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RESIDUAL STRESSES INDUCED BY PEENING AUSTENITIC DUCTILE CAST-IRON

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ABSTRACT

Beneficial compressive surface residual stresses have been induced by peening an austenitic ductile cast iron (20%Ni, 2%Cr, 0.15%Nb weldable-grade). Stress levels of -433MPa and -280MPA were found for shot-peened and needle-peened conditions respectively. Surface compressive residual stresses of that magnitude will impart substantial improvements to the service performance of castings. Stress measurements were made using a standard two-exposure X-ray diffractometer technique. Young's modulus and Poisson's ratio measurements, needed to convert measured strains into stresses, were made using tensile-loaded strain-gauged specimens. Isochronal annealing experiments showed that a large proportion of the induced compressive residual stress could be retained up to 450°C. It has been concluded that substantial practical benefits can be gained by peening austenitic ductile irons. Needle peening has particular appeal since it could be used for selective peening of large castings in situ.

KEY WORDS

Ductile iron, stress, corrosion, hardening, annealing, peening.

INTRODUCTION

Austenitic irons are a family of high-nickel cast irons[1,2] with sufficient nickel and other stabilising elements to ensure an austenitic matrix. The graphite content may be present in either flake or nodular form with nodular irons possessing substantially greater ductility. Typical microstructures of the flake and nodular forms are given in Figs. 1 and 2 respectively. 'Austenitic ductile cast iron' (A.D.C.I.) is therefore characterised by nodular graphite in an austenitic matrix. Compared to ordinary cast irons A.D.C.I's exhibit excellent corrosion, wear and erosion resistance together with good high temperature properties and are potentially non-magnetic. They are, however, relatively expensive and their use is confined to operations in severe environmental conditions. It is, therefore, important that the service properties of A.D.C.I. castings are optimised with respect to such factors as fatigue, stress-corrosion and corrosion-fatigue.

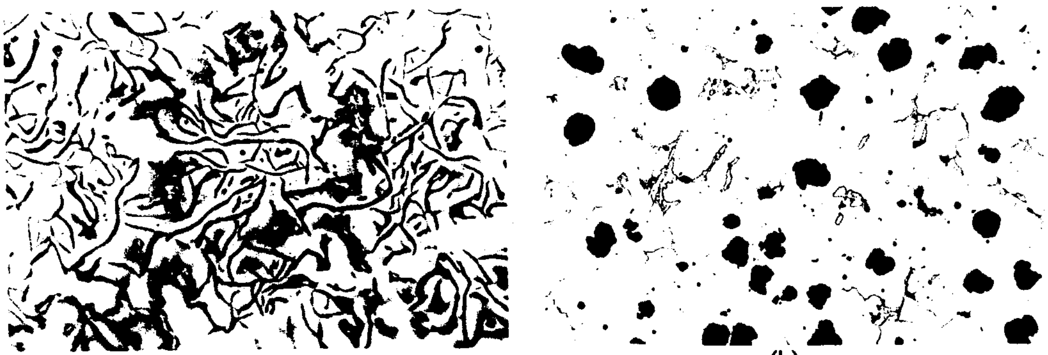
(a) (b)

Fig.1 Typical microstructures of cast irons showing (a) flake graphite in a matrix of cored austenite and cell-boundary carbides and (b) austenitic ductile iron showing nodular graphite in a matrix of austenite and cell-boundary carbides. Both x100, acidified picral etchant.

Castings are particularly prone to the development of residual stresses[3] and stress-relieving treatments[4] are often employed to minimise harmful tensile surface residual stresses. An alternative is to deliberately induce beneficial surface compressive residual stresses. Mechanical surface treatments, such as shot peening, are routinely employed to induce compressive surface residual stresses into steel components that are subject to severe service conditions. These processes are, however, much less commonly applied to iron castings. The efficacy of shot peening on high nickel cast irons is not recorded. Needle peening is a variant of shot peening that has been the subject of recent research[5]. Captive needles accelerated by compressed air can be directed to specific areas of a component. The needles are commercially-available with three types of impacting area – point, chisel and flat, see Fig.2. One attraction of the flat-ended needles is that they should impart a more useful indentation for sensitive materials than the spheres of shot peening. This is particularly relevant with graphitic irons since shot particles can readily be imbedded in surface graphite particles.

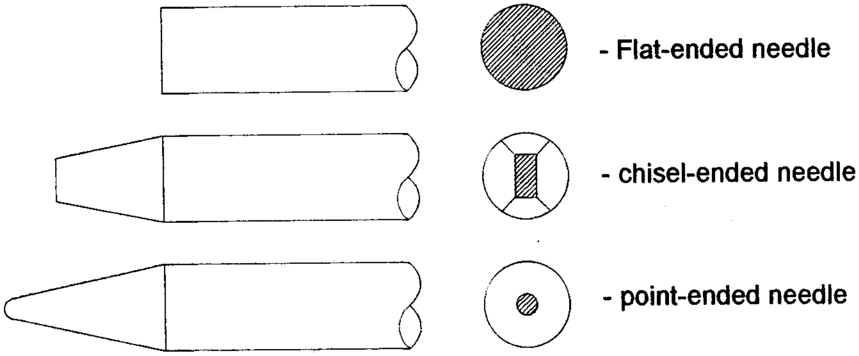

Fig.2 Commercial needle point geometries.

Measurement of residual stresses is well-established with X-ray diffraction[6] being preferred for surface stress measurement and hole-drilling for through stresses. There is, however, no published work on the measurement of residual stresses in high nickel cast irons.

This research has looked at the application of peening treatments to the most commonly-used grade of A.D.C.I. (Ni-Resist™ S2W). This is with a view to (a) establishing the levels of surface residual stresses that can be induced and (b) to giving an indication of the value of peening to the developing technology of high nickel cast irons.

EXPERIMENTAL METHODS

Material and Sample Preparation

Several sample blocks were sand cast in S2W austenitic ductile iron to the "Y-type" or "keel block" pattern incorporated in BS 3468. The chemical composition was determined by X-ray fluorescence and atomic absorption analysis. Test specimens for peening experiments, nominally 75 x 25 x 5mm, were cut from the blocks using an elastic slitting wheel. Larger slices, nominally 210 x 50 x 5mm, were cut for conversion into tensile test specimens - to be used for elastic moduli determination. Round-section tensile test bars were machined for determination of strength parameters. All specimens were radiographed to confirm the absence of shrinkage porosity.

Determination of Mechanical Properties

Bulk elastic constant values for Young's modulus, E, and Poisson's ratio, μ, were determined using duplicate flat rectangular tensile specimens having 90° strain gauge rosettes cemented to the centre of the gauge length. Digital outputs of longitudinal and transverse strain and corresponding applied stresses were plotted to give appropriate slope values. Strength properties, yield strength and U.T.S., were determined using round bar specimens.

Shot Peening

Shot peening experiments were carried out using Coventry University's highly instrumented peening facility. S170 grade cast steel shot was used throughout with the flow rate controlled to 1.0kg/minute by a magnetic valve device. A single suction-fed peening gun was used to fire the mixture of shot and cleaned, dried, air with closely controlled and monitored gun-head air pressures. Flat rectangular specimens were mounted, at 90° to the shot stream, using specified standoff distances. An oscillating jig imposed sideways movement to each specimen in order to give uniform peening coverage over a larger area than the cross-section of the shot stream. Both sides of each specimen were given equal peening treatments so that any bending distortion would be minimised.

Needle Peening

Needle peening experiments were carried out at Coventry University using two air-driven guns, one equipped with 2mm diameter flat-ended steel needles and the other with point-ended steel needles. Both guns used needles arranged in a rectangular array, to give a peening area of approximately 35mm x 10mm, and were held on the vertical column of a drill stand. Samples were bolted to the X/Y traversing table of the drill stand and raised to give the recommended zero clearance between static needles and the sample surface. Timed passes under an active gun were applied using the X-traverse of the table.

Peening Intensity Measurements

Measurements of peening intensity imposed on Almen strips were made using a direct-reading Almen Gauge. The measured deflection of the standard steel Almen strips is the industry-wide control procedure adopted for shot peening. Needle peening intensity curves were not, however, available and had to be produced.

Residual Stress Measurements

Surface residual stress measurements were made at Coventry University using a standard two-exposure diffractometer technique. This involved chromium K_α radiation scanning the 220-austenite matrix peak at approximately $130^\circ 2\theta$ to give computer-analysed peak positions for sample orientations of 0 and 30°. Measured elastic strains were converted into stresses using the bulk modulus values previously determined for the A.D.C.I. tensile specimens. The precision of stress measurement was determined using the method of Kirk and Caulfield[7].

EXPERIMENTS and RESULTS

Material Properties

The analysis of chilled coin samples, taken from the A.D.C.I. melt used to produce the test material, gave the following composition (%): C, 2.46; Ni, 20.4; Si, 2.10; Cr, 1.73; Mn, 1.00; Cu, 0.03; S, <0.01; Mg, 0.06; P, 0.02; Nb, 0.15. These values confirmed that the material satisfied the chemical analysis requirements of BS3468-1986 Specification for the S2W grade of spheroidal graphite austenitic cast iron (and to DIN.1694-1981 for grade GGG.NiCrNb 20.2). Tensile and macro-hardness tests carried out for the as-cast condition gave U.T.S. = 443 MPa, 0.2% P.S. = 240 MPa, % elongation = 14 and hardness = 158/161HB. The mean elastic constant values were estimated to be 132 GPa and 0.243 for E and ν respectively. Fig.3 shows a typical set of stress/strain data points for an as-cast specimen. Linearity is reasonable up to applied stresses of about 100 MPa. At higher stresses considerable deviation from linearity occurs.

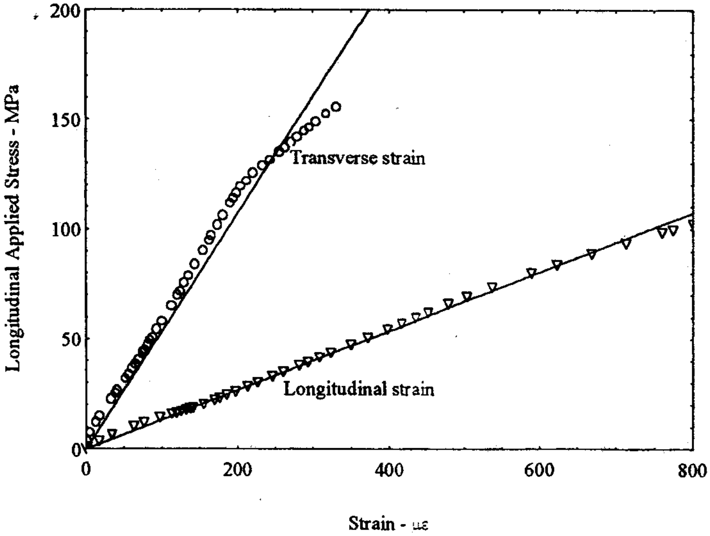

Fig.3 Data for elastic moduli determination for as-cast austenitic ductile cast iron.

Needle Peening Intensity

The effects of gun air pressure, needle geometry and Almen strip type on peening intensity/time curves were investigated. Fig.4 is a composite diagram showing the several effects. Spline-fitted curves only are plotted because of the large number of data points involved. In view of the overall low intensity imparted by needle peening the thinnest Almen strips, N, were appropriate. One curve was generated, for comparison purposes, using A strips. Several features can be observed. The intermediate gun air pressure of 6 bar gives the greatest maximum intensity. Point-ended needles give a greater intensity increase than flat-ended needles but a complete curve could not be generated. This was because of the high point wear rate being experienced. The indicated intensity for A strips is higher than would be expected when compared with the curve obtained using N strips at the same air pressure.

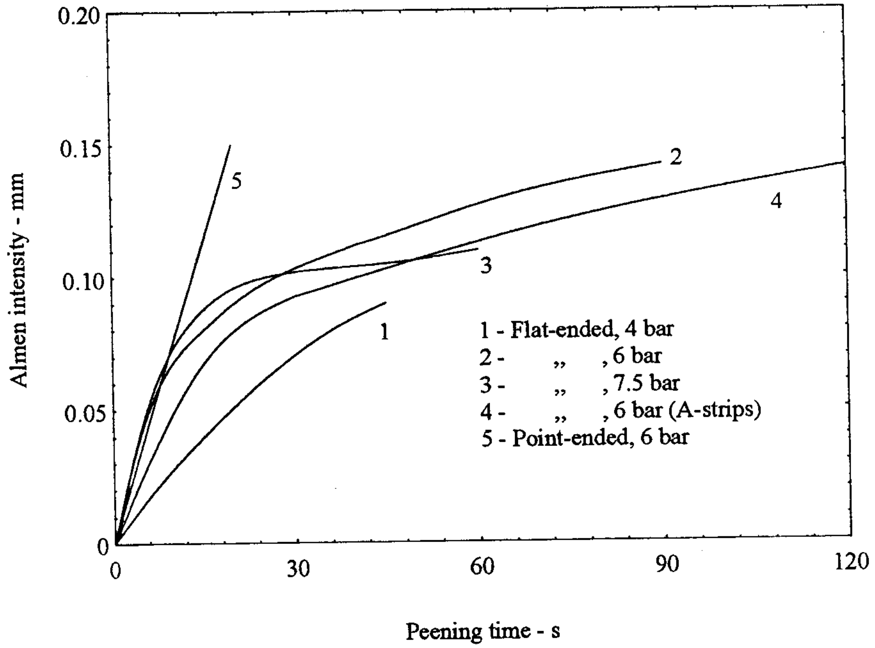

Fig.4 Needle peening intensity curves showing effects of air pressure and needle geometry

Residual Stresses induced by Peening

Experiments were carried out in order to examine the level of surface residual stress induced by both needle peening and shot peening.

One rectangular A.D.C.I. specimen was needle peened for 15s over the whole of one major face using flat-ended needles and 4.0 bar pressure. The variability of the stress measurement technique itself was examined by making eight successive measurements without moving the specimen on the X-ray goniometer table. A mean of –311MPa with a standard deviation of 44.3MPa was obtained. This large standard deviation is to be expected considering the very broad nature of the diffractometer peaks and the relatively-low diffractometer angle (about 129°2θ). Measurements taken at eight different locations on the same needle-peened face gave a mean residual stress of –280 MPa with a standard deviation of 40.5MPa.

Eight rectangular bar specimens were shot peened individually on both major faces for 30s using S170 shot at 1.0kg/minute, 3.0 bar air pressure and at 335mm nozzle-to-sample distance. Longitudinal surface residual stress levels were measured at the centre of both major faces for each of the eight specimens. The sixteen values had a mean of -433MPa with a standard deviation of 111MPa. This large standard deviation includes the influence of inter-specimen variation.

Stress-relief Annealing.

Eleven rectangular shot peened specimens, peened in precisely the same way as for the previous experiment, were subjected to isochronal stress-relieving heat treatments of 30 minutes duration. The specimens were cut from larger pieces for which surface residual stress values had been determined before heat treatment. Longitudinal surface residual stress levels were measured at the centre of both major faces for each of the eleven specimens after heat treatment. Fig.5 shows the change in measured surface residual stress with temperature. The measurements show that a large proportion of the induced compressive residual stress is retained up to 450°C.

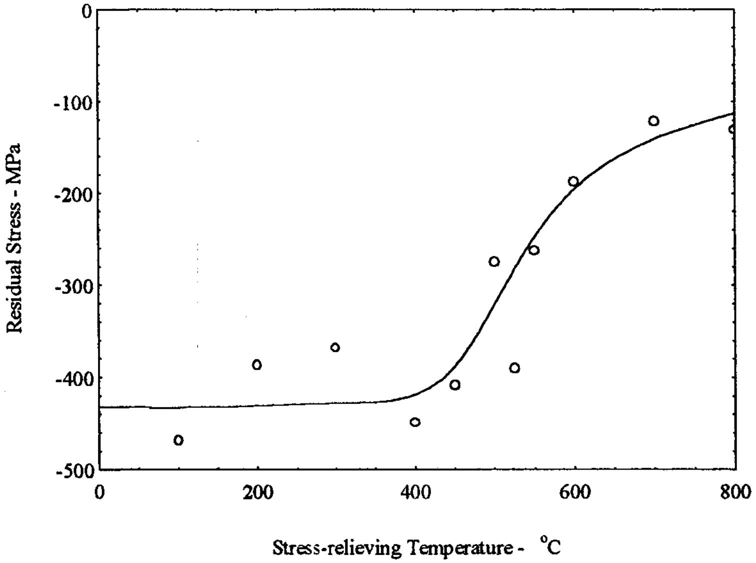

Fig.5 Isochronal annealing curve for shot-peened austenitic ductile cast iron

Surface Hardening induced by Peening

Microhardness surveys were carried out on peened A.D.C.I. specimens in order to investigate the difference between surface hardening induced by shot peening with that induced by needle peening and the effect of annealing on the hardening induced by shot peening.

Fig.6 contains the microhardness surveys carried out for shot-peened and needle-peened specimens. There is a large amount of scatter of the data but that is to be expected given the heterogeneous nature of the cast material. The corresponding profiles indicate that shot peening gives a greater maximum surface hardening but hardens to a lesser depth than does needle peening with flat-ended needles.

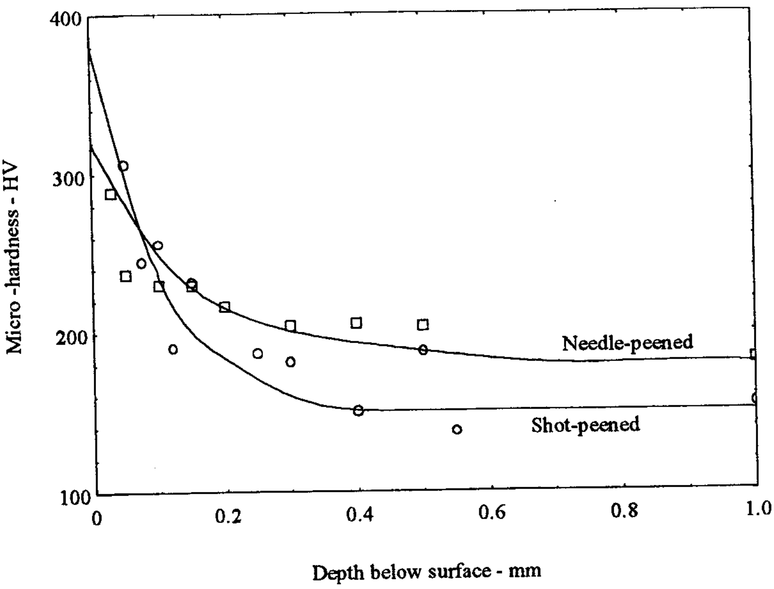

Fig.6 Comparison of surface hardening induced by shot- and needle-peening.

Fig.7 shows measurements made to compare the hardening profile induced using pointed needles as compared with that induced using flat-ended needles. The pointed needles gave a greater degree and depth of hardening than did the flat-ended needles.

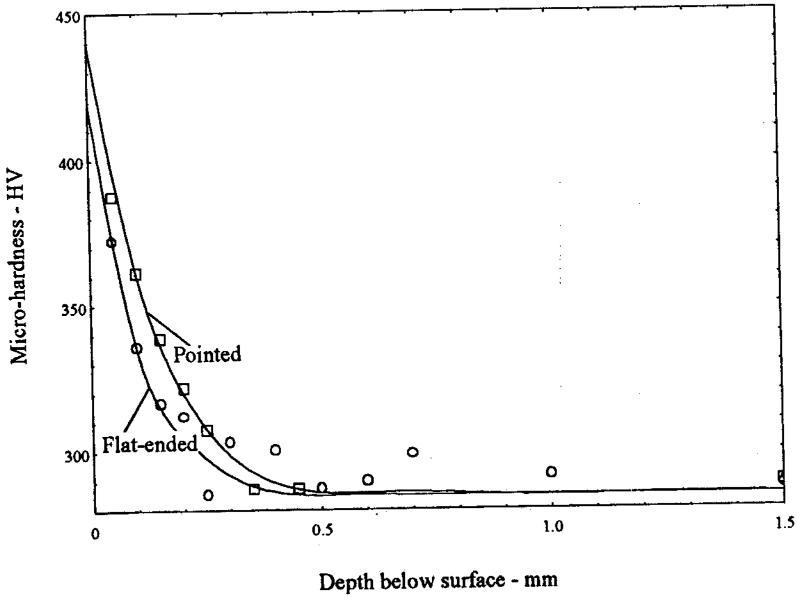

Fig.7 Effect of needle point geometry on induced surface hardening profiles.

The effect of annealing on the hardness profiles of shot-peened specimens is illustrated in Fig.8. Spline-fitted profiles only are included because of the large number of scattered data points involved. A significant amount of hardening is retained for material annealed at 500^0C but very little remains after annealing at 800°C. This is consistent with the previous observation that a significant amount of residual stress is retained at 500°C but that at 800°C most of the residual stress has been removed.

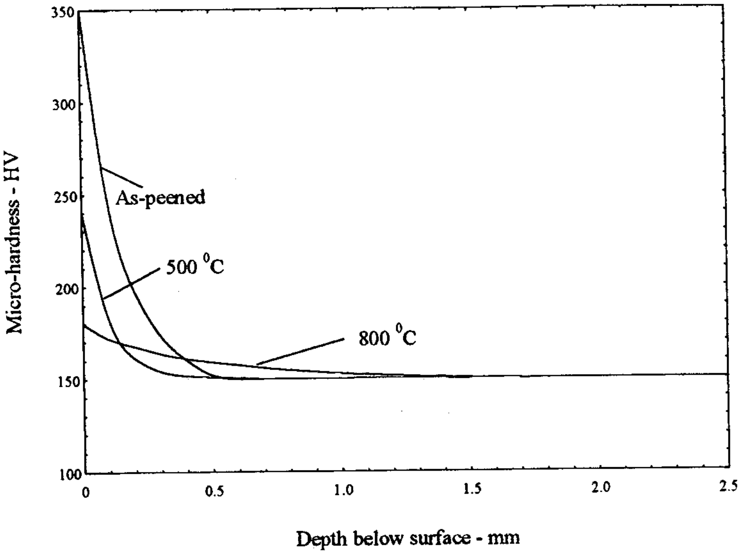

Fig.8 Effect of annealing on hardness of shot-peened austenitic ductile cast iron.

DISCUSSION

Mechanical Testing

The values used for Young's modulus (E) and Poisson's ratio (v) in residual stress calculations are of critical importance. This is because the reported stress magnitude, but not its sign, is directly proportional to the factor E/(1 + v). That factor is, in fact, common to all methods of residual stress analysis since they are universally based on converting measured strains into stresses. The behaviour observed in this research showed that linear stress/strain behaviour in tension only occurs up to about 100MPa which is well below the 0.2% proof stress value of 240MPa. Such deviation from linearity is well established from the work of Gilbert[8] and others. The measured values of 132GPa and 0.243 for E and v respectively were obtained in tension whereas it is to be expected that the values in compression will be different. The difference is known to be substantial for graphitic cast irons but would be much smaller for nodular cast irons.

Needle Peening Intensity

Needle peening is in its infancy as a commercial method of inducing beneficial surface compressive residual stresses. Shot peening, on the other hand, is very well established and specified treatments are centred on required Almen intensity values obtained during the shot peening. The Almen intensities obtainable with needle peening are very much lower than those readily achievable with shot peening. This is not surprising given that the contact area of each needle is large compared with that for spherical steel shot and also the needle velocity is very much lower than that for impacting shot. An Almen intensity of 0.1mm was, however, obtainable in less than sixty seconds with a range of air-gun pressures.

Residual Stresses induced by Peening

The development of a compressively-stressed surface layer is the *raison d'être* for applying peening to critically-stressed components. This research has shown that a compressive surface stress level of –280MPa can be achieved for austenitic ductile iron using needle peening as compared with –433MPa using shot peening. These levels are higher than the 0.2% proof stress value of 240MPa. This apparent anomaly is due to the fact that the peened surface has been cold-worked to a very considerable extent during peening. Hence the corresponding yield strength at the surface will then be even higher than the U.T.S. value of 443MPa that occurs after approximately 10% of tensile elongation. Although the level of compressive stress induced by shot peening is much higher than by needle peening there are other factors to consider. The smooth surface induced by needle peening is less likely to contain the potential stress-raising dimples that are produced by shot peening. Needle peening has practical advantages in specific situations. It can be applied locally without the need for expensive, labour-intensive, masking and without a large enclosure and shot re-cycling and feed facilities. The needles themselves could be made of austenitic steel hence obviating the danger of ferritic pickup from normal steel shot. Both types of peening treatment are, however, capable of inducing levels of surface compressive residual stress that would be of substantial benefit to service performance.

Stress Relief Annealing

Austenitic ductile iron castings are often used at elevated temperatures. It is therefore important to know at what temperature a component could be used without the danger of reducing substantially the level of any protective compressive residual stress. This work has shown that working temperatures of 400°C could be envisaged without significant stress-relief of a peened casting. The measurements showed that low levels of compressive surface stress are retained in peened components even after treatment at 800°C. This is a more favourable situation than that of having low levels of tensile surface stress remaining after stress-relief annealing of unpeened castings.

4.5 Surface Hardening induced by Peening

Both needle- and shot-peening have induced a substantial level of surface hardening but only to a depth of about 0.4mm. This is to be expected as the matrix material is face-centred cubic and therefore work hardens very rapidly. The large scatter of measurements is due to the three-dimensional distribution of graphite nodules and carbides. These phases would induce lower and higher values of hardness respectively if present just below an individual indentation. Deeper levels of hardening could be induced if pointed needles were used. In this research standard commercial de-scaling needles were used. For commercial peening of hard materials with pointed needles it would be necessary to develop and employ hard-pointed needles.

CONCLUSIONS

- Values for elastic moduli of 132GPa and 0.243 for Young's modulus and Poisson's ratio respectively have been determined for the austenitic ductile iron used in this research. These values have allowed surface strains, measured using X-ray diffractometry, to be converted into residual stress levels.

- Surface compressive residual stress levels of some –430MPa and –280MPa have been induced in austenitic ductile iron samples by shot-peening and needle-peening respectively.
- A large proportion of the surface residual compressive stress induced by peening can be retained at temperatures up to 450°C.
- Needle peening is believed to offer important commercial advantages for local surface treatment at low costs.

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