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THE EFFECT OF HARDENING TECHNIQUES ON WEAR RESISTANCE AND FATIGUE LIFE OF DUCTILE CAST IRON

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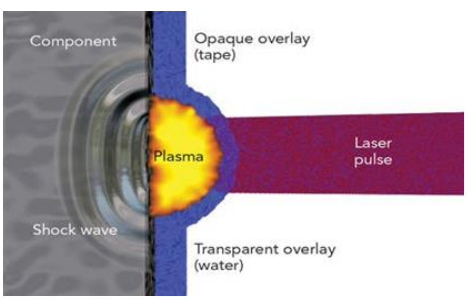
Graphical abstract



Abstract

Many hardening methods have been developed and proposed as an effective technology to produce microstructural modification and improvement of mechanical properties of variety metallic materials. In this experimental study, the effects of applying laser peening (LP) and friction stir processing (FSP) methods on wear resistance and fatigue properties of selected cast iron ASTM A536, grade (80-55-06) with ferrite/pearlite microstructure were investigated. Microscopic study revealed evident refinement and crashing of graphite nodules as 50% of the basic size with FSP and 32% with LP within the processed surfaces hence improving average microhardness by 100% and 48% respectively. The wear resistance and fatigue life were increased by 33% and 122% after FSP whereas, the corresponding increments were 15% and 22% after LP in comparison with the basic ductile iron. These improvements were linked to surface hardening, compressive stresses and structural modification by the employed processes.

Keywords: Ductile cast iron, microstructure, microhardness, wear resistance, fatigue life

1.0 INTRODUCTION

Ductile cast iron possesses a wide range of mechanical properties along with good castability [1]. These properties are largely controlled by iron chemical composition [2]. The global production of ductile cast iron is constantly growing and has the fastest growing rate of all ferrous materials [3]. which assured the ductile iron very wide and successful fields of application. It has incredibly good mechanical properties, such as high ductility, toughness, elongation and strength, and low production costs which makes it the material of choice in very wide and successful fields of applications compared to other materials [4]. The microstructure of ductile cast iron is created from the melting process. The higher the nodularity, the better mechanical properties [5].

Many surface modification techniques such as high energy laser beam, electron beam radiation and plasma spraying have been developed over the last two decades to fabricate metal surfaces [6]. LP experiments were first done at Battelle Institute [7], as a surfacing treatment tool used to enhance the metallurgical, mechanical properties and fatigue strength of metal by modifying the surface layer and producing compressive residual stresses through high energy laser pulse impacting metal surface [8]. Laser transformation hardening and martensitic formation of ductile cast iron was obtained [9] and produced ultra-fine ledeburtici hard surface layer [10-12] and maximum hardness increment was from 150- 600 HV and re-solidification led to retained austenite and some martensite and cementite formation [13, 14]. LP refines and modifies the microstructure of the surface layer of cast iron resulting in increments of hardness and wear resistance [15, 16]. Both ductile and grey cast iron showed marked improvement in erosion resistance and hardness to 800 HV and a greatly refined microstructure after laser processing [17]. LP processing parameters effects were observed on microstructure of ductile iron leading to solid state transformation and martensite in the transformed zone or heat-affected zone [18], and resulted in induced phase transformation of retained austeninte to martensite and increment in hardness (381- 606HV) and improvement in wear resistance [19], also formation of austenite and ledeburite structure in the treated zone and microhardness was enhanced from 250 HV to (500- 1100 HV) with laser travel speeds (0.5- 100 cm/s) [20]. Laser surface hardening of nodular cast iron (GG10) caused dissolved graphite nodules and fine dendritic structure comprising retained austenite with some martensite and cementite and hardness improvement from ranged 800-900 HV compared to untreated iron with 150 HV [21]. Laser peening of austempered ductile iron resulted in existence of martensite, cementite and retained austenite in depth on melted zone and enhanced improvement in wear resistance and hardness ranged (800- 1050 HV) in melted zone compared to untreated hardness of 359 HV [22] and can restrain nucleation of fatigue cracks and extend the fatigue life of nodular cast iron materials [23].

FSP is an emerging novel processing technique to treat metallic surfaces. It is based on the basic principles of friction stir welding (FSW) found in 1990. It can alter various properties of material surface by frictional heat and high strain produced by a hard cylindrical tool imposed on the base material with high rotation speed and applied axial load [24]. Significant refinement of graphite nodules and dense martensite structures were formed in the treated zone that resulted to enhanced microhardness [25]. The fully matrix transformed into acicular ferrite, Fe3C and martensite with retained austenite aggregates, significant increase of microhardness was achieved up to 1000 HV reference to base metal of 215 HV, and an improvement in erosion wear resistance [26]. Ferritic cast iron FCD450 Vickers hardness of (200 HV as base to about 700 HV) was obtained due formation of fine martensite [27] and was applied to flake cast iron (FC300) and nodular cast iron (FCD700) with pearlitic matrices resulted in fine martensite structure formation, and increased hardness to 700 HV for both cast irons compared to base irons (170-210HV) and (200-230 HV) respectively [28].

Little literature has been reported using comparative FSP and LP surfacing techniques on ductile iron. In this experimental study, the surfaces of ductile iron were treated with both methods and microstructure, hardness, wear resistance and fatigue life were evaluated and discussed

2.0 METHODOLOGY

Table 1 shows the chemical composition of the nodular cast iron grade 80-55-06 used in the experimental investigation. The microhardness and fatigue life of the original cast iron were 270 HV and 9* 105 cycle respectively. Plates with dimensions 10 cm × 3 cm × 3 mm were cut, cleaned and polished to be processed and study the influence of FSP and LP techniques on cast iron. Thirty plates were labeled, and friction stir processed using different processing conditions i.e., varying tool rotation speed, traverse speed and applied axial load as shown in Table 2.

Table 1 Chemical composition of the tested ductile cast iron

Element	C	Si	Mn	S	P	Fe
Wt.%	3.5	2.3	0.21	0.022	0.04	93.93

Table 2 Main parameters of FSP

Load L, N	2000	3000	5000
Transvers speed U, mm/sec	30	50	100
Rotational speed V, rpm	500	750	1000

The processing was with a tungsten carbide pinless tool of diameter 3 cm fixed on a vertical milling machine type (DECKEL, FP4M) as shown in Figure 1. LP was performed on anther thirty prepared specimens using Nd-Yag (Figure 2).

Figure 1 Friction stir processing machine and tool

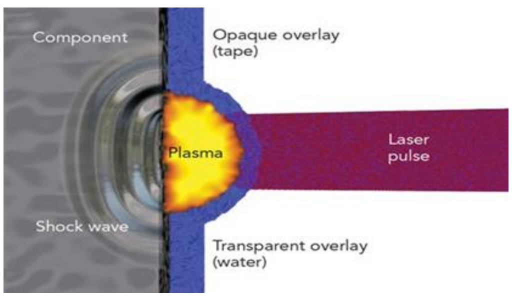


Figure 2 A schematic that shows the laser peening process

The surface was coated with a protective layer (black paint) to increase energy absorption, also the specimens was laid and covered with water to act as a confining and protection layer from the high thermal energy that may happen, experiments were performed with different scanning speeds and power intensities. The processing parameters used in this study are listed in Table 3.

Table 3 Main parameters of LSP

Max. output Power	400 W
Laser wavelength	1070 µmm
Laser power	325 W, 350W, 375W
Scanning speed	1 mm/s ,2 mm/s ,3 mm/s.
Beam overlap	50%

Standard methods of metallurgy were followed using optical microscopy of type (LEICA, DFC 295) to explore the specimen microstructure before and after both processes. Small specimens with transvers cross-sectioned were cut, polished with standard etched in %3 Nital and casted in graphite fixture for microscopic analysis as in Figure 3.

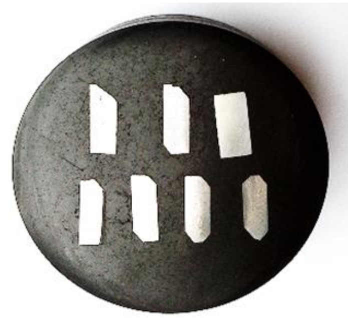


Figure 3 Specimens for optical microscopy test

Processed fatigue specimens were machined parallel to the process direction as shown in Figure 4. Hardness and fatigue tests were conducted on all processed and machined specimens using micro hardness tester (Laryee HVS) an automatic fatigue testing system (INSTRON 8872).

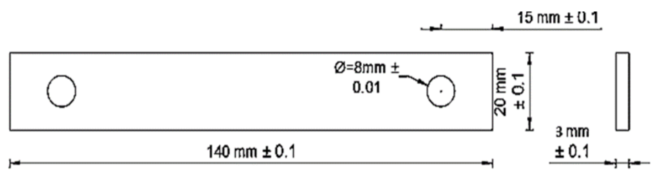


Figure 4 Schematic of machined fatigue specimens

The abrasive wear test was conducted using pin-on –disk. The specimen surfaces were ground with cleaned with alcohol and dried before the test which was carried out at sliding speeds of (0.2, 0.3, 0.5and 0.75 m/s) and normal loads of (5, 10,15, and 20 N) corresponding to a period of 30 min. The weight losses of the original and processed specimens were measured after cleaning with acetone and drying specimens with dry air using Sartorius electronic balance with an accuracy of ±0.1 mg. The wear rates were computed with the following equation:

$$WR = \frac{W2-W1}{S.t} \qquad (1)$$

where: *WR*, is the wear rate (gm/mm), *W1*, is specimen weight before test (gm), *W2*, is specimen weight after test (gm), *S*, is sliding speed (mm/min) and *t* is sliding period (min).

3.0 RESULTS AND DISCUSSION

3.1 Microstructure

Optical micrographic investigation was conducted on the transverse sections which are cut from treated specimens by both methods in the direction perpendicular to the movement of the tools after etching 3% nitric acid solution in ethyl alcohol. Microstructure of the original iron shows graphite nodules surrounded by ferrite/pearlite matrix. The graphite nodules size ranged between 50-100 µm. Both processes showed microstructural modification in the surface of the cast iron. The selection of the process parameters plays a key factor in the resulted microstructures. Examination of the processing zones at high magnification microscopy revealed reduction in size of graphite nodules and mixed austenite, cementite and martensitic structure throughout the melt zones depending on applied processing parameters as shown in Figure 5. The refinement in depth close to surface with FSP is higher than with LP and the averages were (50-75 µm) and (50-65 µm) respectively [15, 16 and 25]. The difference in microstructure between FSP and LP specimens can be as result of partial dissolution, diverse cooling rates and plastic deformation amounts. The higher refinement connected with higher plastic deformation during the processing in both methods.

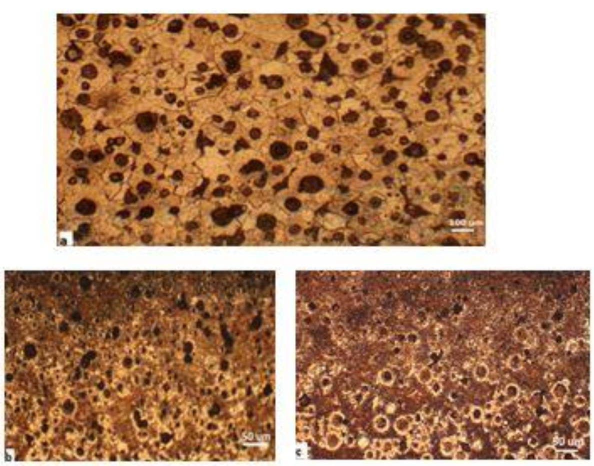


Figure 5 Original iron(a), FSPed (b), LPed (c)

Figure 6 shows the effects of varying FSP processing parameters, the effect of applied load is more effective than other parameters. Increasing the applied load and rotation speed at lowest translation speed resulted in the best refinement due to highest temperature and melting led to microstructural modification in the processing zone. At the optimum parameters (L=5000N, V=1000 rpm, U=30 mm/s), the grain size refinement was 50%

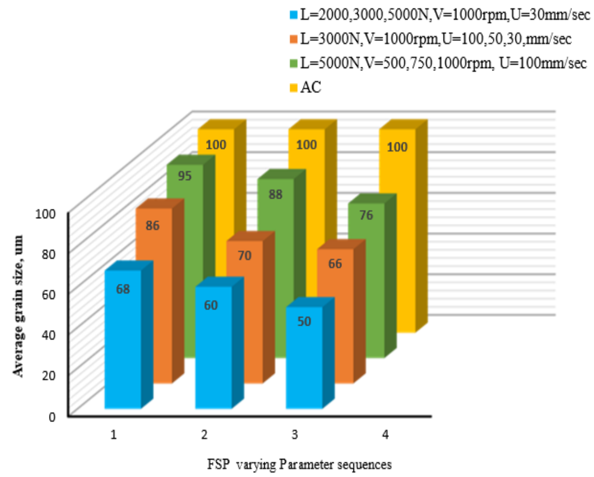


Figure 6 Average grain size at different FSP parameters

Figure 7 shows the effects of varying LP processing parameters (laser power and scanning speed), increasing the laser power to 375 W with decreasing scanning speed to 1 mm/s resulted in the best refinement of 32%. It is obvious increasing the laser power caused more heat to be absorbed by specimens and melting occurrence was also increased.

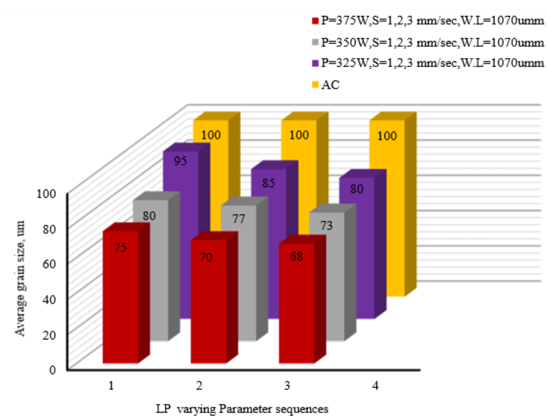


Figure 7 Average grain size at different LP parameters

3.2 Hardness

Similarly, the hardness increased after FSP from 270 HV to 546 HV at the best processing parameters, i.e., improvement of 100% was achieved. It can be deduced from Figure 8 that, as applied load increased, microhardness in the melted zone also increased significantly. Whereas increment from 270 HV to 400 HV at best LP parameters was noticed. improvement of 48%. Also, as the scanning speed decreased, microhardness increased. The slower the scanning speed, the more time for LP to interact on the specimen as shown in Figure 9. This achievement is related to grain refinement, phase transformation, heat generation and the consecutive cooling rate in both processes [20, 26].

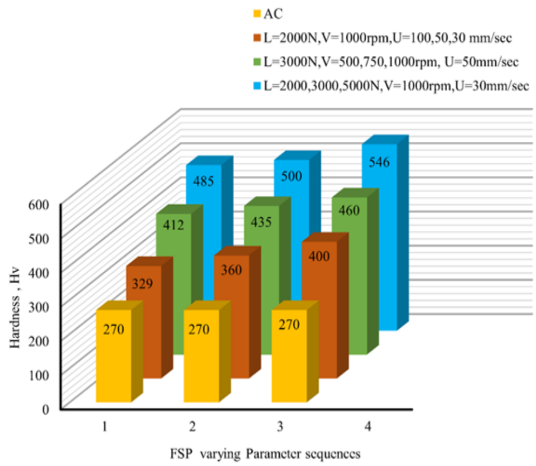


Figure 8 Average hardness at different FSP parameters

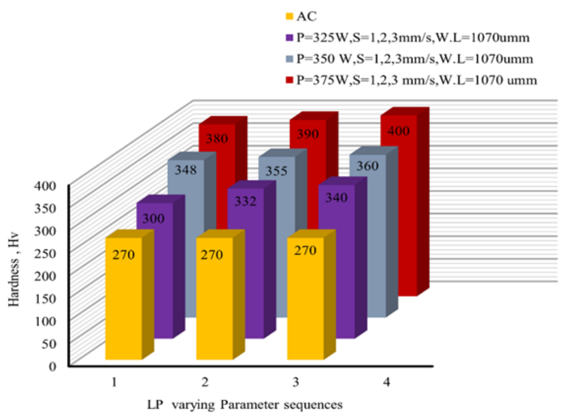


Figure 9 Average hardness at different LP parameters

3.3 Wear Resistance

The weight loss of treated specimens in both techniques increases with increasing the wear test parameters (applied load and sliding speed) as shown in Figure 10 and 11. The weight loss of treated specimens at specified applied load and sliding speed decreases compared with weight loss of as cast iron and was the lowest for FSP compared with LP. At maximum applied load (20 N) and sliding speed (0.75m/s), the weight loss was 1.8, 2.3 and 2.7 mg for FSP, LP and as cast specimens respectively. i.e. improvement of 33% and 15% for wear rate respectively. The enhancement in hardness caused decrease in weight loss and these results are in agreement with [19, 26]. These achievements can be related to the grained structural refinement after surface treatments that introduced hardened structure and phase transformation of retained austenite phase to martensite.

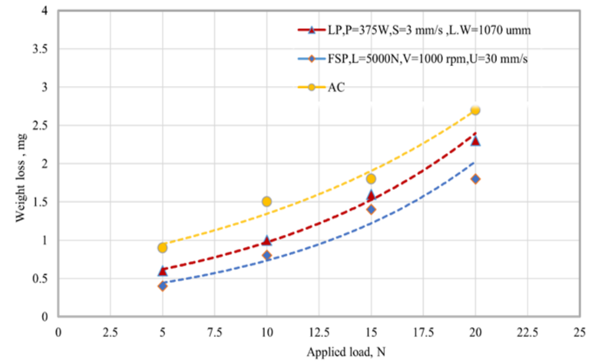


Figure 10 Weight loss with different wear loads (constant sliding speed 0.75 m/s)

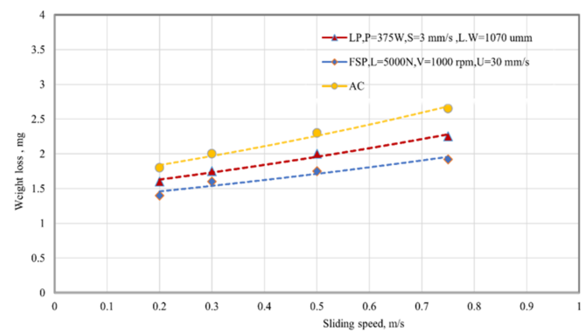


Figure 11 Weight loss with different sliding speeds (constant load 20 N)

3.4 Fatigue Life

The fatigue life of FSPed specimens was extended from 900000 cycle to about 2 million cycles, while was 1.1 million cycles for LPed specimens at best processing conditions as shown in Figure 12. Comparing the fatigue life for both treatment methods with as cast specimens revealed there is significant increment of 122% for FSPed specimens while 22% for LPed specimens. This improvement can be attributed microstructure refinement, phase transformation and induced compressive stresses that inhibits crack initiation and propagation as result of surface modification by both methods. FSP produced pronounced effects on cast iron properties in compassion with LP. This could be due to the size and amount of the compression stress zone on processing surface and in depth, hence better fatigue life.

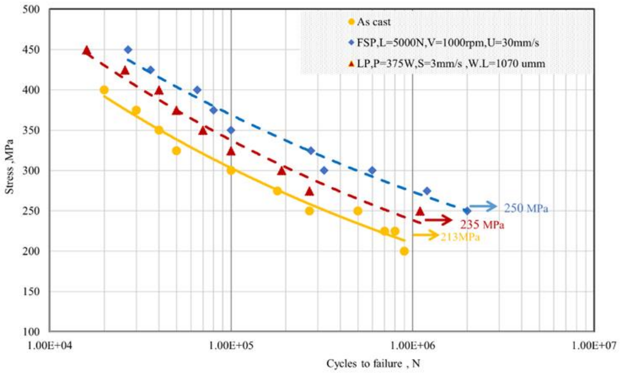


Figure 12 Fatigue life for FSP, LP and as cast

4.0 CONCLUSION

FSP and LP surface treatment techniques on the ductile cast iron were investigated to determine and optimize the parameters of both processes that will contribute to fulfill best improvement of mechanical properties of cast iron.

The results demonstrate that different microstructural transformations were produced in both techniques which consist mainly of martensite, retained austenite, remaining cementite lamellae and non-dissolved graphite nodules.

Enhancement in microhardness was achieved from 270 HV for as cast to 546 HV and 400 HV on the surface of treated iron with FSP and LP, respectively.

Accordingly, the wear resistance of processes cast iron was considerably improved by 33% with FSP and 15% with LP.

Additionally, the improvement in fatigue life was 122% with FSP, while was 22% with LP and related to inducing of compressive residual stresses and reduce initiation and propagation of surface cracks.

Refinements in microstructure (23% with FSP and 17% with LP) linked to the enhanced mechanical properties as microhardness, wear resistance and fatigue life of processed cast iron. Therefore, both techniques are strongly recommended for enhancement of mechanical properties of metals.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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References

[1] Tiedje, N. J. 2010. Solidification Processing and Properties of Ductile Cast Iron. *Materials Science and Technology*. 26: 505-514. Doi: 10.1179/026708310X12668415533649.

[2] Bockus, S., Zaldarys, G. 2009. Influence of the Section Size and Holding Time on the Graphite Parameter of Ductile iron Production. *Metalurgija*. 48: 19-22. https://hrcak.srce.hr/28856.

[3] Zmak, T. F. 2009. Mechanical Properties of Ductile Cast Iron Determined by Neutral Networks. *Proceedings of the Third International Conference on Modelling, Simulation and Applied Optimization*, January 20-22, Sharjah, U.A.E.

[4] Gagné, M. 2004. The Sorel Metal Book of Ductile Iron, Rio Tinto Iron & Titanium, Montreal.

[5] Metals Handbook. 1988. Ninth Edition, 15, Casting, ASM International, Metals Park, Ohio.

[6] Funatani, K. 2000. Emerging Technology in Surface Modification of Light Metals. *Surface and Coatings Technology*. 33: 264-272. Doi: 10.1016/S0257-8972(00)00940-3.

[7] Wei, T., Ye, L., Clark, G., Mai.Y.2006. Laser Shock Processing and Its Effects on Microstructure and Properties of Metal Alloys: A Review. *International Journal of Fatigue*. 24: 1021-1036. Doi: 10.1016/S0142-1123(02)00022-1.

[8] Hill, M. R., Dewald, A. T., Rankin, J. E., Lee, M. J. 2013. Measurement of Laser Peening Residual Stress. *Journal of Materials Science and Technology*. 21: 3-9. Doi: 10.1179/ 174328405 X14083.

[9] Gadag, S. P., Srinisavan, M. N., Mordike, B. L. 1995. Effect of Laser Processing Parameters on the Structure of Ductile Iron. *Materials Science and Engineering*. 196: 145-154. DOI: 10.1016/0921-5093(94)09719-4.

[10] Masse, J. E., Barreau, G. 1995. Surface Modification by Laser Induced Shock Waves. *Surface Engineering*. 11(2): 131-132. Doi: 10.1179/sur.1995.11.2.131.

[11] Chen, C. H., Altestetter, C. J., Figsbee, J. M. 1988. Laser Surface Modification of Ductile Iron: Part 1. *Microstructure Materials Science and Technology*. 4: 161-166. Doi: 10.1179/mst.1988.4.2.161.

[12] Grum, J., Sturm, R. 2002. Comparison of Measured and Calculated Thickness of Martensite and Ledeburite Shells Around Graphite Nodules in the Hardened Layer of Nodular Iron after Laser Surface Remelting. *Applied Surface Sciences*. 187: 116-123. Doi: 10.1016/S0169-4332(01)00823-6.

[13] Benyounis, K. Y., Fakron, O. M. A., Abboud, J. H., Olabi, A. G., Hashmi, M. J. S. 2005. Surface Melting of Nodular Cast Iron by Nd-YAG Laser and TIG. *Journal of Materials Processing Technology*. 170: 127-32. Doi: 10.1016/j.jmatprotec.2005.04.108.

[14] Trafford, D. N. H., Bell, T., Megaw, J. H. P. A., Bransden, S. 1983. Laser Treatment of Grey Iron. *Metals Technology*. 10(1): 69-77. Doi: 10.1179/030716983803291703.

[15] Mahmoud, A. K., Dhia, A. S., Ghazali, M. J. 2008. The Effect of Laser Surface Hardening on the Wear and Friction Characteristics of Acicular Bainitic Ductile Iron. *Diyala Journal of Engineering Sciences*. 1: 110-121. Doi: 10.24237/djes.2008.01108.

[16] Ju, C. P., Chen, C. H., Rigsbee, J. M. 1988. Laser Surface Modification of Ductile Iron: Part 2. *Wear Mechanism, Material Science and Technology*. 4(2): 167-172. Doi: 10.1179/mst.1988.4.2.167.

[17] Chen, C. H., Altstetter, C. J., Rigsbee, M. 1984. Laser Processing of Cast Iron for Enhanced Erosion Resistance. *Metallurgical and Materials Transactions A*. 15(4): 719-728. Doi: 10.1007/BF02644203.

[18] Gadaga, S. P., Srinivasan, M. N., B. L. Mordike, B. L. 1995. Effect of Laser Processing Parameters on the Structure of Ductile Iron. *Materials Science and Engineering: A*. 196: 145-154. Doi: 10.1016/0921-5093(94)09719-4.

[19] Mahmoud, A. K., Mohamed, M. T. 2013. Laser Surface Hardening of Ductile Cast Iron. *Scientific Proceeding*

International Congress, Machines, Technologies, Materials. 8-11.

[20] Zarubova, N. Z., Kraus, V., Cermak, J.1992. Mechanisms of Phase Transformations during Laser Treatment of Grey Cast Iron. *Journal of Materials Science*. 27: 3487-3496. Doi: 10.1007/BF01151824.

[21] Rathod, M. J., Deore, H. A. 2014. Laser Surface Hardening of Ductile Irons. *International Conference on Automotive Materials and Manufacturing Pune, India.* Doi: 10.4271/2014-28-0021.

[22] Deore, H., Rathod, M. J., Hiwarkar, V. D. 2017. Influence of Laser Hardening on Microstructure and Mechanical Properties of Austempered Ductile Iron. *International Conference on Ideas, Impact and Innovation in Mechanical Engineering*. 5(6): 1126-1132.

[23] Yang, J. C., Zhou, J. Z., Zhang, Y. K., Yang, C. J., Lu, J. Z.2004. Investigation on Performance of QT700-2 Material by Laser Peening. *Materials Science Forum*. 471: 43-46. Doi: 10.4028/www.scientific.net/MSF.471-472.43.

[24] Mishra, R. S. *et al*. 2005. Friction Stir Welding and Processing. *Materials Science and Engineering R*. 50: 1-78. Doi: 10.1016/j.mser.2005.07.001.

[25] Yao, X., Feng, X., Shen, Y., Kuang, B. 2015. Microstructure Feature of Friction Stir Processed Ductile Cast Iron. *Materials and Design*. 65: 847-854. Doi: 10.1016/j.matdes.2014.10.021.

[26] Cheng, T. W., Lui, T. S., Chen, L. H. 2012. Microstruactural Features and Erosion Wear Resistance of Friction Stir Surface Hardened Spherical Graphite Cast Iron. *Materials Transactions.* 53: 167-172. Doi: 10.2320/matertrans.M2011224.

[27] Imagawa, K., Fujii, H., Morisada, Y., Yamaguchi, Y., Kiguchi, S. 2012. Surface Hardening of Ferrtitc Spheroidal Graphite Cast Iron by Friction Stir Processing. *Materials Transactions.* 53(8): 1456-1460. Doi: 10.2320/matertrans. F-2012817.

[28] Fujii, H., Yamaguchi, Y., Kikushi, T., Kiguchi, S., Nogi, K. 2013. Surface Hardening of Two Cast Irons by Friction Stir Processing. *International Conference on Advanced Structural and Functional Materials Design.* 1-4. Doi: 10.1088/1742-6596/165/1/012013.