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EFFECTS OF FRICTION STIR PROCESSING ON MICROSTRUCTURAL, HARDNESS AND DAMPING CHARACTERISTICS OF FERRITIC NODULAR CAST IRON

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Abstract

Experimental investigations had been done in this study to explore the effects of friction stir processing (FSP) on the microstructure, hardness and damping capacity of fully ferrite nodular cast iron ASTM A536, grade 65-45-12. The main process parameters employed in this study were the rotational speed, translational speed and axial applied load which were varied within selected ranges. Their influence to be analysed and optimized for best process conditions compared with as cast material. Detailed investigations were carried out using optical microscopy, hardness test and impact test. Results showed that graphite grain refinements of 2-3 times the original size and phase transformations of a fully ferritic to bainite/martensite were achieved within the processed zone and across thickness. Matrix modifications caused improvement in hardness of 3.5 times compared to hardness of original cast iron. Increment in the damping capacity up to 14% was achieved. The stated improvements were related to the process parameters employed in the test.

Keywords: Nodular cast iron, FSP, Applied load, Rotational speed, Translational Speed, Microstructure, Hardness, Damping capacity.

1. Introduction

Recently, a new processing technique, friction stir processing (FSP), was developed by Mishra et al, Friction stir processing (FSP) is based on the basic principles of friction stir welding (FSW) developed by the Welding Institute (TWI) of United Kingdom in 1991 to develop local and surface properties at

Nomenclatures

P	Applied load, ton
U_r	Rotational speed, rpm
U_t	Translational speed, mm/min

Greek Symbols

δ	Logarithmic decrement
ϕ	Tool diameter, mm.
φ	Specific damping capacity
ζ	Damping ratio

Abbreviations

FSP	Friction Stir Processing
FSW	Friction Stir Welding
HAZ	Heat Affected Zone
HV	Vickers Hardness
TMAZ	Thermo-Mechanical Affected Zone
TWI	The Welding Institute
WEDM	Wire Electric Discharge Machine

selected locations [1]. Friction stir processing (FSP) has been utilized to locally process regions of industrial components to improve the microstructure and mechanical performance.

Nodular cast iron is one of the most commonly requested structural materials in the world for various industrial applications due to its favourable mechanical properties, design flexibility and low cost. The increased use of nodular cast irons concerns many applications, especially in automotive, engineering equipment and non-automotive transportation industries [2, 3]. The significant interest in fully ferritic nodular cast iron by foundries is due its structural homogeneity, remarkable ductility and good machining properties. The contact interaction of graphite inclusions with the ferritic matrix and properties of the matrix introduce additional sources of high damping. Cast iron can be an economical solution for problems created by noise and vibration. The free machining characteristics of cast iron offer an environmentally friendly alternative to steels, and its wide range of properties allows the design engineer to select the best-suited grade for an application. The most common use of FSP is grain refinement and phase transformation [1]. High refinement of graphite and a dense martensite structures were formed in the processed zone as the peak temperature exceeded the eutectoid transformation temperature the improvement of hardness [4] and ductility of the base material [5]. FSP applied on nodular cast iron and resulted in graphite nodule refinement, phase transformation and improvement of hardness with varying process parameters. There are very few studies with respect to FSP performed on cast iron. Fujii et al. [6] reported the possibility of martensitic transformation emerging in FCD700 (ductile cast iron) after FSP.A Vickers hardness of about 700HV was obtained due to the formation of fine martensite even in the ferrite-based spheroidal graphite cast irons FCD450 [7], Also a significant increase in the microhardness of about 1000HV yielding a primarily martensitic accompanying bainitic phase transformation was achieved using FSP on ferrtic SG cast iron [8]. The experimental results also show that the process has resulted in significant improvement in erosion resistance. The contact interaction of graphite inclusions with the ferritic matrix and properties of the matrix introduce additional sources of high damping.

The damping characteristics of the nodular cast iron are due to the shape of graphite inclusions rather than the quantity of graphite in the matrix [9]. Precipitated graphite particles absorb noise vibration; therefore, the relative damping capacity of ductile iron is twice that of steel. Gray cast iron has twice the damping capacity of ductile iron [10]. The damping capacity generally decreases with increased matrix hardness and increases with carbon content [11, 12]. The only exception to the damping-hardness relationship is for as-quenched martensite, in which the internal stresses produced by the formation of martensite increase micro plastic deformation and thus increase damping [13, 14].

2. Experimental Work

A powerful controlled vertical milling machine was successfully used to perform the friction stir processing on the fully nodular cast iron specimens (140*40*5 mm) as shown in Fig. 1 with chemical composition shown in Table 1. The processing tool employed in this study was a pinless shoulder Ø= 20 mm in diameter and made totally of tungsten carbide because of its thermal stability, conductivity, hardness and rigidity at elevated temperatures.

Fig. 1. Vertical Milling machine type DECKEL, FP4M used for FSP of ferritic nodular cast iron specimens.

The selected main process parameters were the rotational speed, translational speed and axial applied load to be applied throughout processing scheme are shown in Table 2. The processing parameters were used based on previous studies and the fixed setting of the used processing machine.

Table 1. Chemical composition comparison of nodular cast iron with the nominal alloy.

	%C	%Si	%Mn	%P	%S	%Fe
Nominal chemical composition	2-4	2-2.5	0.3-0.9	≤0.06	≤0.02	Rem
Actual chemical composition	3.51	2.43	0.76	0.035	0.009	Rem

Table 2. FSP main parameters and their selected ranges.

Applied load, ton	1	2	3
Rotational speed, rpm	800	1000	1250
Translational speed, mm/min	50	107	180

A carefully prepared as cast and FSPed specimen were used for microscopic and Vickers hardness examinations. The specimens were sectioned perpendicular to the FSP traverse direction to analyse the in depth microstructural, material flow and phase modifications.

To measure the vibration damping capacity, as cast and FSPed specimens with dimensions of 140 mm × 10 mm × 4.5 mm were machined using wire electrical discharge machining (WEDM) according to schematic drawing shown in Fig. 2. The experimental set up of the instruments used in the damping measurement consists of a hammer was used to vibrate the model by striking the free end of the test specimen and response of the model was picked up by accelerometer (fixed at span tip of the beam) to extract the signals of vibrations that were displayed on an oscilloscope through a charge amplifier and import the data into PC as shown in Fig. 3. The damping ratio was also calculated with the help of logarithm decrement method. The method of calibration curve and sensitivity of the accelerometer was conducted by using a computer interface that works as the accelerometer calibrator.

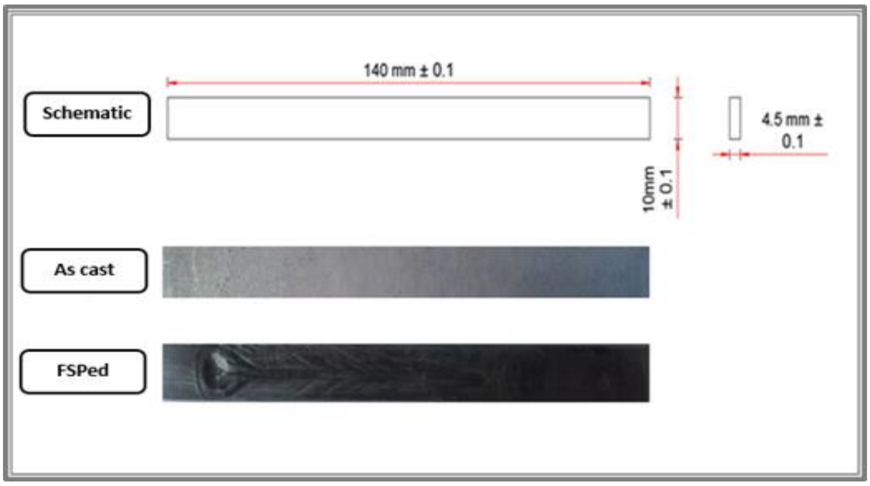

Fig. 2. Damping test specimen.

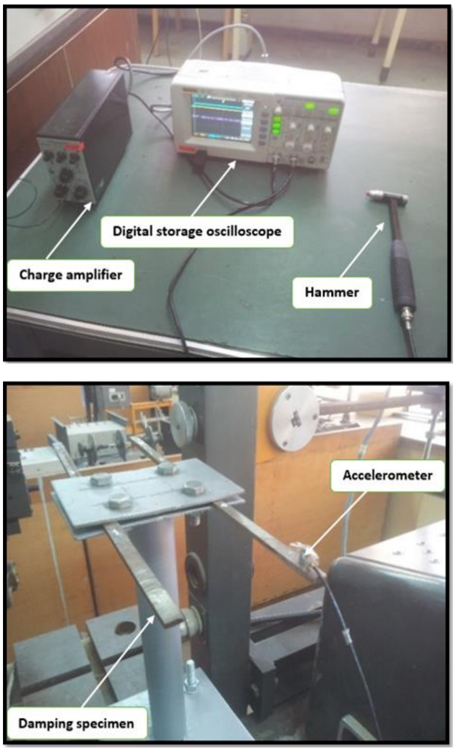

Fig. 3. Damping test experimental setup.

3. Results and Discussion

The processing parameters exhibited significant effects on the formation of surface layer and microstructure within the process zone and across the entire specimen’s thickness. FSP altered the microstructure greatly and resulted in very fine microstructures and different matrix forms of average graphite nodule sizes 15-25 μm compared with comparative that of as cast specimen 40 μm. The ferrite graphite nodules had been broken up into finer nodules. FSP also eliminated defects and porosity, which typically exist in matrix, creating a fully-consolidated fine grain microstructure at the surface of the process zone.

The microstructure of the processed layer was more refined with increasing load. The high applied load provided a suitable heat input and was important for obtaining the large modified region. The processed specimens showed a multiphase matrix of ferrite, bull eyes, retained austenite and bainite / martensite.

The microstructure of As cast and FSPed specimens are shown in Fig. 4. The FSPed microstructure can be defined as three different regions respectively: - (1) The top surface layer which contains deformed graphite nodules due to high temperature stirring flow is defined as TMAZ with martensite structure and refined or crashed graphite. This generated structure has a fine and very hard microstructure. (2) The microstructure is martensite/bainite and also contains deformed graphite nodules, defined as HAZ1 where the matrix structure is similar to TMAZ. (3) The region HAZ2 is pearlite and contains chunk-like phases surrounding the graphite nodules also known as a hard eye structure and contains bainite and retained austenite towards base metal.

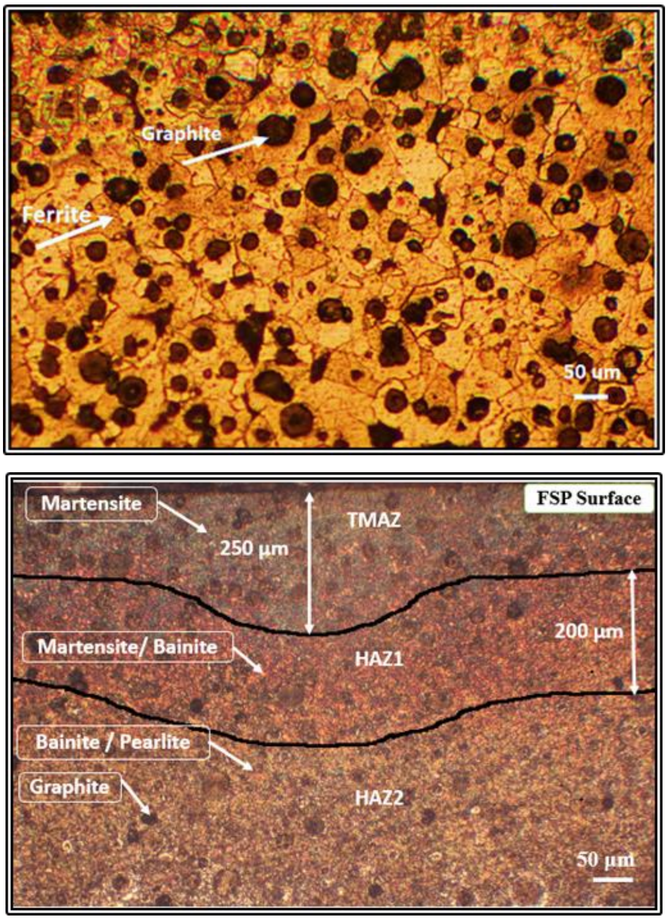

Fig. 4. As cast and FSP microstructure with different zones across thickness zones at 3 ton, 1250 rpm, 50 mm/min.

The effect of increasing the applied load from 1 to 3 ton resulted in graphite nodule refinement 37% to 62%, respectively with respect to original graphite size, as shown in Fig. 5(a). Similarly, increasing the tool rotational speed from 800 to 1000 rpm (at 1 ton, 50 mm/min.) resulted in refinement 25% to 37%, respectively, Fig. 5(b).

The effect of reducing the translational speed from 180 to 107 mm/min (at 1 ton, 1250 rpm) resulted in reduction of graphite diameter 14% to 28%, respectively, Fig. 5(c). This refinement analysis confirmed that increasing the applied load and rotational speed with reducing translational speed confined the optimum process conditions for successful processing of surface hardening of nodular cast iron.

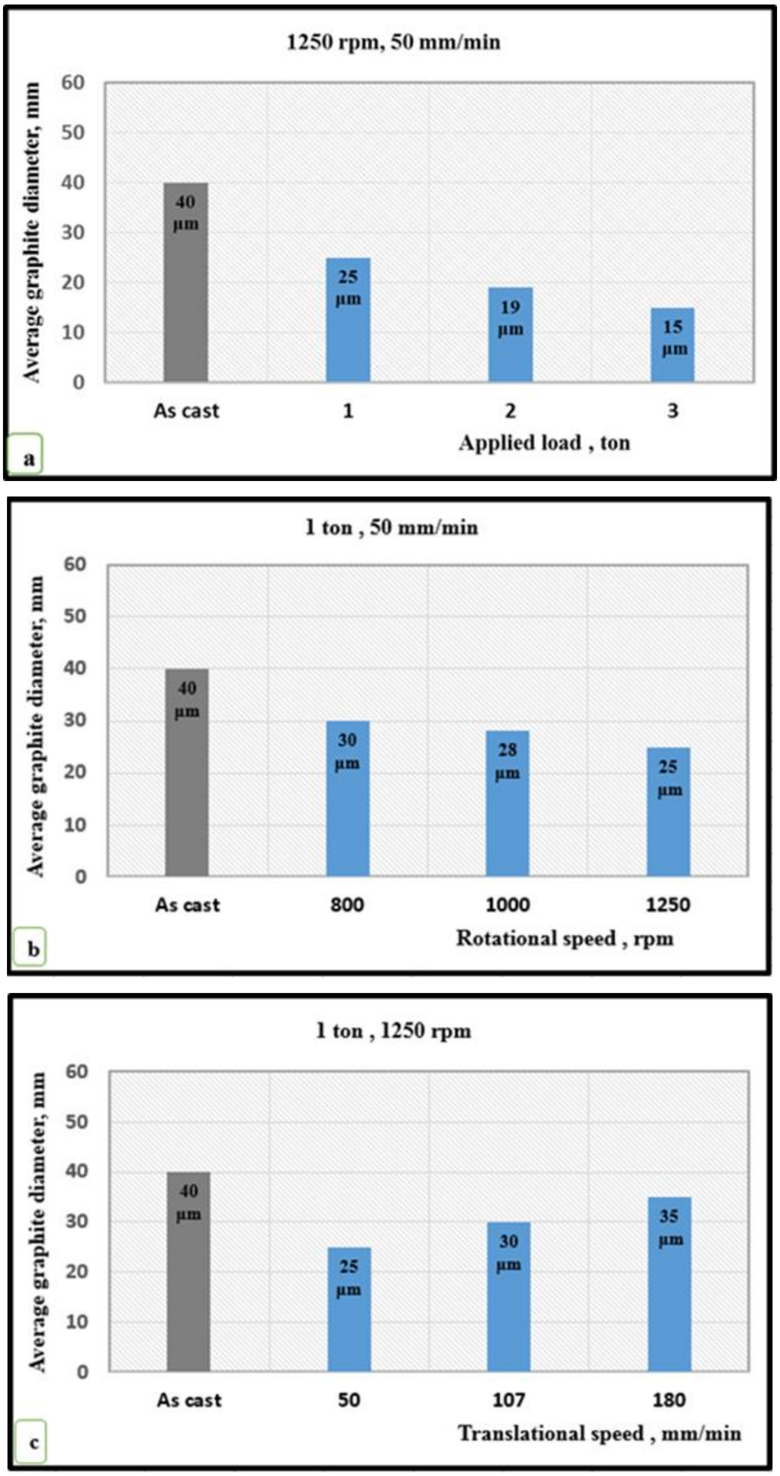

Fig. 5. Average graphite diameter in PZ with various process parameters: (a) applied load (b) rotational speed and (c) translational speed.

The hardness increased in the central region 551 HV, 565 HV and 632 HV with increasing applied load 1, 2 and 3 ton , respectively at constant rotational and translational speeds 1250 rpm, 50 mm/min, respectively (Fig. 6) and that gave the best condition at load 3 ton . This increase was 190%, 197% and 232% compared to as cast hardness 190 HV. The highest hardness improvement was clear from the greatest area under the hardness profile with highest load and rotational speed at low translational speed.

The general profile of hardness distribution across the process path in the advancing and retreating sides of the specimens showed increased hardness with increasing the applied loads, and that the maximum increase was at/near the path center reaching 700 HV at 2 mm from the path center in the advancing side and reduced gradually towards both the advancing and retreating sides. Generally, the hardness level in the advancing side was always higher than at the center and in the retreating side, this was due to that the flow direction in the advancing side is coinciding with the translational speed and opposing the translational speed in the retreating side which causes slightly higher heat input in the advancing side than in the retreating side.

The data presented in this section represent the average values of three individual measurements for damping properties .The relative damping capacities of ferritic nodular cast irons increases, as the percentage of spherical graphite decreases. The damping capacity generally decreases with increased matrix hardness and increases with carbon content. The only exception to the damping-hardness relationship is for as-quenched martensite, in which the internal stresses produced by the formation of martensite increase micro plastic deformation and thus increase damping.

The damping characteristics of FSPed specimens showed limited improvements, depending on the employed processing parameters, as shown in Table 3. In general, increasing the load and rotational speed with reduction of translational speed revealed noticeable increments in damping ratio and capacity of processed specimen in comparison with as cast. Increasing the load from 1 to 3 ton at constant 1250 rpm and 50 mm/min showed the best damping ratio increment of 4% to 14%, respectively (Figs. 7 and 8). Whereas, increasing the rotational speed from 800 to 1000 rpm caused increment of 2 to 6%, respectively and reducing the translational speed from 180 to 107 mm/min depicted increment of 1 to 5%, respectively.

Table 3. Damping characteristics of as cast and FSPed ferritic nodular cast. iron

FSP parameters	Logarithmic decrement δ	Damping ratio ζ	Damping capacity Ψ
As cast	0.04155	0.006613	0.0831
1 ton, 1250 rpm, 50 mm/min.	0.04335	0.006899	0.0870
2 ton, 1250 rpm, 50 mm/min.	0.0452	0.007194	0.0904
3 ton, 1250 rpm, 50 mm/min.	0.04735	0.007536	0.0947
800 rpm, 3 ton, 50 mm/min.	0.0425	0.006764	0.0850
1000 rpm, 3ton , 50 mm/min.	0.0443	0.007050	0.0886
107 mm/min, 3 ton, 1250 rpm	0.04365	0.006947	0.0873
180 mm/min, 3 ton, 1250 rpm	0.0420	0.006684	0.0840

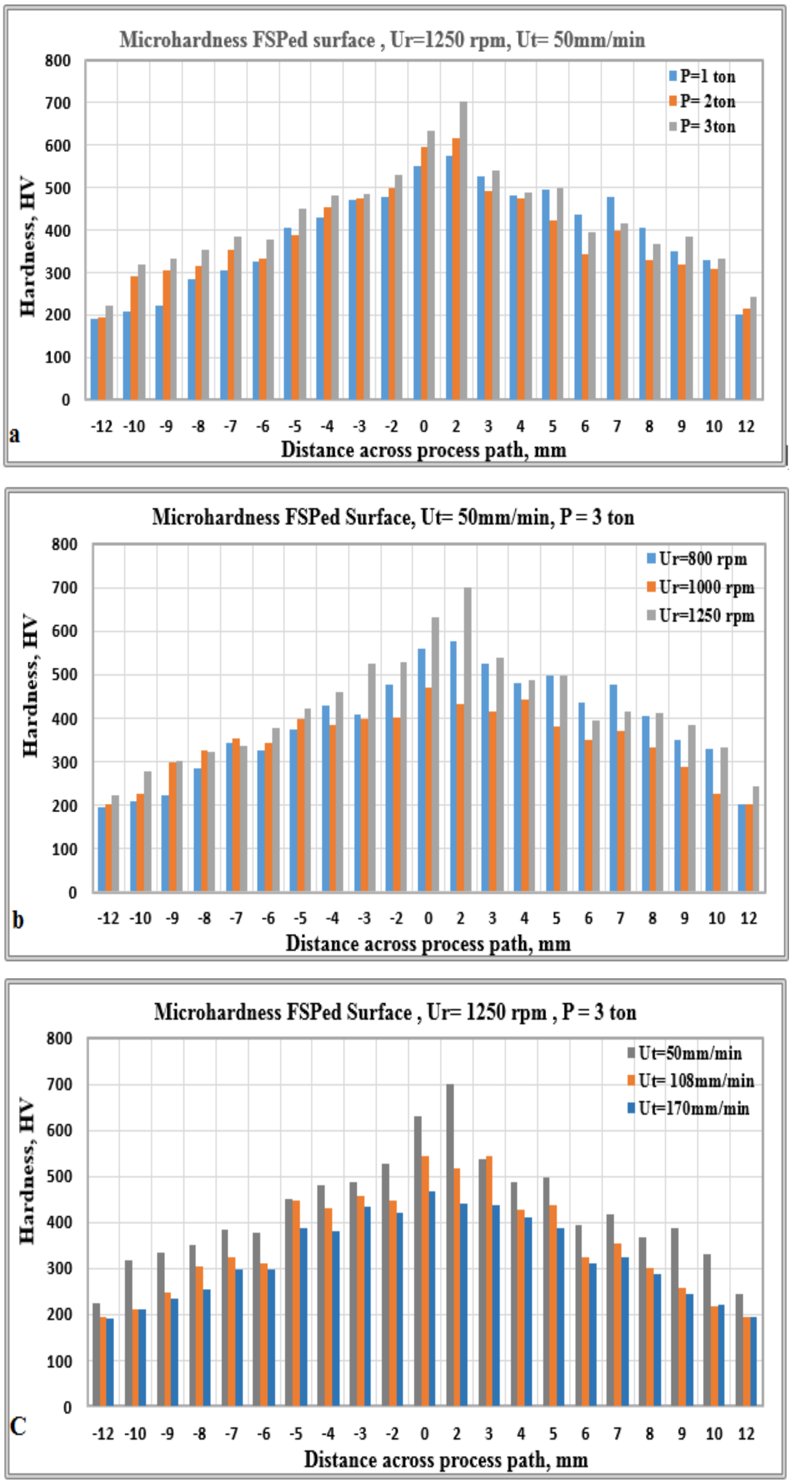

Fig. 6. Hardness variation across process path with process parameters: (a) applied load (b) rotational speed and (c) translational speed.

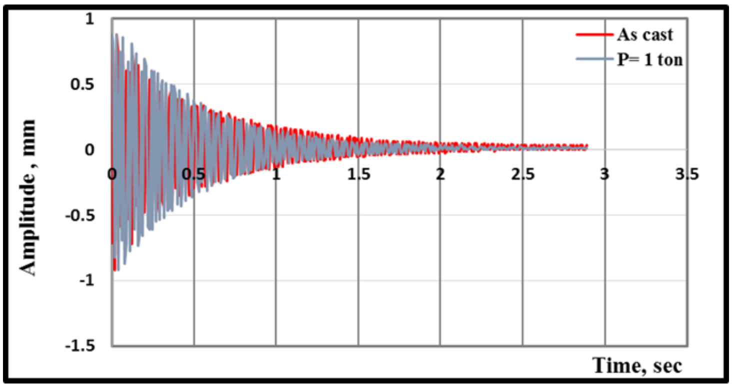

Fig. 7. Decay signal (time domain) for as cast and FSP specimen with 1 ton, 1250 rpm and 50 mm/min.

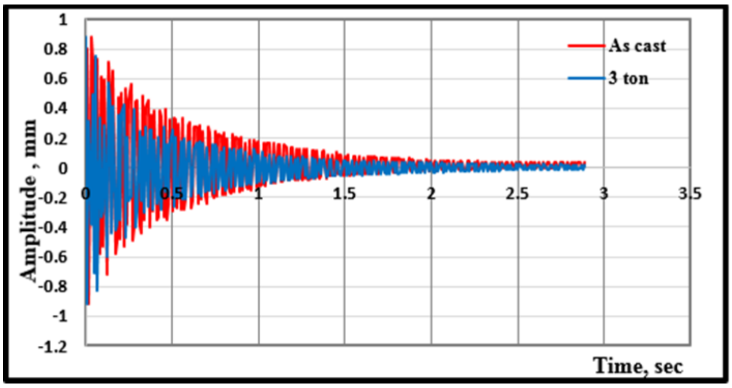

Fig. 8. Decay signal (time domain) for as cast and FSP specimen with 3 ton, 1250 rpm and 50 mm/min.

It is clear that the improvement achieved with FSP compared to as cast with varying the processing parameters well shown in Fig. 9 as overlapped decay profiles of each process parameter. The best improvement again was with the highest applied load and rotational speed with the lowest translational speed. This improvement was due to the heat input, refinement and phase transformation that affected all the mechanical properties stated previously.

4. Conclusions

Friction stir processing (FSP) proved to be a viable technique for microstructural modification of nodular cast iron. The following concluding remarks are pointed out:

- FSP altered the microstructure of the nodular cast iron and resulted in very fine nodular graphite at the surface layer and less towards the base metal.
- The improvement of hardness associated with the refinement of graphite and bainite, and martensite formation was observed to cover the whole thickness of the specimens, resulting in highest hardness increment in the PZ up to 700 HV.
- After FSP, the damping characteristics of nodular cast iron samples showed increments up to 14% as result of graphite nodule size reduction accompanied with martensite phase transformation relative to original ferritic matrix.

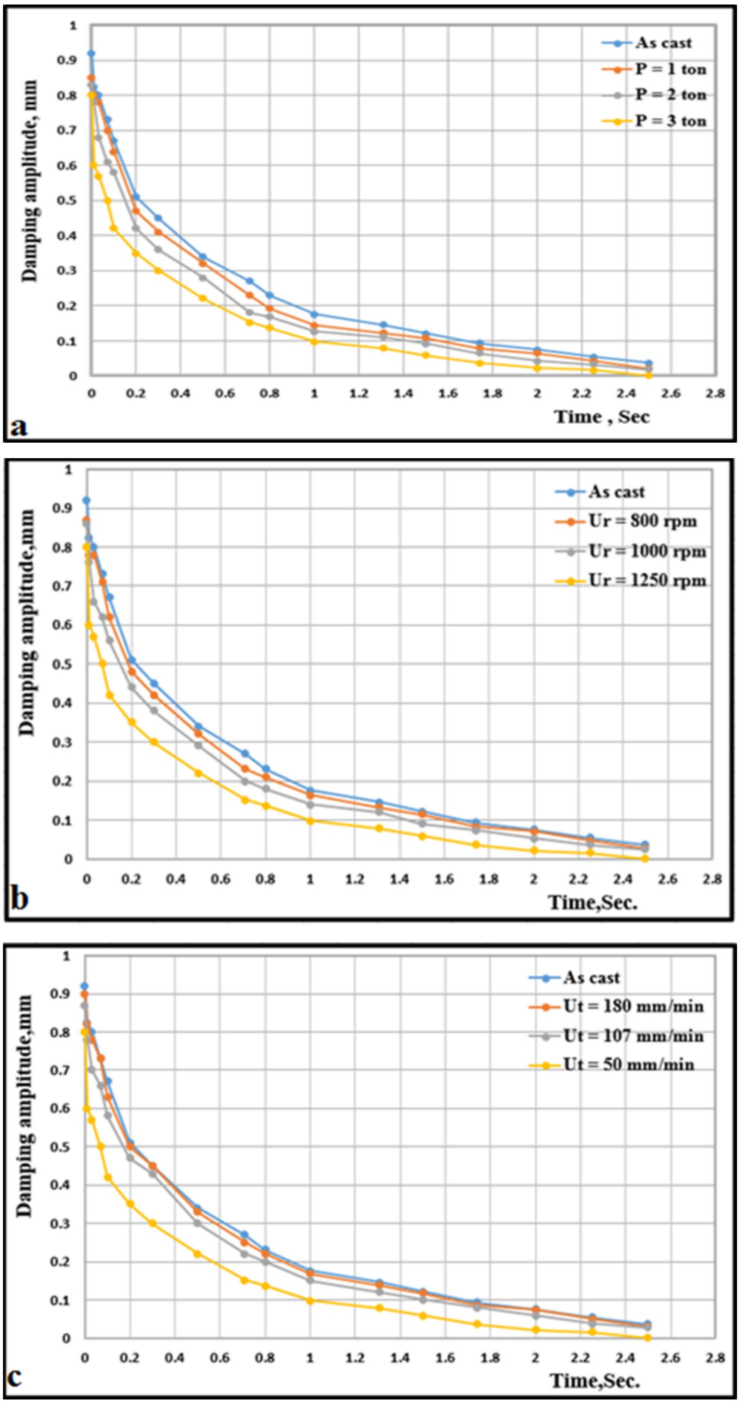

Fig. 9. Decay profiles (time domain) for FSP specimen with varied process parameters: (a) applied load, (b) rotational speed, (c) translational speed.

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