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Development of Steel Surface Composite by Friction Stir Processing

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Abstract: Friction stir processing (FSP) is a solid-state process where the material within the process zone undergoes intense plastic deformation resulting in dynamically recrystalized grain. FSP structure has smaller grain size, low porosity level and improved mechanical properties. By this process hardness of produced composite surfaces is improve more compared to that of Parent metal. Today steel is one of the most common materials in the world. It is a major component in buildings, infrastructure, tools, ships, automobile machines and weapons. That's why the main focus on this work is to improve mechanical properties of steel through FSP. Conventional vertical milling machine, capable of withstanding the forces generation during processed and having a powerful spindle motor to generate torque needed for friction stir processing was selected for the purpose. Essentially trial runs were conducted to develop the correct processing procedure for obtaining defect free processing. Metallurgical testing was carried out using Macro-hardness testing, microstructure examination. Macro-hardness in the process zone and the heat affected zone were found to be more than the base material.
Keywords: FSP, Hardness, Microstructure, Tensile strength.

I. INTRODUCTION

Friction stir processing (FSP) is a new solid-state processing technique that can be used for surface hardening through microstructural modification. This process is a modification of the friction stir welding (FSW) process used for solid state joining of two separate pieces of metallic materials. Basically, FSP involves the use of a non-consumable rotating tool with a pin and shoulder inserted into a single piece of material and traversed along the desired path to cover the region. This action results in significant microstructural changes in the processed zone as a result of severe plastic deformation, mechanical mixing and thermal exposure of the material. The characteristics of FSP have led to several applications for microstructural modification in metallic materials, including enhanced superplasticity, surface composite, homogenization of nanophase alloys, metal matrix composites and microstructural refinement of cast alloys.. Friction stir processing can be applied as a single-pass for processing a small area. For large engineering components in which the contact areas are relatively large, single pass FSP may not be adequate. In such cases, multi-pass FSP with a layer of components is reinforced by ceramic phases while the bulk of components retain the original composition and structure with higher toughness. Friction Stir Processing (FSP) was attempted to incorporate ceramic particles into surface layer of steel alloy to form surface composite. The aim of this work is to investigate the possibility of incorporating ceramic particle into surface layer of steel to form surface composite by means of FSP technique.

II. EXPERIMENTAL PROCEDURE

The basic concept of FSP is a non-consumable tool comprising a shoulder and pin rubs against the work material and produces enormous frictional heat. The heat, combined with deformation by the stirring action of tool pin and pressure due to tool shoulder, produces a defect-free, recrystallized, fine-grained microstructure. Two parameters are very important for FSP, tool rotation rate (ω, rpm) in clockwise or counterclockwise direction and tool traverse speed (v, mm/min) along the line of processing. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes FS process. Higher tool rotation rates generate higher temperature because of higher friction heating and results in more intense stirring and mixing of material.

The tool serves two primary functions: (a) localized heating and (b) material flow. Friction stir processing is a method of changing the properties of metal through intense, localized plastic deformation. This deformation is produced by forcibly inserting a non-consumable tool into the workpiece and revolving the tool in a stirring motion as it is pushed laterally through the workpiece. The important process parameters in friction stir process are the tool rotational speed (Tool RPM), The speed at which the tool is traversed (processing speed), The angle of tilt given to tool (tilt angle), Diameter of the shoulder of the tool(shoulder diameter), Depth up to which the tool shoulder is plunged in work piece (z- plunged depth),Preheating of workpiece.

A. *Tool Fabrication*

Tool Fabrication is the most influential aspect of process development. The tool geometry plays a critical role in material flow and in turn governs the traverse rate at which FSP can be conducted. An FSP tool consists of a shoulder and a pin as shown in Fig 2.1. In the initial stage of tool plunge, the heating results primarily from the friction between pin and workpiece. Some additional heating results the deformation of material. The friction between pin and work piece results in biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important and the other design features are not critical. The shoulder also provides confinement for the heated volume of material. The second function of the tool is to 'stir' and 'move' the material. The uniformity of microstructure and properties as well as process loads is governed by the tool design. The dimension of the tool used in this study are presented in table 2.1

Figure 2.1 Tool with shoulder and pin.

Table 2.1.Tool dimensions

Tool material	Tungsten carbide
Shoulder diameter(d)	20mm
Pin diameter(d_1)	5mm
Pin length(l)	2.7mm

B. *Process parameter*

One of the most important work to study the effect of the processed parameters on development of the composite surface. The processed parameters commonly mentioned in here are tool traversed speed, tool rotational speed, tilt angle.

This is one of the most important parameter that has drawn the interest of researchers working in the area of friction stir processing. Processing speed along with tool RPM decided whether enough heat input is being supplied to the processed which is favorable to develop the metallurgical and mechanical properties. Processing speed lower than 100mm/min, generate excessive heat and the processed made slow. If the processing speed is high the peak temperature is not reached up to recrystalization temperature because for that appeared the defect formation. Thus for performing the experiment the speed selected 100mm/min, 125mm/min and 160mm/min is shown in table 2.1.The another importance parameter for friction stir processing. Most of the researchers have tried to vary it to improve the mechanical properties of the friction stir processing. Tool RPM is deciding the amount the heat generation during the processed. Tool rotation above 710 RPM generates excessive heat cause of that tool got deformed and partially sheared. Less than 450 tool RPM heat generation is very less and the work material did not soften properly. For this the experimentation tool RPM were selected 450 RPM, 560 RPM and 710 RPM is shown in table2.2

Other important parameter is suitable tool tilt angle. Tilt angle is given toward the traveling direction of processing. Researchers specify the value of tilt angle range within 1-3^o for this experimentation tool tilt angle was selected 3^o is shown in table 2.2

Selected processed parameters for this work is shown in table 2.2

Process speed (mm/min)	Tool rotational speed (rpm)	Tilt angle (degree)
100	450	3
100	560	3
125	560	3
160	560	3
160	710	3

III. EXPERIMENTAL WORK

Experiments were carried out in a vertical milling machine made by Bharat fritz Werner Ltd**.** Vertical milling machine can be used as a position control friction stir processing machine. It consists of a vertical spindle on to which the tool is mounted with the help of a collate. The tool can be brought in a contact with the workpiece by lifting the machine table and it can be moved in both vertical and horizontal axis .The plate to be processed can be fixed on the machine table by clamping. The machine can be set to range of weld speeds (31 to 1600mm/min) and spindle speeds (45 to 1800 RPM).The machine is powered by an 11 KW/15HP three phase induction motor. Most of the requirements of friction stir processing are satisfied by a vertical milling machine that is why researchers have used vertical milling and modified vertical milling machine for friction stir processing.

A. FS processing Without Particles

Prior to processing, the backing plate was ground and working plate surface was cleaned with acetone. The plate was clamped tightly with backing plate, before processing the tool rotational speed was set to the desired value. The traverse speed was manually controlled in order to avoid high stresses on the tool. Three degree tilt angle was given. Frictional heating is produced from the rubbing of the rotating shoulder with the workpiece, while the rotating pin deforms and stirs the locally heated material. FSP is considered to be a hot working process where severe plastic deformation occurs within the FS processed sheet. FS processed zone is characterized by
dynamic recrystallization which results in grain refinement, and homogenous, equiaxed grain structure. Figure 3.1 shows the experimental setup of FS processing without particles. Typical process parameters of FSP are presented in table 2.1.

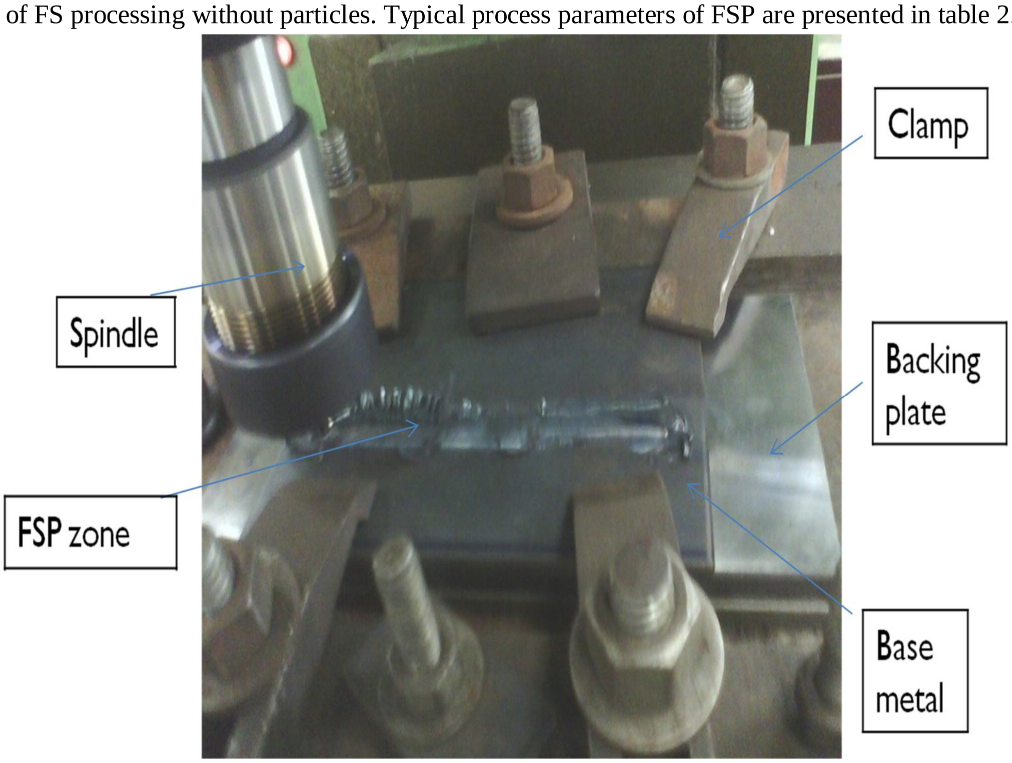

Figure 3.1 processing without particles

B. FS processing with B_4C particles

Friction stir processing (FSP) was employed for the fabrication B_4C composite surface layer on steel plate. Commercially available B_4C micro particles was added into a small amount of methanol and then the B_4C powder was filled into a groove (depth of 1mm×width of 2 mm) on the steel plate before the FSP was carried out. The tool was inserted into the groove filled with the B_4C powder. The tool tilt angle of 3°was used during processing. Figure3.3 shows the experimental setup of FS processing with B_4C particles.

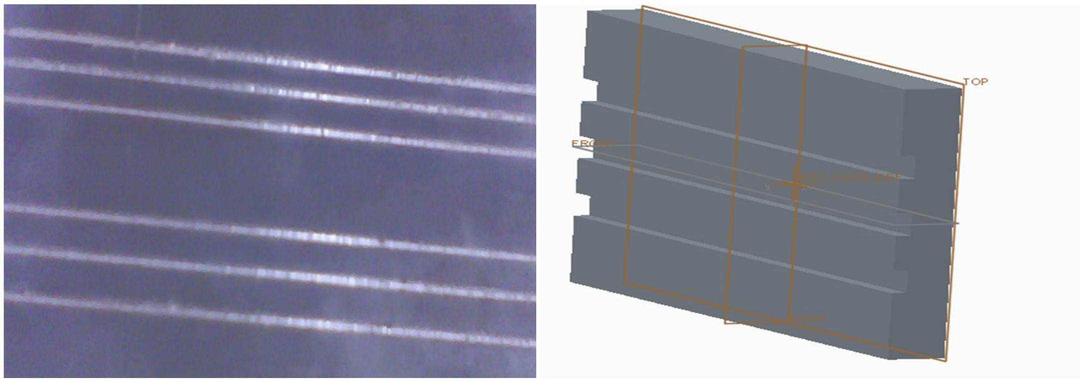

Figure.3.2. Plate used in FSP with B_4C Grooves (depth of 1mm×width of 2 mm) made on the steel plate

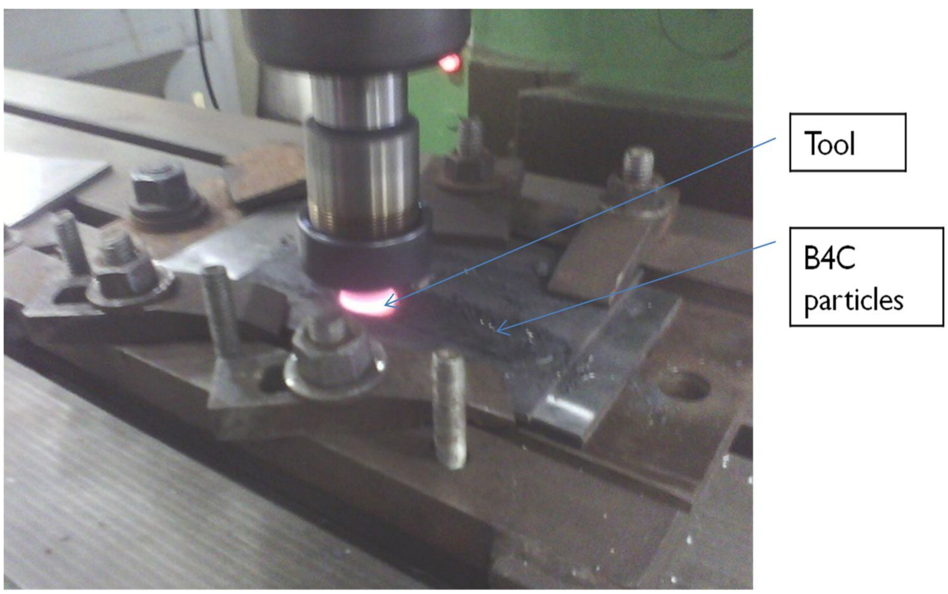

Figure 3.3 Processing with B_4C particles

IV. RESULT AND DISCUSSION

A. Macro Hardness testing

Leica's vicker macro hardness tester was used to measure the macrohardness of the different samples, unaffected base metal, heat effected zone of processed metal and heat effected zone of processed metal with B_4C. The hardness were measured alone the centre line of the process horizontally from one end to the other. A total of 13 indentations 1.5 mm apart were made covering 20mm processed zone for all the processing condition. During making indentation on samples, load was taken 10kg. Indentations were taken on polished surface (prior to etching) so that the indentions are very clear for accurate measurements of the diagonals. Care was taken to ensure that the effect of one indentation is not affecting the hardness values of the adjacent indentation. Vicker Hardness No (VHN)=$1.854P/L^2$, Where P=applied load and L=average length of diagonals in mm.

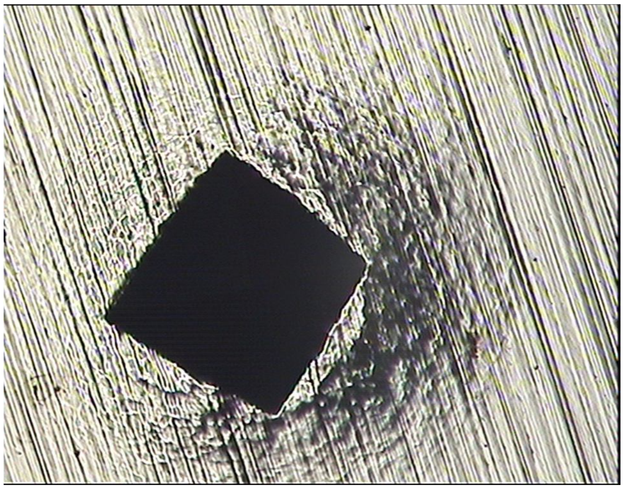
Figure 4.1.1 indentation produced on an uneatched surface

Hardness is resistance of material to plastic deformation caused by indentation and it gives indication about the strength of the material. The load on the Vickers macro-hardness indenter usually ranges from a few grams to several kilograms. The indentations should be as large as possible within the confines of sample geometry to minimize errors in measuring the indentation. Vickers hardness is also sometimes called Diamond Pyramid Hardness (DPH) owing to the shape of the indenter. Leica's vicker macro hardness machine was used to measure the macro-hardness of the different samples base metal, heat effected zone of processed metal without B_4C and heat effected zone of processed metal with B_4C.

The hardness were measured alone the centre line of the process horizontally from one end to the other. Indentations were taken on polished surface so that the indentions are very clear for accurate measurements of the diagonals. Hardness was measured transverse section of the three different samples. In most of the cases increase in hardness values was observed in processed zone. The hardness value in the FS processed specimens with B_4C particles is higher than that of the base metal. This is because of (1) dispersion of the B_4C particles as a harder phase in the steel (2) Severe grain refinement with respect to the base metal and (3) quench hardening resulted from different thermal contractions between the B_4C particles and the matrix.

In the transverse section the hardness values were found around 193HV in the base metal. The processing zone entitled constantly very high hardness at the processed area. After FS processed the average macrohardness value was found around 223HV and after processing with B_4C the macrohardness value was found to be 487HV at processing speed of 100mm/min, tool RPM of 450. Figure 4.1.1 shows the hardness profile across the processed zone.

Table 4.1.1Vicker's hardness data at processing speed of 100mm/min, tool RPM of 450

Distance from centre	Vickers Hardness No of base metal	Vickers Hardness No of FS Processing without particles	Vickers Hardness No of FS processing with B_4C particles
-9	170	200	348
-7.5	192	233	317
-6	180	210	421
-4.5	175	235	399
-3	167	276	483
-1.5	185	264	542
0	173	289	486
1.5	181	240	550
3	168	219	407
4.5	193	206	488
6	161	189	354
7.5	172	199	349
9	160	218	298

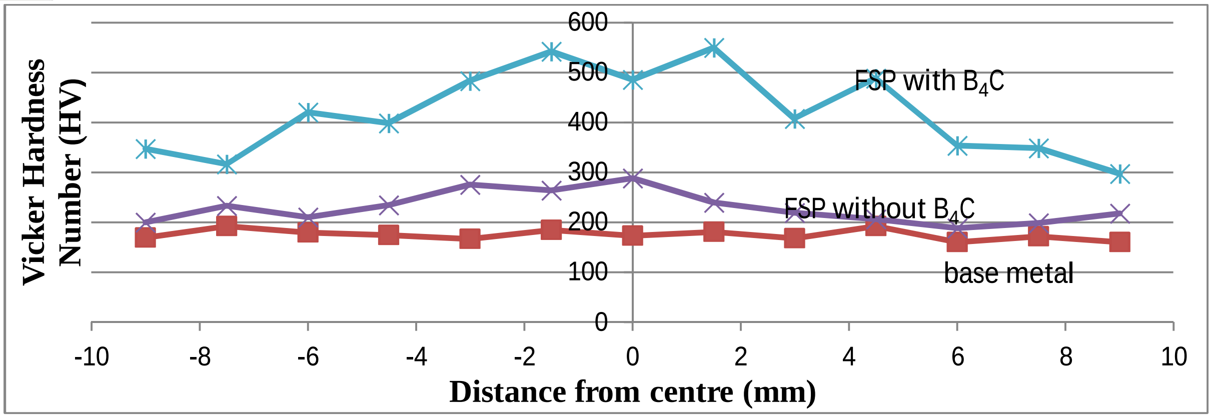

Figure 4.1.1 Result of the Hardness taken on the traverse section (at processing speed of 100mm/min, tool RPM of 450)

The processing zone entitled constantly very high hardness at the processed area. After FS processed the average macrohardness value was found around 251 HV and after processing with B_4C the macrohardness value was found 376 HV at processing speed of 100mm/min, tool RPM of 560. Figure 4.1.2 shows the hardness profile across the processed zone.

Table 4.1.2Vicker's hardness data at processing speed of 100mm/min, tool RPM of 560

Distance from centre	Vickers Hardness No of base metal	Vickers Hardness No of FS Processing without particles	Vickers Hardness No of FS processing with B_4C particles
-9	170	312	385
-7.5	192	249	299
-6	180	294	405
-4.5	175	227	360
-3	167	221	281
-1.5	185	297	525
0	173	336	478
1.5	181	206	437
3	168	206	354
4.5	193	219	380
6	161	281	299
7.5	172	197	348
9	160	285	312

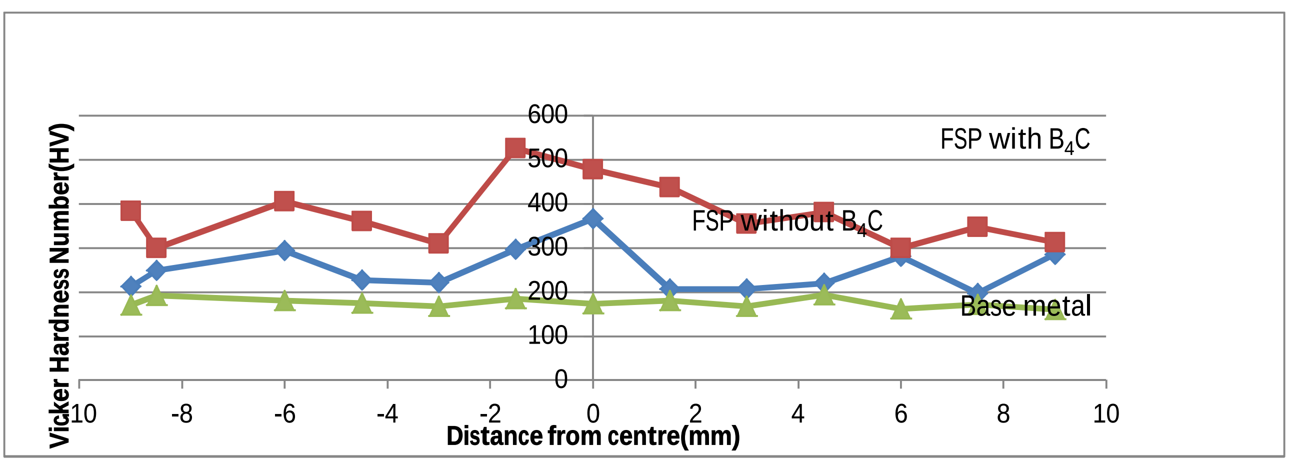

Figure 4.1.2 Result of the Hardness taken on the traverse section (at processing speed of 100mm/min, tool RPM of 560).

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The processing zone entitled constantly very high hardness at the processed area. After FS processed, the average macrohardness value was found around 216 HV and after processing with B_4C the average macrohardness value was found 350HV at processing speed of 125mm/min, tool RPM of 560. Figure 4.1.3 shows the hardness profile across the processed zone.

Table 4.1.3 Vicker's hardness data at processing speed of 125 mm/min, tool RPM of 560.

Distance from centre	Vickers Hardness No of base metal	Vickers Hardness No of FS Processing without particles	Vickers Hardness No of FS processing with B_4C particles
-9	170	205	274
-7.5	192	194	218
-6	180	198	319
-4.5	175	207	268
-3	167	188	283
-1.5	185	218	390
0	173	216	405
1.5	181	199	384
3	168	209	336
4.5	193	292	464
6	161	240	383
7.5	172	216	327
9	160	232	294

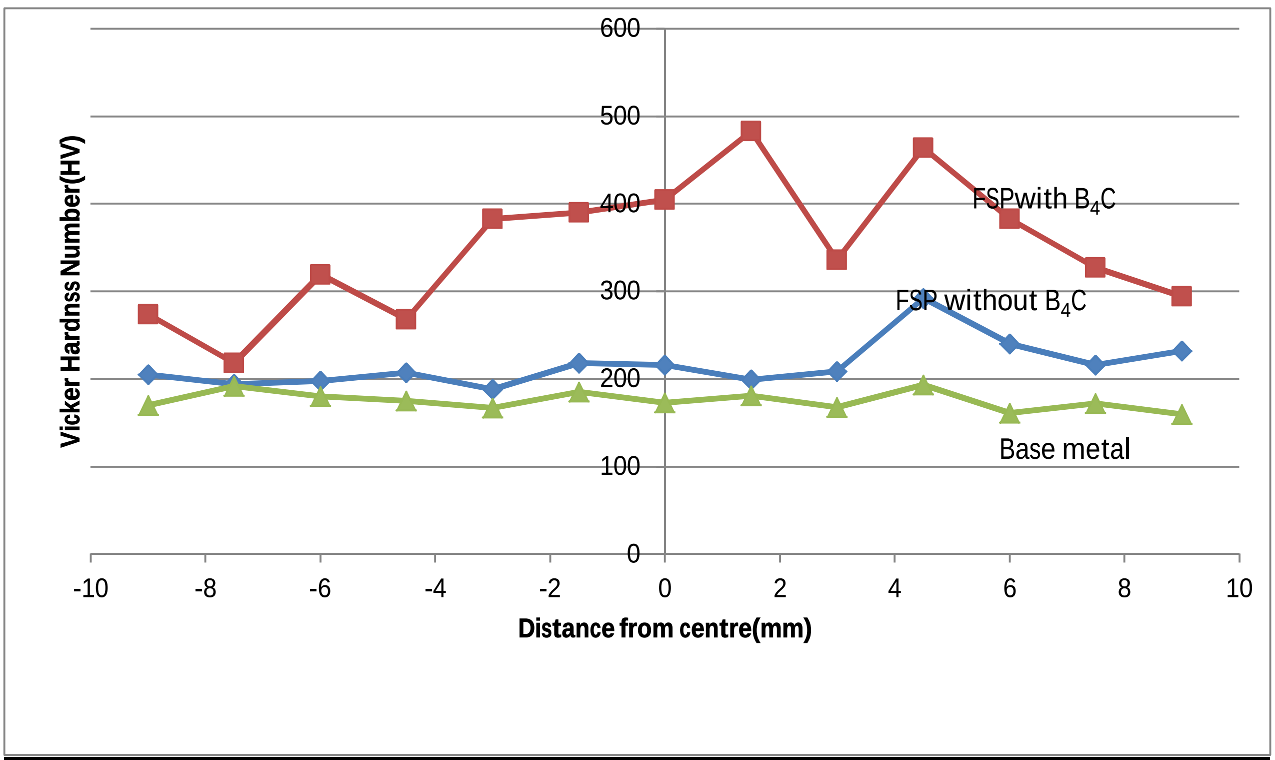


Figure 4.1.3 Result of the Hardness taken on the traverse section (at processing speed of 125mm/min, tool RPM of 560).

The processing zone entitled constantly very high hardness at the processed area. After FS processed, the average macrohardness value was found around 240 HV and after processing with B_4C the macrohardness value was found to be 360 HV at processing speed of 160mm/min, tool RPM of 560. Figure 4.1.4 shows the hardness profile across the processed zone.

Table 4.1.4 Vicker's hardness data at processing speed of 160mm/min, tool RPM of 560

Distance from centre	Vickers Hardness No of base metal	Vickers Hardness No of FS Processing without particles	Vickers Hardness No of FS processing with B_4C particles
-9	170	183	306
-7.5	192	191	322
-6	180	279	287
-4.5	175	210	450
-3	167	175	498
-1.5	185	306	383
0	173	276	464
1.5	181	281	409
3	168	292	413
4.5	193	285	306
6	161	202	289
7.5	172	185	289
9	160	212	270

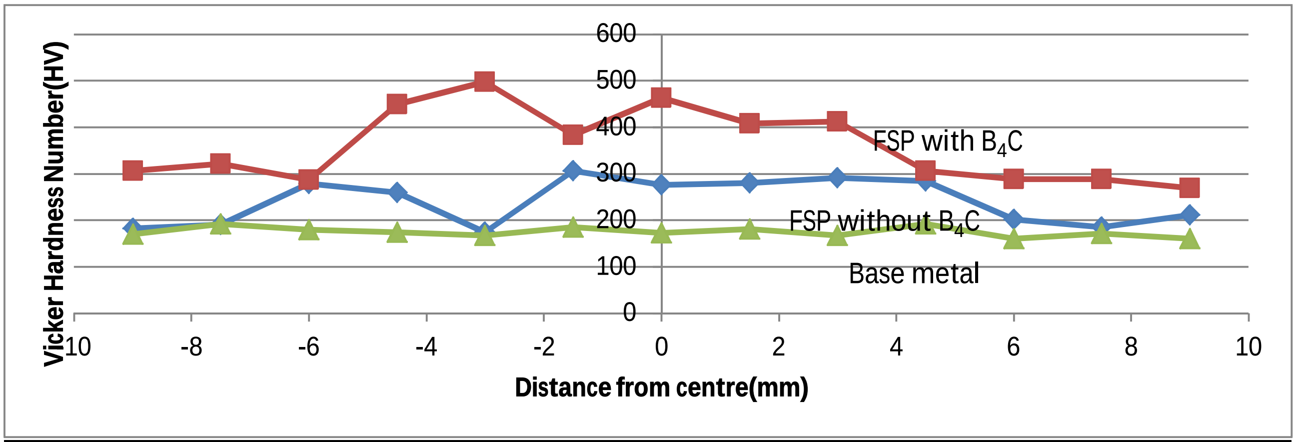


Figure 4.1.4 Result of the Hardness taken on the traverse section (at processing speed of 160mm/min, tool RPM of 560).

The processing zone entitled constantly very high hardness at the processed area. After processing with B_4C the macrohardness value was found to be 387 HV at processing speed of 160mm/min, tool RPM of 710. Figure 4.1.5 shows the hardness profile across the processed zone.

Table 4.1.5 Vicker's hardness data at processing speed of 160mm/min, tool RPM of 710.

Distance from centre	Vickers Hardness No of base metal	Vickers Hardness No of FS processing with B_4C particles
-9	170	333
-7.5	192	368
-6	180	327
-4.5	175	483
-3	167	394
-1.5	185	426
0	173	455
1.5	181	370
3	168	519
4.5	193	354
6	161	383
7.5	172	409
9	160	312

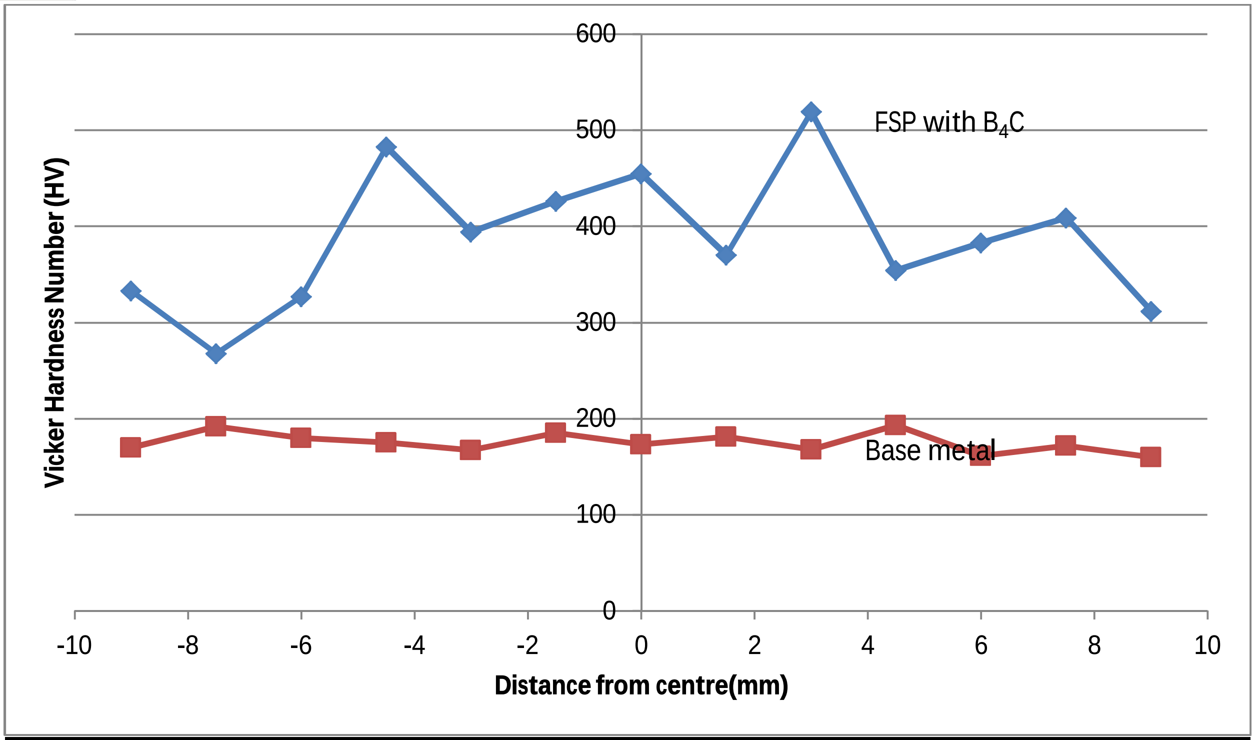
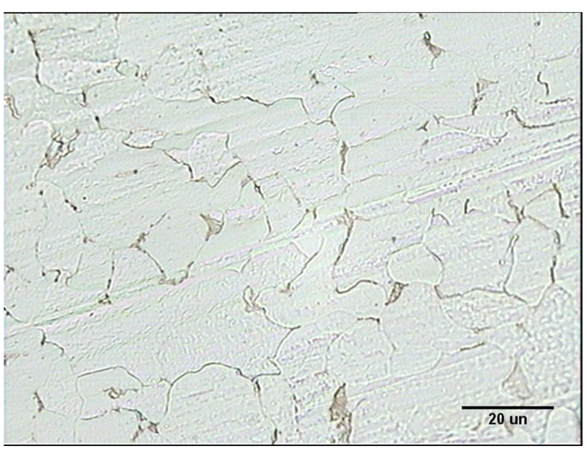


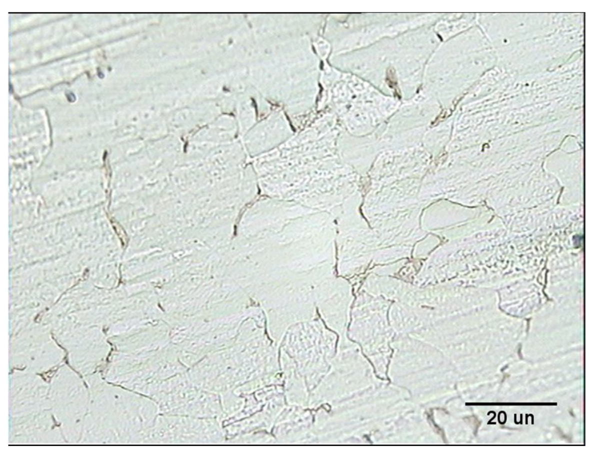
Figure 4.1.5 Result of the Hardness taken on the traverse section (at processing speed of 160mm/min, tool RPM of 710).

B. Optical Microscopy

Different aspects of the microstructure of FS processed steel were studied. The studied features included grain structure and grain size. The process exhibits several distinct microstructural region i.e. processed zone (PZ) and the heat affected zone (HAZ).There is a reduction in grain size from base metal to processed zone. This is because of the dynamically recrystallization happening in processed zone because of friction heat and plastic share. In heat affected zone, there is no much reduction in grain size. Very fine grain of austenite is formed by the processed of dynamically recrystalizaion. The fine recrystallized grains of austenite transform back into ferrite when the temperature falls down. The processed parameters also affected the rate of cooling and the subsequent Austenite→ferrite transformation. The microstructure of the base metal at 500x magnification is shown in figure 4.2.1.



(a)



(b)

Figure 4.2.1 Microstructure of base metal (500 x magnifications).

The microstructure of processed zone and heat effected zones of the FS processed without B_4C specimens at 500x, 200x magnification is shown in figure 4.2

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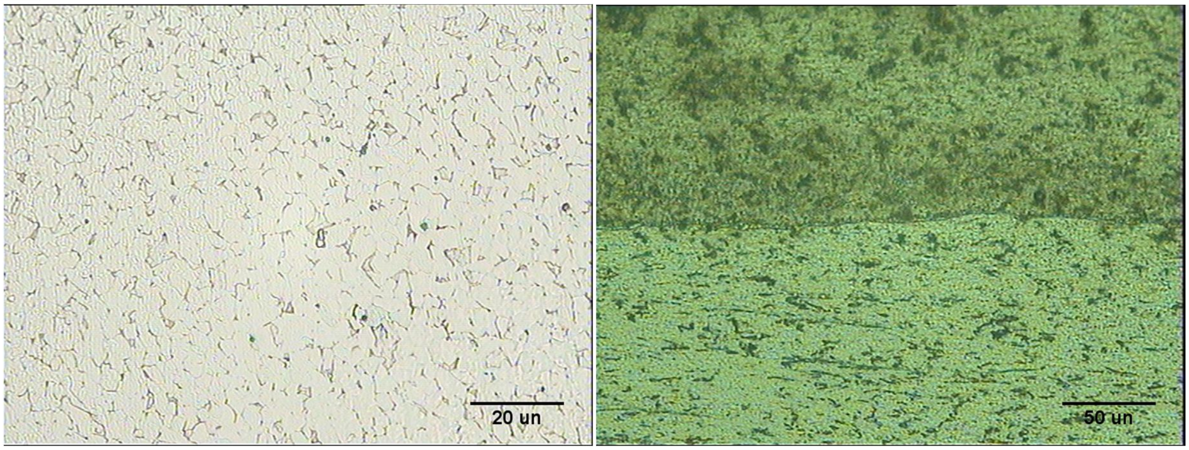

(a) (b)

Figure 4.2.2 microstructure of FS processed without B_4C specimens at500x, 200X magnification (a- PZ and b- PZ and HAZ).

It is evident that B_4C particles were uniformly distributed in steel and no discernible porosities and defects were detected. The surface composite layer was well bonded to steel and no defects were visible. The microstructural features clearly indicate that FSP is very effective technique to fabricate surface metal matrix composite with well-distributed particles. Figure 4.3 shows that the B_4C particle led the grain to be refined by the FSP through a recrystallization process. The grain size in the B_4C particles in processed region was clearly fine compared with that of the region without the B_4C particles. Figure 4.2.3 showing the microstructure of FS processed specimens with micro sized B_4C particles, respectively exhibit that the grain size decreases significantly by increasing the micro-sizes B_4C particles.

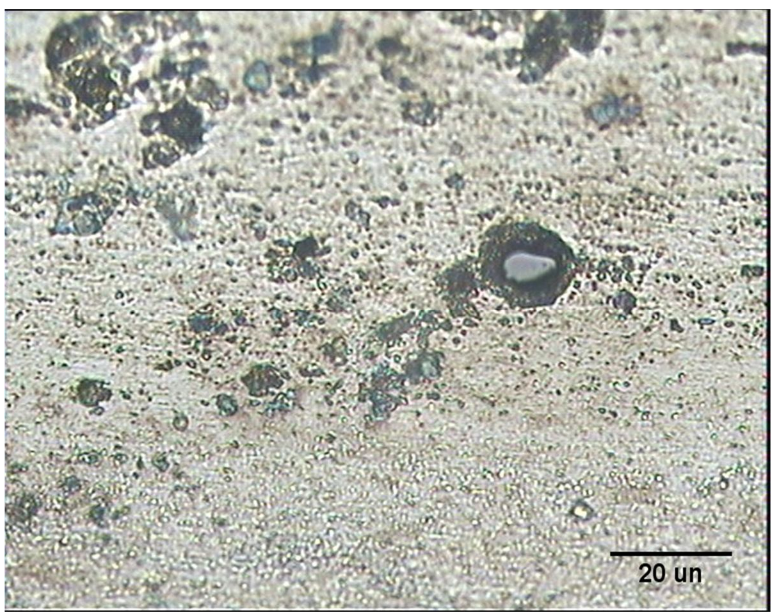

Figure 4.2.3 microstructure of processed specimen with B_4C at 500 x magnifications.

C. Scanning Electronic Microscopy

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with electrons in the sample producing various signals that can be detected and that contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern and the beam's position is combined with the detected signal to produce an image. SEM can achieve resolution better than one nanometer. Specimens can be observed in high vacuum, low vacuum and in environmental SEM specimens can be observed in wet condition. The SEM macrograph taken from the cross-section of process zone of FS processed specimens with B_4C particles shown in figure 4.3.1.

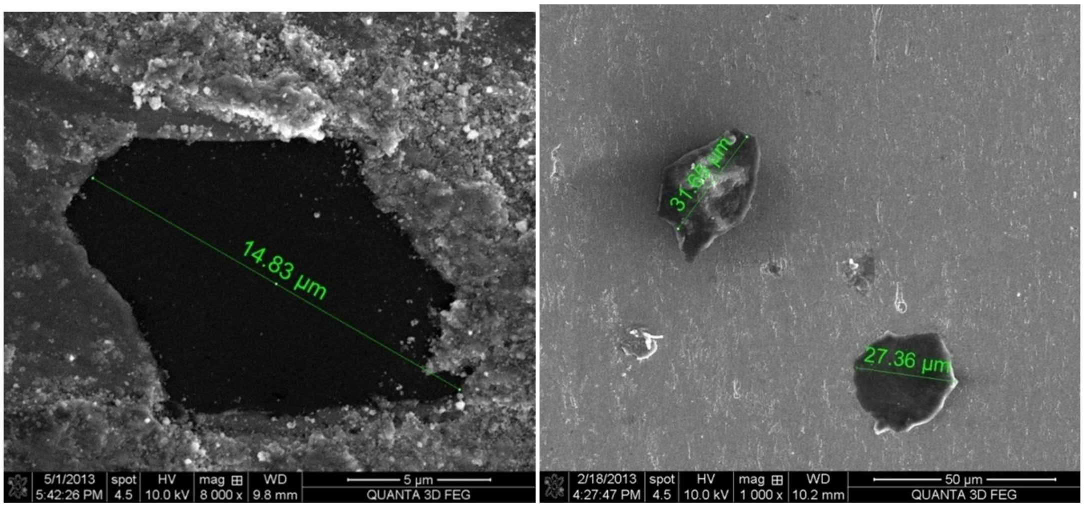

Figure 4.3.1 Microstructure of FS processed specimen with B_4C by SEM.

V. CONCLUSIONS

A. Friction stir processing of steel has been successfully carried out and it has been demonstrated that friction stir processing results in better mechanical and metallurgical properties as compared to base metal

B. Tungsten carbide can work satisfactorily as a tool material for friction stir processing of steel. The tool can work well without failure. It is important to choose the correct grade of tungsten carbide for making tool

C. Friction stir processing shows three distinct microstructures namely the processed zone heat affected zone and the unaffected base metal.

D. The mechanism of microstructural evolution during friction stir processing of steel starts with the formation of small grains of austenite and this is followed by transformation of these fine austenite grains into ferrite and pearlite.

E. The values of macrohardness in the processed specimens are higher than that of base metal, for all combination of process parameters. Though the hardness values vary within the processed zone, and with process parameters, they never fall below the base metal hardness values. The values of macrohardness in FS processed specimens with B_4C particles are larger by two times than that of the base material.

F. Processing speed at 100mm/min, tool rpm 560 is suitable for FS processing without B_4C and for FS processing with B_4C 100mm/min, tool rpm 450 is suitable.

G. FS processed composite surface has been studied through optical microscope and scanning electronic microscope and conforming the B_4C particles to make composite surface.

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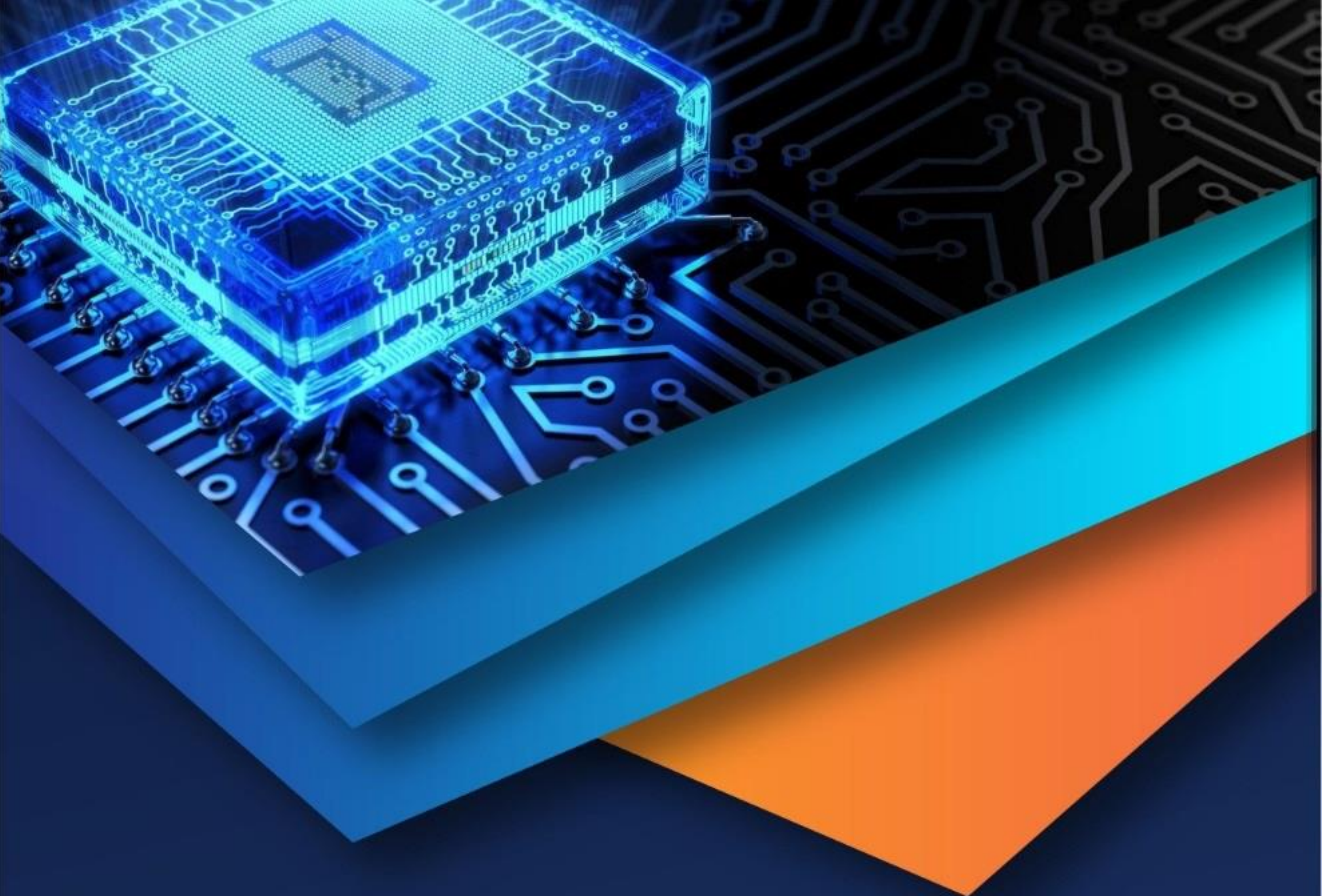

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