Influence of Laser Surface Hardening on Microstructure and Mechanical Properties of Austemperd Ductile Iron

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ABSTRACT

Ductile irons are widely used in various industries, particularly for automobile applications like brake cylinders, camshafts, connecting rods, gears, pistons and yokes. Traditionally surface heat treatments like induction hardening and in recently electron beam and laser hardening are being used to improve wear resistance. In this work, laser surface hardening austempered ductile iron (ADI) was carried out. Hardening was performed with a 400W continuous wave fibre laser with the objective to investigate effect of single pass and multiple pass scans on the microstructure and case depth. The process parameters such as power density, scanning speed, scan length and beam overlap was optimized. The effect of surface condition on hardness profile and case depth were determined. The surface hardened specimens were characterized by metallography, hardness traverse, pin on disc wear testing, XRD analysis and residual stress analysis. The effect of laser surface hardening on the impact toughness was also determined by using Charpy Impact test. Transformation hardening resulted into shallow depth and limited rise in case hardness, whereas melting cases were deeper and harder. The melted cases of ADI iron showed mainly martensite, cementite and retained austenite with depth of 0.3 and 0.7 mm with hardness between 850 and 1000 HV. Optimum hardness and case depths were found in case of graphite coated irons, compared to as-cast and as-machined surfaces. The cases were induced with compressive residual stresses. Overall wear resistance was improved due to molten case; however the impact toughness drastically reduced compared to base metal.

Keywords*: Laser Surface Hardening, Austempered Ductile Iron, Microstructure, Mechanical Properties.*

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1. INTRODUCTION

The finding of Ductile Iron in 1948 opened a new era to the cast iron family. The combination of the castability of gray iron and the toughness of steel gave Ductile Iron a wide recognition as an cost-effective choice for high performance complex ferrous parts. Seventy years of research and development have led to a material whose properties can be customized for applications requiring high toughness, corrosion resistance or high tensile strength [1]. In 1948, it was found that, addition of Cerium or Magnesium in molten liquid of hypoeutectic cast iron liquid gives spheroids of graphite after solidification, because of which it has good toughness [2,3]. Ductile Iron has undergone exceptional growth to become, now, the only ferrous casting material with a positive growth rate [1]. Its applications range from pipes and fittings, automobile components, agricultural to road and transport industry [4].

Austempered ductile iron (ADI) is a subclass of ductile irons that have undergone a particular, isothermal heat treatment called austempering. Contrasting conventional "as-cast" irons, its properties are achieved by heat treatment, and not by specific alloying addition. Therefore the lone requirement for a good ADI is a quality ductile iron [5]. ADI offers superior blend of properties as it can be cast like any other member of the ductile iron family. It offers all production advantages of usual ductile iron castings. Subsequently, it is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminium and many cast and forged steels [6]. The properties of ADI depend on the matrix, the nodule count and nodule shape. The matrix in conventional ductile iron is guarded by a mixture of pearlite and ferrite. The properties of ADI are due to its characteristic matrix of acicular ferrite and carbon-stabilized austenite, called ausferrite. Ausferrite and bainite are not identical, bainite mainly contains acicular structure of austenite, ferrite and €-carbides while Ausferrite mainly enclose acicular ferrite and high-carbon austenite [7].

ADI is widely used in several industrial applications due to its fine mechanical and tribological properties and reasonable cost. Strength, wear and fatigue resistance can be enhanced by means of various conventional surface heat treatments like carburizing, nitriding, flame and induction hardening and more modern technologies like

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electron beam and laser hardening. Nevertheless, the laser surface hardening (LSH) is being noticed for a number of reasons. LSH has advantages such as low distortion due to high power density, process flexibility, accuracy, self quenching and limited grain growth. In laser surface hardening a focused laser beam is impinged on the material, which, heats up a thin layer depending on its power, physical properties of the material, optical and kinematic conditions. The heated thin layer of surface does not require additional cooling since the bulk of the material serves as a sink [8.9]. LSH of ADI has received not as much of attention as the laser processing of ductile cast irons, even if the enhancement of ADI properties, using $CO_2$and Nd-YAG laser sources, has been inspected by quite a few authors. Considerable difference between laser surface melting and hardening was reported by Roy and Manna [10]. Putatunda et al. [11] performed LSH on ADI and found improved wear resistance because of martensitic transformation in laser melted case. Laser meted case microhardness was found to be more than 1000Hv along with compressive residual stresses. Similar experiment was performed by C. Soriano [12] to investigate the effect of laser surface hardening on the microstructure, hardness and residual stresses and observed coarse martensite with retained austenite structure in the treated area, ensuing a wear resistant effective layer with microhardness to the tune of 800 HV.

The objective of present work is to study the effect of laser surface hardening, using a fiber laser, on the microstructure and related mechanical properties such as hardness, wear resistance and impact toughness of ADI along with effect of surface condition and local tempering in multiple pass laser surface hardening on hardness profiles.

2. EXPERIMENTAL DETAILS

Chemical composition of the austempered ductile iron (ADI) used in this investigation is shown in table 1. The material was in the form of Plate 305 mm long 100 mm wide and 16 mm thick. This material was cut into several pieces of 40 mm × 50 mm. Before laser hardening, milling was carried out on the surfaces of these specimens to decrease reflectivity and to improve absorption of laser beam. The measured roughness was about 4.1 µm. Typical microstructure of ADI is shown in Fig.1(a and b) shows graphite nodules in ausferrite matrix, which consists of acicular ferrite and carbon stabilized austenite. Nodule count and percentage Nodularity were 123 and 92% respectively, measured by image analysis. The diameters of the graphite nodules ranged between 10 and 20 µm. The average microhardness of the material was 359 Hv(0.3).

Continuous wave fiber laser of 1070 nm wavelength , 5 mm beam size and maximum power 400 W was used to harden the specimen's surface. The beam mode used was near Gaussian. The distance between the nozzle and the samples was kept constant at 30 mm. The Collimator of laser beam is held stationary and feed is given to the workpiece with the help of CNC operated X-Y table. No shielding gas is used during LSH and schematic is shown in Fig.2. After laser hardening, transverse cross-sections were obtained from the processed samples which were examined for microstructure and microhardness. Optical microscopy was used for this investigation. The etching solution (Nital) was 5 percentage HNO_3 in ethyl alcohol. Microhardness measurements across the laser-hardened zone were carried out in longitudinal as well as radial directions using a Futuretech FM-700Vickers microhardness tester with an applied load of 300 g for dwell time 10 sec.

Table-1: Composition of Austempered Ductile Iron (ADI)

C	Si	Mn	S	P	Ni	Mo	Cu	Fe
3.425	1.895	0.312	0.014	0.020	0.018	0.019	0.015	93.990

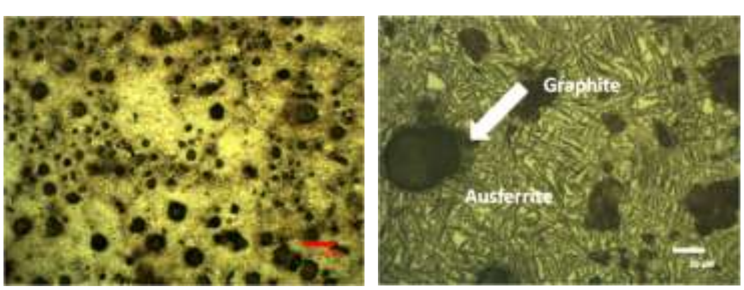

Fig-1: Microstructures of untreated ADI (etched with 3% nital)

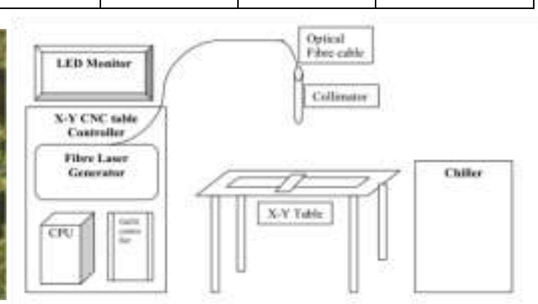

Fig-2: Schematic diagram of LSH by fibre laser.

Table-2: Process parameters used during laser surface hardening

Laser make	SPI 400W	**Laser powers used**	340W, 360W. 380W
Laser type	Fibre laser	**Scanning speeds used**	1mm/s, 2mm/s, 3mm/s
Max. output power	400W	**Scan Lengths used**	20mm,30mm,40mm
Laser wavelength	1070µm	**Beam overlap used**	50%,60%

Charpy Impact test of the material was carried out to find out susceptibility of materials for brittle failures. Impact test specimens of standard size (Charpy) without notch were machined and then laser hardening of one surface was carried out. These samples were then subjected to impact test on machine and impact energy values in Joule were obtained on electronic indicator. Fractured Charpy impact samples were examined under Scanning Electron Micrograph (SEM) to analyze nature of failure. Wear test of selected samples was performed on pin on disc machine. For this purpose pins were machined into required dimensions (10mm diameter and 25mm length) first and then LSH was carried out. Track Diameter used in the experiment was 30mm; test was carried out for 42mins at 600 RPM. Total Sliding Distance for the static wear test was 2.375Km. The pin specimen was pressed against the disk at a 20N load by means of an arm and attached 2Kg weight. The amount of wear was determined by weighing both specimens before and after the test. Laser surface hardened samples were subjected to XRD analysis to find out phases present in melted zone. It was carried out between 30 to 90 diffraction angles. For the calculation of the residual stresses the sin2 ψ method was employed.

3. RESULT AND DISCUSSION

3.1 Microstructural Observation:

Fig. 3(a) shows the microstructure of the Austempered ductile iron after it was treated with a laser beam of 360W power, scanning speed 1mm/s, scan length 20mm and beam overlap 60%. The microstructure shows three different zones; melt zone, partially melt zone (PMZ) and heat affected zone (HAZ). The microstructure in the treated area is dependent on the heating and cooling cycles that take place during the process. The main constituents obtained in melt zone were coarse martensite, small quantities of retained austenite and cementite which is confirmed by X-ray diffraction shown in Fig. 3(c). Enlarged view of melt zone shows that complete dissolution of graphite has taken place. Partially melted zone enlarged view shows that size of graphite nodules is reduced, because of partial dissolution. Finally, in the lower region of the PMZ, the austenite of the base metal has been transformed into tempered martensite and due to temperature gradient along the depth, the volume fraction of tempered martensite decreases, until base metal structure of retained austenite and acicular ferrite is found.

3.2Hardness observations:

Microhardness profile in the cross sectional plane of the laser hardened ADI is shown in Fig. 3(b). The microstructural regions previously described are visible and represented in Fig.4.6. The martensitic zone (Melt Zone) hardness of the ADI is in the range of 800–1000 Hv(0.3) and it decreases at the end of this region due to the higher presence of retained austenite. It was observed that, in HAZ, initially hardness increases and immediately it decreases remarkably. Hardness increase in initial HAZ region could be due to partial melting of graphite nodules. Carbon from partial melting of graphite enters the matrix, and due to this extra carbon in PMZ, hardness increase was observed.

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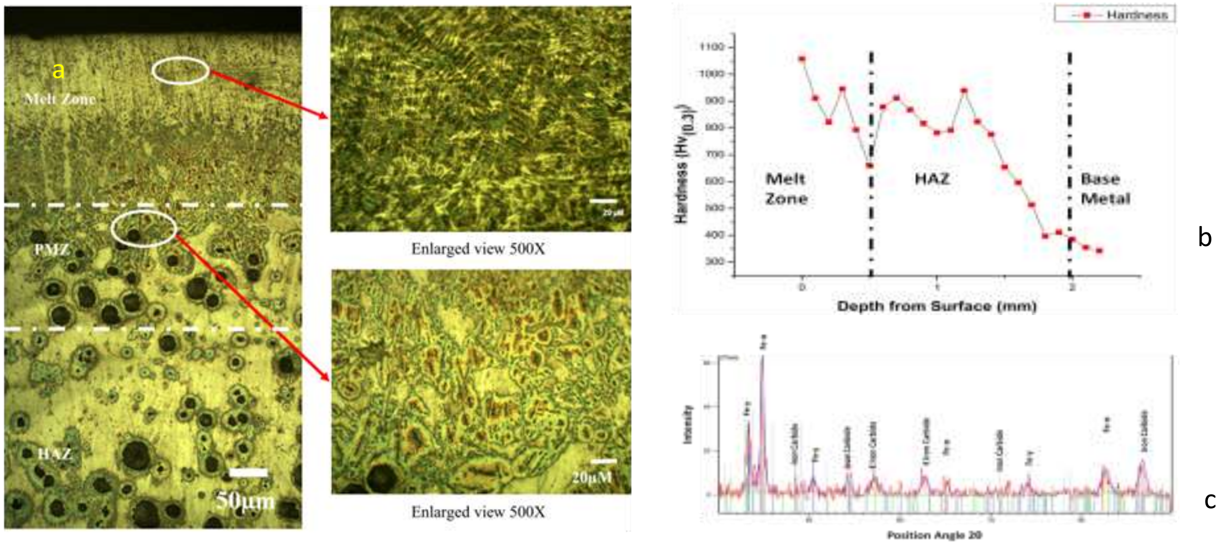

Fig-3: (a) Micrograph showing laser hardened zone of ADI (b) Hardness profile along the depth (C) X-ray diffraction pattern (Scanning speed 1mm/s, scan length 20mm, power 360W, beam overlap 60%)

3.3 Effect of laser power and Scanning speed on hardness and depth of hardening:

Fig.4 a) shows the effect of increasing the beam power on the microhardness of the ADI in the melted region for different scan lengths, while the scanning speed and beam overlap was kept constant. It can be interpreted from this graph that as laser power was increased, for 20mm and 40mm scan lengths, initially hardness in the melted region was increased up to 360W, but after that it decreases as laser power was increased further. For 30mm scan length, surface hardness in the melted region increases as laser power increases. Decrease in hardness in melted region at 380W power, for scan lengths 20mm and 40mm, could be attributed to decarburization of surface of ADI specimen due to very high temperatures achieved during treatment. Fig.4 (b) shows effect of laser power on hardened/melted depths of ADI specimens. It is evident that as laser power was increased, more heat was absorbed by the specimen and melted depth as well as overall hardened depth was also increased.

Fig. 5 (a) shows the effect of increasing the scanning speed on the microhardness of ADI. It can be seen that microhardness in the melted region was decreased as the scanning speed was increased. The faster the scanning speed, the lesser is the interaction time between the laser beam and the specimen. This results into less heat input and the less melted as well as overall hardened zone, so depth of melted zone as well as hardened depth was decreased as scanning speed is increased as shown in Fig. 5 (b).

3.4 Effect of surface condition on laser surface hardening:

Absorptivity is therefore one of the most important parameters directly influencing the LSH process. It is very difficult to determine an accurate absorptivity of a material because it depends on many parameters, such as surface roughness, irradiation angle, and surface coating. Experiments were performed to investigate the effect of surface roughness and graphite coating on microstructure and hardness of laser treated ADI. Fig.6 shows effect of surface conditions on surface hardness, melted depth and overall depth of ADI, keeping all other process parameters constant. In case of as cast specimen, for which, surface roughness (9.318µm) was maximum and non glossy surface, shows highest melted depth as well as overall hardened depth compared to that of specimens on which milling was done and graphite coating was applied. It indicates that surface roughness has major role in absorptivity of laser irradiation. Specimen on which only milling was done has least melted depth and overall hardened depth amongst the three. Specimen on which graphite coating was applied after milling was performed has melted depth and overall hardened depth in between the other two, so from these results, it is evident that absorptivity of ADI can be improved by applying graphite coating to its surface. Surface roughness and graphite coating improves the absorptivity of laser irradiation of ADI surface, due to this high absorptivity, more heat is generated, which in turn increases the melted depth and overall hardened depth.

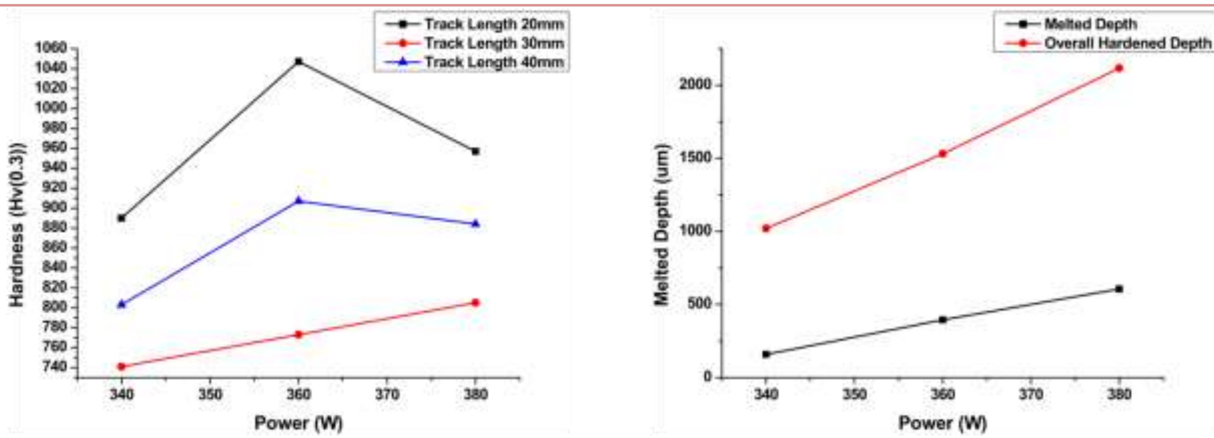

Fig-4: Laser Power on (a) surface hardness (b) on melted depth and hardened depth of ADI

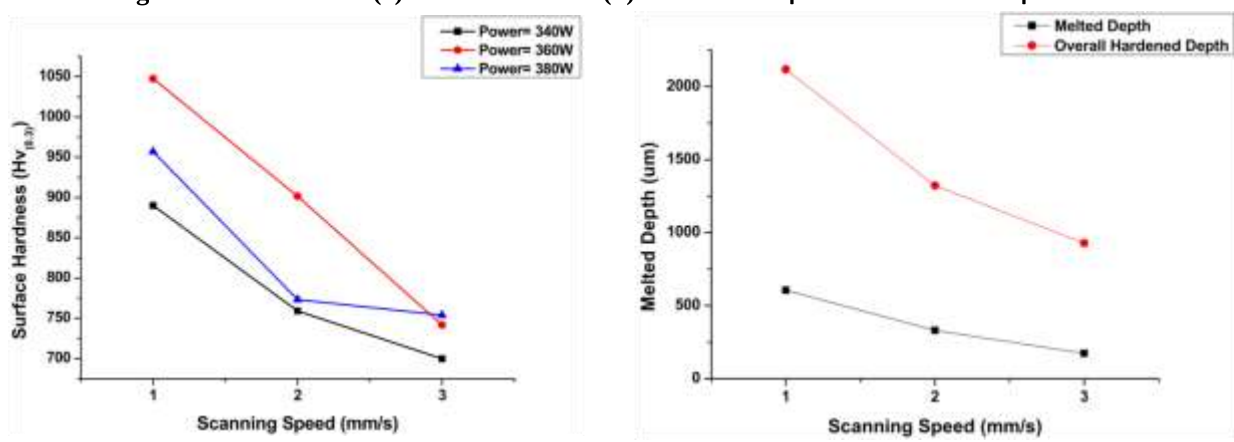

Fig-5: Effect of Scanning speed on (a) surface hardness (b) on melted depth and hardened depth of ADI

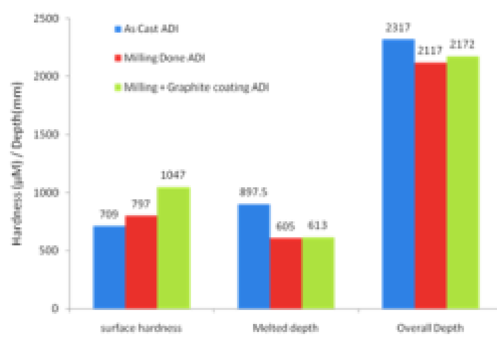

Fig.6. Effect of surface conditions on surface hardness, melted depth and overall depth of ADI

3.5 Effect of laser surface hardening on impact toughness:

Fig.4.44 shows the effect of laser treatment on impact test energy during Charpy impact test. Impact energies has decreased for laser hardened specimens compared to that of untreated specimen for ADI, which indicates complete brittle failures for laser treated specimens. Impact energy for ADI has decreased from 110J (untreated) to 11.5J (treated with parameters 380W power and 1mm/s scanning speed). These results show that, ADI lost its toughness due to laser treatment. It is also evident from Fig. 8 and 9, which shows actual photographs and SEM micrographs of fractured surfaces of ADI respectively. Fig. 9 (a) shows SEM photographs of untreated ADI, which indicates ductile failure, whereas, Fig. 9 (b) shows SEM micrographs of laser treated ADI, presenting complete brittle morphology of fractured surface which suggest that there could be formation of nano or micro cracks during LSH of ADI.

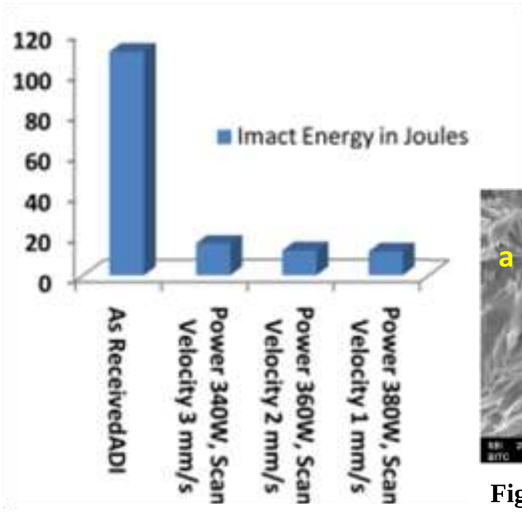

Fig. 7: Effect of laser treatment on Impact test energy during Charpy impact test

Fig. 8: Actual photographs of fractured Charpy impact test

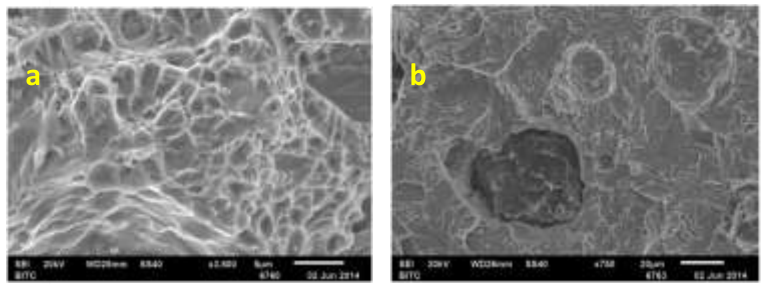

Fig. 9: SEM micrographs showing fractured surfaces of ADI showing (a) Ductile cup and cone morphology of as received ADI (b) Cleavage morphology of LS hardened ADI during Charpy impact test.

3.6 Effect of laser surface hardening on wear resistance:

The influence of laser surface hardening on the tribological behaviour of ADI was evaluated using a pin on disc wear test apparatus which provides the sliding contact between the stationary cylindrical pin and a EN31 steel rotating disc. Pins of diameter 10mm were machined and then laser treated before the wear test was performed. Track diameter was set to 30mm and 20N load was applied for the test duration of 42 min, covering overall sliding distance of 2.375Km. The benefits of the laser treatment could be clearly seen for both ductile iron grades as shown in Fig.10. Wear loss for untreated condition was 52mg. It dropped to 13mg for laser treated specimen under 360W power and 2mm/s scanning speed. Wear loss increased marginally to 17mg for the specimen laser treated under 380W power and 1mm/s scanning speed. It could be attributed to change in surface roughness of the sample due to laser remelting hardening. In case of laser treated sample, under 380W power and 1mm/s scanning speed more melted depth was achieved than that of treated under 360W power and 2mm/s scanning speed. Surface roughness could have been increased due to resolidification of large molten pool in case of specimen treated under 380W power and 1mm/s scanning speed.

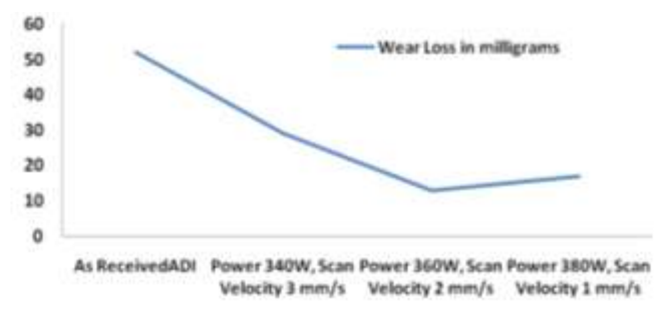

Fig. 10: Effect of LSH on wear loss of ADI

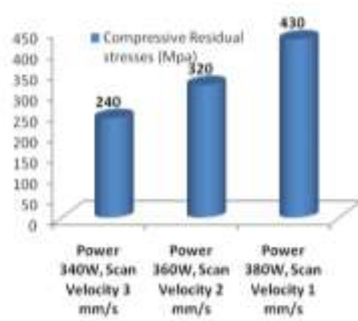

Fig. 11: Residual stress comparison for varying parameters

3.7 Residual stresses:

For the calculation of the residual stresses the sin2ψ method has been employed [13], measuring the diffraction peak position at nine different inclinations, from −45° to +45°. The Poisson coefficient and Young modulus values of the materials have been obtained from literature. The (2 1 1) Fe-α X-ray diffraction peak, located at 2θ ~ 156, has been used for the measurement of residual stresses. It was found that, due to laser surface hardening compressive stresses was induced in the case of specimen. Surface compressive stresses ranges between 150 to 400 Mpa for ADI, as shown in Fig. 11.

4. CONCLUSION

Laser surface hardening ADI iron was conducted with the objective of optimizing the process parameters for hardness and wear resistance improvement. Following conclusions can be drawn:

- By using fiber laser, surface hardening was successfully carried out on austempered ductile iron (ADI). Optimum conditions were determined with process windows for both irons. Hardening effect was more pronounced in molten cases than in transformed cases.
- Laser surface hardening of ADI leads to dissolution of graphite nodules in melted region and its rapid solidification results into homogeneous and fine dendritic structure comprising of martensite, cementite (Fe_3C) and retained austenite.
- The maximum melted depth of ADI achieved was 605 µm and hardness ranged between 900 and 1050 HV.
- There was considerable decrease in hardness of HAZ in ADI when scan length and beam overlap were increased.
- As-cast surface condition produced deeper melted case depth compared to as-machined and graphite coated surfaces. Surface roughness was found to be important for higher absorptivity of laser power. However surface hardness of graphite coated specimen was high and that of as-cast was low due to decarburization and large amount of retained austenite in the melted zone.
- Wear resistance of laser surface hardened ADI irons was considerably improved, whereas, impact toughness values were sharply reduced compared to base metal. This is attributed to formation of brittle phases such as cementite and martensite on solidification of molten layer. Very high heating and cooling rates might have formed micro cracks in molten case resulting in early crack propagation. Therefore laser surface hardening is strongly recommended for enhancement of wear resistance and not for impact toughness applications.

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