respectively.
** Test discontinued.

Table 3. Residual Stress and Fatigue Test Results for 18/8 Stainless Steel Specimens

peening has imparted a large surface compressive stress. The fine polish given to the as-polished specimens also imparts a substantial level of surface compressive stress. In the latter case, however, the depth of the compressed layer would be much less than that for the shot peened specimen. It is reasonable to use as-polished specimens for comparison since this would be the alternative finish applied to components in critically-stressed areas. The machined shank of the test specimen gave a tensile surface residual stress of +28MPa. This tensile stress is due to the relatively coarse method of metal removal associated with most machining operations.

The results of the residual stress measurements show that a large proportion of the compressive surface stress imparted by shot peening is removed by fatigue cycling. At the higher stress ranges the measurements indicate that a tensile residual stress is introduced. The removal of stress is associated with strain-induced relief which is accelerated by the specimen heating that occurs during cycling. Selective plastic deformation of the shot peened surface during compression cycles may account for the tensile surface stress values.

The fatigue test results show that shot peened specimens have shorter lives than as-polished specimens in all three test media for the two highest stress ranges. The reverse is true for the lowest stress range. Lives in air are generally shorter than those in the two liquid media. This is because of the specimen cooling provided by the liquids even at 37°C. The as-polished specimen tested in air at the lowest stress range is an exception. At this stress the heating effect caused by cycling is much less and is over-ridden by induced corrosion. The 3%NaCl solution has accelerated failure relative to the failure rate in distilled water. Fatigue results are notoriously susceptible to scatter. The limited number of tests reported here, although interesting in themselves, are only the basis of a much more extensive investigation.

CONCLUSIONS

Shot peening is established as a method capable of improving the service performance of components. A general understanding of the surface changes induced by peening is necessary if such improvement is to be realised. X-ray diffractometer studies can make an important contribution to this understanding.

The measurements on masked steel plates showed that peening can induce tensile surface residual stresses adjacent to the peened area. If this tensile stress promotes premature failure then peening can be considered to be harmful. It can be assumed that there will be some variation in surface compressive residual stress for overall peened components and within peened areas. The magnitude of this variation can be determined using x-ray diffractometry.

Transformation of austenite by shot peening steels can be either harmful or beneficial. Transformation in a steel intended to be fully austenitic will generally be harmful to properties. Transformation of retained austenite in carburised steels can effect dramatic improvements in residual stress distributions. This potential for improvement should be used in conjunction with correct control of the carburising process.

Improvements in fatigue and corrosion fatigue properties due to shot peening can be expected when relatively low cyclic stresses are involved. These improvements are related to the particular environment involved. Shot peening may reduce fatigue and corrosion fatigue properties at relatively high cyclic stresses.

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