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Experimental Investigations on Mechanical Properties of Friction Stir Processed AISI 4140 Steel

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Abstract: ***In the present experimentation, optimization of friction stir processing parameters in terms of tool rotational speed, tool feed and axial load for maximizing the tensile strength and hardness in processing zone is carried out using Taguchi design. Orthogonal array of L16 was used to design a set of experiments concerning rotational speed, tool feed, and axial load. Processing variables were analysed by means of signal-to-noise ratio analysis to find the optimum parameters. ANOVA analysis was used to determine the contribution of each parameter.***

Keywords: Taguchi method, Friction Stir Processing, Tool rotational speed, ANOVA analysis, Tensile strength, Axial Load

1. Introduction

AISI 4140 is a Cr-Mo series low alloy steel having comparable density with other steel alloys combined with high strength, allows to be used for design and construction of complex structures particularly for aerospace, automobile industries and manufacturing industries. The included alloying elements of Cr and Mo provide AISI 4140 steel with a high hardenability and toughness [1-2]. However, structural defects, such as pores, oxide inclusions and intermetallics, reduce the mechanical properties of steel alloy particularly hardness, fatigue strength and elongation [23]. This has pushed the development of surface engineering which includes range of technologies e.g. anodizing, surface hardening, carburizing, nitriding, Physical Vapour Deposition (PVD) and Friction stir processing (FSP) etc. Friction stir processing (FSP) is a novel technique based on the principles of Friction stir welding which can be used for modifying surface properties. FSP process possess numerous application in aerospace, marine, railroad and transport industries [5]. FSP is considered an environment friendly technology due to its energy efficiency and absence of gases or fumes produced [8]. It is a solid state technique which instead of joining samples together, modifies the local microstructure of monolithic specimens to achieve specific and desired properties by surface modification of microstructure [27]. It is an effective technology for microstructure refinement as well as for defect removal of cast and forged components as surface cracks and pores. Some of the technical and metallurgical benefits of the FSP process include minimal distortion of parts, metallurgical solid state process, grain refining and homogenization, no cracking and possibility to treat thermal sensitive material [2,8,9]. The deformed material is transferred from the Retreating Side (RS) of the tool pin to the Advancing Side (AS) and is forged by the tool shoulder, resulting in a solid state modification of the material [12-13]. For the FSP process the most important area is between stir zone and thermos-mechanically affected zone. [21].

The critical parameters which influences the FSP process are rotational speed, traverse speed, tilt angle, penetration depth of the tool, tool axial force, tool geometry, cooling system, clamping system [13,26]. These operating or processing parameters determine the amount of plastic deformation, generated heat and material flow around the non-consumable tool.

Xue et al. [11] studied low carbon steel plate subjected to Friction Stir Processing (FSP) at a tool rotation rate of 400 rpm and a travel speed of 50 mm/min with additional rapid water cooling using a low-cost cermet tool without pin.. The ultrafine polygonal ferrite grains (1µm) were distributed around the martensite phase which consisted of nanostructured laths with a width of 200 nm. The FSP steel exhibited a good combination of strength and ductility.

Sekban et al. [21] analysed a low carbon steel subjected to friction stir processing. A tungsten carbide (WC) tool with a convex shoulder and a cylindrical pin was used. FSP was performed at a rotation speed of 630 rpm and 45 mm/min traverse speed. It was found that two distinct zones called Stir Zone (SZ) and Heat-Affected Zone (HAZ) were formed during FSP.FSP considerably refined the microstructure of the steel by means of dynamic recrystallization mechanism and formed a volumetric defect-free basin-like processed region. This microstructural evolution brought increase in both hardness and strength values without a considerable decrease in ductility.

Peng et al. [12] investigated AISI 316L steel produced through Selective Laser Melting (SLMed 316L) which was successfully modified through friction stir processing (FSP). FSP was carried out using the WC tool with 37.5 mm/min and 375 rpm processing and rotation speed, respectively. It was demonstrated that FSP could effectively eliminate the holes and cracks of Selective Laser Melted 316L, leading to refined, homogenous and dense microstructure. Subsequently to FSP, the grain size was refined from 6.6 to 0.9 µm, total dislocate ion density decreased, while geometrically necessary dislocation density increased There was improvement in average micro-hardness and nano-hardness. The yield and tensile strengths increased by 29% and 18%, respectively, while elongation was maintained.

Singh et al. [13] investigated strengthening of SA 210 Grade A1 boiler steel using Friction Stir Processed with pin less WC tool, plunge depth of 1 mm, transverse speed as 40 mm/min and tool-spindle rotational speeds of 800 rpmand 1400 rpm respectively with two numbers of passes in each case. The initial grain sizes of the selected boiler steel have been reduced to 7.8 μm and 5.9 μm respectively with increase in rotational speed. The micro-hardness of the Friction Stir Processed samples was enhanced by factor of 1.72 and 2.38 in comparison to base steel respectively. This was due to phase transformation (austenite to martensite and ferrite) and refinement in grain size. The ultimate tensile strength was improved by 7.2% in comparison to base metal, which may be accredited to enlarge in grain boundaries which hinder the dislocation movement.

EI-Sayedet al. [16] investigated the effects of rotational speed in range of 800–1600 rpm and traverse speed in range of 12–40 mm/min on the mechanical and microstructural properties of 2205 duplex stainless steel (DSS) using a tungsten carbide stir tool. It was found that by increasing the advancing speed from 50 mm/min to 200 mm/min, grain structure became more refined in the processed zone; however, a groove-like defect was produced at 250 mm/min. This was due to the fact that frictional heat is insufficient to soften the material around the spinning tool at this higher welding speed, resulting in a lack of material flow, consequently creating fill defects in the processed zone. The authors concluded that due to the reduction in grain size, hardness, and tensile strength of the DSS were increased. It was also reported that the grain sizes in the stir zone were not of the same size, and there was more grain refinement on the advancing side compared with the retreating side of the processed zone indicating the asymmetric grain structure in Friction Stir Processed zone.

Ma et al. [4-5] investigated 2507 Duplex Stainless Steel using the W-25Re FSP tool with a transverse speed in the range of 50–200 mm /min and a constant rotation speed of 400 rpm. The effect of traverse speed on the microstructure, mechanical properties and corrosion resistance of the processed area was analysed. The grain size in the stir zone was refined. The tensile strength and micro-hardness of the stir zone were higher than that of the base metal, while the elongation decreased to a certain extent. The traverse speed had little effect on the ratio of ferrite to austenite content in the processed zone. The refined grains in the stir zone promoted the diffusion of elements and enhanced the stability of the passivation film, which resulted in better corrosion resistance of the stir zone than that of the base metal.

Pan et al. [20]studied Friction-stir processing (FSP) to harden the surface of a high-carbon martensitic stainless steel (AISI 440C) and to improve its corrosion resistance.FSP was executed at a rotational speed of 2000 rpm and processing speeds ranging from 150 to 300 mm/min, using W-Re tool. PDP (Potentio-dynamic polarization) tests were performed in 3.5% NaCl solution, and results showed an increase in corrosion resistance for the Friction stir processed sample processed at 150 mm/min due to the formation of a thick passive film. The surface hardness at centres of the Friction stir processed zones is in the range of 728–779 HV_1 and higher than the conventionally hardened 440C (618 HV_1) because of the presence of martensite, grain refinement and severe plastic deformation.

Aldajah et al. [18]applied Friction Stir Processing (FSP) to 1080 carbon steel to enhance the near-surface material properties. The process transformed the original pearlite microstructure to martensite, resulting in significant increase in surface hardness. This surface hardening produced a significant benefit for friction and wear behaviour of the steel. Under dry sliding, FSP reduced friction coefficient by approximately 25%. Under oil lubrication, FSP had only a marginal effect on friction, but it reduced wear rates by a factor of 4. The improvement in tribological performance of 1080 steel by FSP technique is attributed to reduced plasticity of the near-surface material during sliding contact.

Tinubu et al. [22] studied the effect of Friction Stir Processing (FSP) on the microstructure, mechanical properties and wear behaviour of a low carbon steel. FSP was performed with a processing tool having a convex shoulder with a cylindrical pin and a tool rotation of 635 rpm and a traverse speed of 45 mm/min. The shoulder tilt angle was set at 30, and the tool plunger downforce was kept constant at 11 kN during process. A fine grained microstructure having mean grain size of 5 μm was obtained. Such grain refinement lead to a significantly enhancement in strength and hardness without notably sacrifice in elongation. Friction Stir Processed sample has slightly lower coefficient of friction than un-processed sample. FSP increases the wear resistance of steel. This is associated with a considerable increase in its strength and hardness values after one-pass FSP.

Yasavol and Jafari [23] studied AISI D2 tool steel processed by friction stir processing (FSP). The microstructure, mechanical properties, and corrosion resistance of the FSPed materials were evaluated. A flat WC-Co tool was used, the rotation rate of the tool varied from 400 to 800 rpm, and the travel speed was maintained constant at 385 mm/s during the process. Mechanical properties improvement was attributed to the homogenous distribution of two types of fine (0.2-0.3 μm) and coarse (1.6 μm) carbides in duplex ferrite-martensite matrix. In addition to the refinement of the carbides, the homogenous dispersion of the particles was found to be more effective in enhancing mechanical properties at 500 rpm tool rotation rate. The improved corrosion resistance was observed and is attributed to the volume fraction of low-angle grain boundaries produced after friction stir process of the AISI D2 steel.

Eskandari et al. [15] investigated the microstructure and wear behaviour of Friction Stir Processed (FSPed) AISI 430 ferritic stainless steel. FSP was performed with a tool rotation and advancing speeds of 1400 rpm, 16 mm/min respectively by employing a tungsten carbide tool. The FSPed microstructure consisted of a mixture of ferrite and martensite. After FSP, microhardness increased with respect to that of the as-received material. The wear resistance of the FSP processed material was significantly enhanced compared to that of the as-received substrate. According to the SEM analyses of the worn surfaces and wear debris, a combination of adhesive wear and delamination was observed in the case of the base metal. The superior wear resistance of the FSP processed AISI 430 steel was attributed to the pronounced grain refinement and to martensite formation in the stir zone.

Chen and Nakata [24]studied tool steel grade SKD61 which was friction stir processed using the PCBN tool at a rotational speed of 300 rpm and travel speed of 30 mm/min. Microstructure, tensile properties and wear characteristic were evaluated. Fine grains with a martensite structure were produced in the friction stir processed zone, which led to the increase of the micro-indentation hardness. The grains became finer when the heat input was lowered. The transverse tensile strength of the friction stir processed zone was equal to that of base metal. The wear width and depth of the friction stir processed zone at the load of 1.96 N were 339 μm and 6 μm, as compared to 888 μm and 42 μm of the base metal, decreased by 62% and 86%. The study suggested that low heat input is an effective method to produce a friction stir processed zone composed of relatively fine grain martensitic structure with good tensile properties and wear characteristic.

Lorenzo-Martin and Ajayi [26] studied the impact of FSP on surface hardening, friction and wear behaviour of Alloy 4140 steel material. The results showed that the steel can be successfully hardened to a level superior to the conventional heat treatment and quenching procedure. While the friction behaviour of the baseline, heat hardened and FSP materials are similar, significant improvement in the wear performance was observed with FSP. It also appeared that wear in FSP material is less dependent on the contact load, when compared to the baseline and other heat treatment. FSP also changed the wear mechanisms in the 4140 steel material. All these improvements in wear behaviour is attributed to the effect of FSP on the microstructure of near-surface layer of the material. The extreme grain refinement resulting from FSP resulted in the formation of ultrafine martensite phase in the processed material.

From the above literature, Friction stir processing has been found to produce beneficial effects on improvement of mechanical properties such as hardness, tensile strength, fatigue, corrosion and wear resistance for various materials.FSP has also proven to be an effective treatment to achieve major microstructural refinement, densification and homogenisation of the processed zone. Friction stir processing has also been investigated for Optimization of the various operating parameters to enhance properties of Metal Matrix Composites (MMCs) and Functional Graded Materials (FGMs) opening new possibilities to modify the surfaces. Despite considerable interest identified from the review of the literature, limited work has been investigated on optimization of parameters for the processing of AISI 4140 alloy steel via Friction Stir Processing in the study of improvement of mechanical properties.

2. Experimental Procedure

2.1. Materials and Processing

For this experiment AISI 4140 alloy steel was selected because of its excellent formability and good weldability [18]. The mechanical properties of AISI 4140 alloy steel are 655 MPa tensile strength and 25.7% elongation [16].The chemical composition of AISI 4140 is presented in Table 1.

Table 1: The table of chemical composition of AISI 4140 [12]

C	Cr	Mn	Si	Mo	S	P	Fe
0.35-0.45%	0.85-1.15%	0.65-0.95%	0.10-0.35%	0.15-0.25%	0.04%	0.04%	Balance

In present study, tensile strength testing machine with the standard of ASTM E8and (Rockwell hardness tester) with the standard of ASTM E18-22 were utilized to conduct the mechanical test. In this investigation, the base materials prepared have the dimensions of 80 mm × 80 mm × 4 mm. In this study, coated tungsten carbide pentagonal tool material was utilized for processing due to its high toughness and wear-resistant property. The pentagonal tool pin profile was obtained by surface grinding and in CNC milling. The dimension of the pentagonal tool pin profile was 3.77 mm pin length and 26 mm shoulder diameter as shown in Figures 1(a) and 1(b). The required size of the base metal marked with a centre line, and the influence of the tool pin profile produced on the surface of the material to manipulate the characteristics were shown in Figures 2(a) and 2(b) respectively.

Figure 1: (a) friction stir processing and (b) Pentagonal tool pin profile

Figure 2: (a) Friction stir processed image and (b) Tensile test specimens

2.2. Method of Process Parameters

The optimization of friction stir processing parameters for AISI 4140 alloy steel was carried outusing Taguchi method, which reduces time for experimentation among a large number of decision variables[14-15]. Signal-to-noise ratios were used to measure and predict the quality of the output w.r.t input parameters. Moderate improvement in the costs can be achieved by this efficient process. Analysis of variance (ANOVA) is used to transform the experimental data into the required decision variables [15, 22, 27]. The Taguchi technique was used to prefer the most reasonable orthogonal array to design the experiments and to consign process parameters [10]. Based on the literature review, the parameters of friction stir processing with three factors and four levels of each process parameters were presented in Tables 2. During the hardness test, each plate has 3 average values that are marked. In the present study, the percentage contribution of input processed parameters to the mechanical properties was determined and successfully implemented by ANOVA. By using the statistical software of MINITAB, the investigational responses were modified into the S/N ratio [13,18,]. Table 3 describes the estimated S/N ratio values.

Table 2: Friction Stir Processing parameters along with factor levels

Process parameters	Notation	Factor levels			
		1	2	3	4
Tool spinning speed (rpm)	TRS(A)	1800	1500	1200	900
Traverse speed (mm/min)	TF(B)	30	50	70	90
Axial load (kN)	AL(C)	7	9	11	13

3. Results and Discussion

3.1 Influence of Process Parameters on the Tensile Strength

Table 4outlines response table of tensile strength for S/ N ratio (Larger is better). From the response table, Axial Load is the most significant influencing factor on the tensile strength, followed by tool feed and tool rotational speed. Accordingly, an increase in axial load leads to maximize the friction occurring between the tool and process material AISI 4140 steel, hence delivering high temperatures at the interface of the processed specimen, which helps in increasing the tensile strength. Figures 3depicts the graph of mean of S/N ratios for tensile strength versus process parameters. Itis found that the maximum tensile strength attained by the optimization of process parameter are A4B1C4,which shows the tool rotational speed at level4 (1800 rpm),tool feed at level1 (30 mm/min),and axial load at level 4 (13 kN).Table 5 displays the ANOVA outcomes for tensile strength. It is validated that tool axial load is the most significant process parameter with a37.75% contribution, succeed by tool feed of34.81%. The tool rotational speed is a least significant process parameter with a19.75% contribution. The 64.83% RSq value of tensile strength shows that the model is capable of predicting the response with great precision.

The interaction plots of process input parameters on the tensile strength are displayed in Figures 4.Interaction graphs depicts that, the parallel line and nonparallel line have no interaction and significant interaction of process parameters on the tensile strength, respectively. In Figure 4(A), the interactions of the tool rotational speed with tool feed were significant at the tool rotational speed of 1800 rpm and 30 mm/min tool feed due to the reason that lower tool feed increases the tensile strength for the entire tool rotational speed as it creates lower heat zone around processed zone. Figure 4(B) shows the interactions between the tool rotation speed and axial load. Consequently, the tensile strength of the AISI 4140 steel processed specimen decreased for the lower axial load (7 kN) if tool rotational speed is at lower level (900 rpm) due to lower penetration in the stirring zone, although it was found that the tensile strength increases with the increase in tool rotational speed at high axial load. High tool rotational speed (1800 rpm), low tool feed (30 mm/min), and the high level of axial load (13 kN) produced higher tensile strength. It is perceived that the higher level of axial load and moderate level of tool feed achieved better tensile strength due to sufficient heat produced in the region.

Table 3: Design of Experimentation using the L16 OA along with Estimated S/N ratio values for Tensile Strength and Hardness

Runs	TRS(A) (rpm)	TF(B) (mm/min)	AL(C) (kN)	Tensile strength (MPa)	Hardness (HRc)	Tensile strength (MPa) S/N Ratio	Hardness S/N Ratio
1	900	30	7	1071	44	60.5958	32.8691
2	900	50	9	1029	42	60.2483	32.465
3	900	70	11	1082	42	60.6845	32.465
4	900	90	13	1088	45	60.7326	33.0643
5	1200	30	7	1093.52	45	60.7765	33.0643
6	1200	50	9	1062	43	60.5225	32.6694
7	1200	70	11	1078	42	60.6524	32.465
8	1200	90	13	1045.94	45	60.3901	33.0643

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9	1500	30	7	1061.43	43	60.5178	32.6694
10	1500	50	9	1050.89	41	60.4311	32.2557
11	1500	70	11	1061.74	41	60.5204	32.2557
12	1500	90	13	1039.82	43	60.3392	32.6694
13	1800	30	7	1673.3	40	64.4715	32.0412
14	1800	50	9	1093.62	42	60.7773	32.465
15	1800	70	11	1031.12	39	60.2662	31.8213
16	1800	90	13	1065	42	60.547	32.465

Table 4: Response Table for Tensile strength of S/N Ratio (Largeris better)

Levels	TRS(A)	TF(B)	AL(C)
1	60.57	61.59	60.55
2	60.59	60.49	60.41
3	60.45	60.53	60.59
4	61.52	60.5	61.57
Delta	1.06	1.1	1.16
Rank	3	2	1

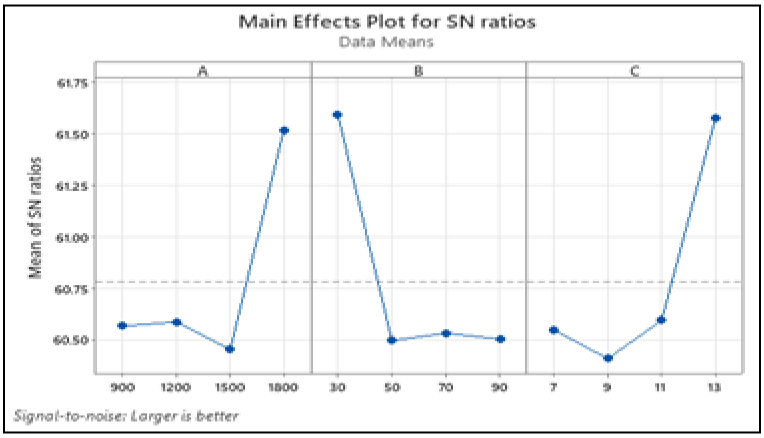

Figure 3: Main effect plot for S/N Ratio of Tensile Strength (MPa) [(a) Tool Rotational Speed (rpm) (b) Tool Feed (mm/min) c) Axial Load (kN)]

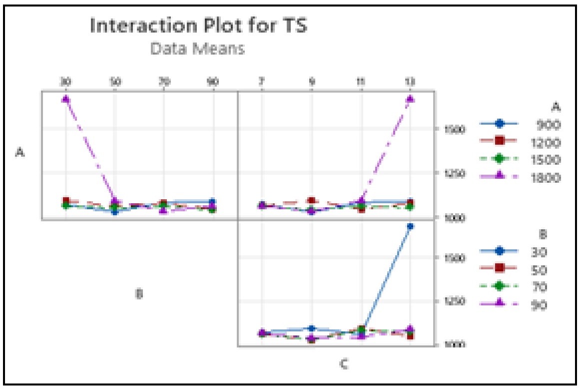

Figure 4: (A) Interaction Plot of Tensile Strength with Tool rotational speed and Tool feed

(B) Interaction Plot of Tensile Strength with Tool rotational speed and Axial Load
(C) Interaction Plot of Tensile Strength with Tool Axial Load and Tool fee

Table 5: Analysis of Variance ANOVA for Tensile Strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A(TRS)	3	70076	19.75%	70076	23359	1.12	0.411
B(TF)	3	120946	34.81%	120946	41982	1.3	0.158
C(AL)	3	133973	37.75%	133973	44658	2.43	0.116
Error	6	33958	7.65%	33958	12802		
Total	15	354867	100%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
144.229	64.83%	12.07%	887552	0.00%

3.2. Influence of Process Parameters on the hardness:

Table 6 presents the response table of hardness for S/N ratio. From the response table, tool rotational speed is the most significant influencing factor on the hardness, followed by tool feed and axial load. An increase in tool rotational speed minimize the friction between the tool and base material AISI 4140 which delivers lower temperatures at the interface of the processed specimen helping increasing the hardness. Figures 5 exhibit the graph of mean of S/N ratios for hardness with respect to process parameters. It exposed that the maximum hardness attained by the optimum level of process parameter unifications is A2B4C3, which shows the tool rotational speed at level 2 (1200 rpm), tool feed at level 3 (90 mm/min), and axial load at level 2 (11 kN).Table 7 displays the ANOVA outcomes for hardness. It is validated that the tool rotational speed is the most significant process parameter with 47.21% contribution, succeeded by tool feed of 37.41%. The axial load is a least significant process parameter with a 4.76% contribution. The 89.39% R-Sq value of tensile strength conceded that the model is capable of predicting the response with greater efficiency[18].

The interaction influence of process parameters on the hardness is exhibited in Figures 6. From the interaction graph, the parallel line and nonparallel line show no interaction and significant interaction of the process parameters on the hardness, respectively. Figure 6(A) shows the interaction of tool feed with tool rotational speed which is significant at a tool rotational speed of 1200 rpm and tool feed of 90 mm/min, due to the reason that higher tool feed increases the hardness for the tool rotational speed as it increases plasticity of processed surface. Therefore, the hardness of the AISI 4140 alloy steel processed specimen decreased for the high axial load (13 kN) if tool rotational speed (1800 rpm) and tool feed (70 mm/min) were high due to non-existent effect on the processed surface, although moderate tool rotational speed of 1200 rpm, high level of tool feed 90 mm/min, and the medium level of axial load of 11 kN produced higher hardness

Fsp increase tensile strength and hardness because grain structure of the processed material is asymmetric; grains on the advancing side of the processed material are more refined than those on the retreating side with different orientations/textures. While it decreases ductility [27-28]

Table 6: Response Table for hardnessof S/N Ratio (Largeris better)

Levels	TRS(A)	TF(B)	AL(C)
1	32.72	32.66	32.56
2	32.82	32.46	32.5
3	32.46	32.25	32.67
4	32.2	32.82	32.46
Delta	0.62	0.56	0.21
Rank	1	2	3

Figure 5: Main effect plot for S/N Ratio of Hardness (HRc) [(a) Tool Rotational Speed (rpm) (b) Tool Feed (mm/min) c) Axial Load (kN)]

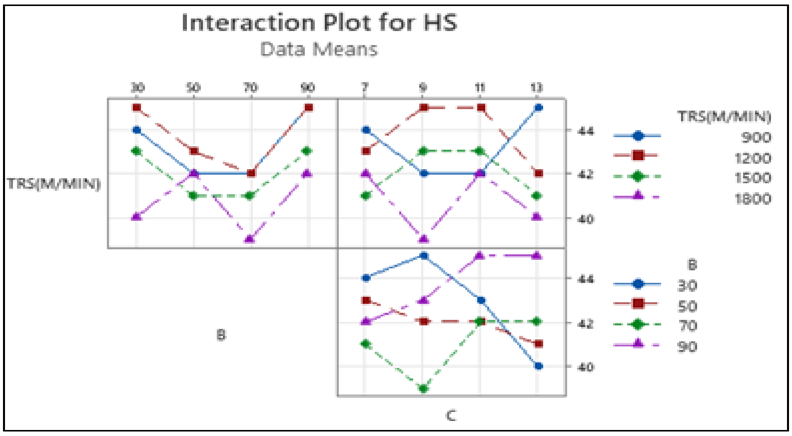

Figure 6: (A) Interaction Plot of Hardness with Tool Rotational speed and Tool feed

(B) Interaction Plot of Hardness with Tool Rotational speed and Axial Load

(C) Interaction Plot of Hardness with Tool Axial Load and Tool feed

Table 7: Analysis of Variance ANOVA for Hardness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A(TRS)	3	21.688	47.21%	21.687	7.2292	8.9	0.013
B(TF)	3	17.188	37.41%	17.188	5.7292	7.05	0.022
C(AL)	3	2.187	4.76%	2.187	0.7292	0.9	0.495
Error	6	4.875	10.61%	4.875	0.8125		
Total	15	45.938	100%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0.901388	89.39%	73.47%	34.6667	24.54%

4. Conclusions

This work aimed to examine the effect of friction stir process parameters such as tool rotational speed, tool feed and axial load on the tensile strength and hardness of AISI 4140 steel. The following conclusions are drawn from the experimental investigations and analysis of results.

Friction stir processing resulted in increasing the tensile strength and hardness of the material by nearly 62% and 200% respectively. The optimal process parameters for maximum tensile strength are observed as tool rotational speed of 1800 rpm, tool feed rate of 30 mm/min and axial load of 13 kN whereas maximum hardness is observed for the tool rotational speed of 1200 rpm, tool feed rate of 90 mm/min, and axial load of 11 kN. The increase in tool rotational speed and axial load leads to an increase in tensile strength and hardness. The ANOVA outcomes revealed that axial load is the dominant process parameter for tensile strength whereas for hardness, tool rotational speed is the dominant process parameter.

The results show the usefulness of FSP in improving the mechanical properties of AISI 4140 steel. Future work may be carried out in evaluating the effect of FSP on tribological properties of AISI 4140 steel.

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