Development of Mild Steel - B$_4$C Surface Composite by Friction Stir Processing

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Abstract

Objectives: Friction Stir Processing (FSP) is being attempted in this study to process the surface layer of mild steel and to explore the possibility of incorporating B$_4$C particle into surface layer of mild steel to form surface composite by means of FSP technique. Methods: FSP with B$_4$C particle was carried out on 5.0 mm mild steel and specimens 250 mm x 100 mm were processed in a single pass. The tool material used was tungsten carbide. Trial runs were carried out at different process parameters and the final parametric windows have been developed for getting the defect free surface. With optimized process parameters sound and defect free surface was made. Mechanical Properties were investigated through microstructure and hardness test. The micrographs and hardness graph have been presented and discussed in this paper. Findings: The Micrographs were taken using optical microscope at different location of the processed zone. There was distinct alteration in size and shape of the grains at different location of the processed area. Temperature in the stir zone is sufficient to convert the base material ferrite into austenite region of phase diagram. Since the recovery is slow in austenite, dynamic recrystallization occurs. The amount of deformation in friction stir processing is very large, therefore the critical condition for discontinuous dynamic recrystallization are met. This leads to very fine austenite grain formation. These fine recrystallized grains of austenite transform back into ferrite when the temperature falls down. Macro hardness test was also done using the Vickers hardness test. It was found that the average hardness has increased to more than three to four times in the processed zone as compared to the parent metal. Applications: Technology developed in this study can be effectively used in several areas like mining, mineral processing, aerospace and railway industry, where surface modification is a need to reduce various losses like wear and corrosion.

Keywords: Boron Carbide (B$_4$C), Friction Stir Processing (FSP), Metal Matrix Composites, Nano Particles

1. Introduction

Friction Stir Processing (FSP) is a solid state technique which is generally used for the surface modification of a material. This process could be adopted to improve the surface property like wear resistance, corrosion resistance without affecting the base material property. The tool serves two primary functions:

- heating of work piece, and
- movement of material to produce the modified surface.

The heating is accomplished by friction between the tool and the work piece and plastic deformation of work piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. The near surface properties enhancement by FSP is also expected to induce effects on the wear properties of the friction stirred processed surface. Since surfacing of mild steel by fusion welding results in so many defects like porosity, inclusion etc. and also on the other hand surface gets some coarse microstructure which is also not desired in case of surfacing. This makes use of mild steel difficult in Special applications, FSP can be used in these cases for localized modification of microstructure to improve mechanical properties in the desired areas. * Author for correspondence
2. Materials and Methods

FSP of mild steel was carried out on 5.0 mm thick mild steel plates of dimensions 250 mm x 100 mm. The chemical composition of the base material (mild steel) plate is given in Table 1. A robust vertical Milling Machine (VF-3.5 of Bharat fritz Werner Ltd, with spindle motor power of 11 KW) was used for performing the experiments. The tool material used was tungsten carbide. The dimensions of the tools and tool drawings used are shown in Table 2 and Figure 1.

![Figure 1. Tool drawings (All dimensions are in mm).](image)

The tool was held rigidly in a tool holder and the tool holder was held directly in the collet of the machine. Trial runs were carried out at different process parameters namely tool traverse speed (mm/min), tool rotational speed (rpm), tilt angle (degree) with different tool dimensions and the final parametric windows has been developed for getting the defect free surface which are tabulated in the Table 3.

3. Results and Discussion

Extensive trial runs were performed to get the defect free specimen. Theses specimens were evaluated through metallography and hardness test.

3.1 Metallography

Optical microscopy was performed using Optical microscope. The Micrographs were taken using optical microscope at different location of the processed zone. There was distinct alteration in size and shape of the grains at different location of the processed area. Micro structural examination was taken in top surface as well as in cross sectional direction. Various friction stir processed specimen with B₄C particles with different tool rotational speed and tool traversing speed were taken for microstructure study and analysis.

The microstructure of base metal and processed metal at various magnifications are shown in Figure 2 to 7.

3.1.1 Microstructure Analysis

Different aspects of the microstructure of FSPed mild steel were studied. The studied features included grain structure and grain refinement. The various mechanisms involved in microstructural change are explained in succeeding paragraphs.

3.1.1.1 Stir Zone (SZ)

Due to high temperature of about 1000°C generated in the friction stir processing dynamic recrystallization takes place in the stir zone. The following mechanisms are involved.

### Table 1. Chemical Composition of base metal (Mild Steel)

| Element | Fe  | C   | Si  | Mn  | S   | P   | Cr  | Ni  | Al  | Cu  | N   | B   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Weight in percentage (%) | 99.1 | 0.13 | 0.1 | 0.43 | 0.03 | 0.07 | 0.01 | 0.02 | <0.001 | 0.03 | 0   | 0.01 |

### Table 2. Tool dimensions

| Tool type                  | Cylinder diameter (mm) | Cylinder length (mm) | Pin length (mm) | Pin diameter (mm) |
|----------------------------|------------------------|----------------------|-----------------|-------------------|
| Cylindrical without pin    | 20                     | 75                   | 0               | 0                 |
| Cylindrical with pin       | 20                     | 75                   | 3.5             | 7                 |
| Cylindrical with tapered pin | 20                     | 75                   | 3.5             | 05 and 07 with 29.74 degree taper |

### Table 3. Process window chosen for friction stir processing

| Tool Shoulder diameter (mm) | Processing speed (mm/min) | Tool rotational speed (rpm) | Tilt angle (degree) |
|-----------------------------|---------------------------|----------------------------|--------------------|
| 18 to 22                    | 100 to 160                | 450 to 900                 | 0 to 3             |
Figure 2. Top surface microstructure of Base metal and FSPed mild steel at 100X magnification at 450 rpm and 100 mm/min feed rate.

Figure 3. Cross sectional microstructure of Base metal and FSPed mild steel at 100X magnification at 450 rpm and 100 mm/min feed rate.

Figure 4. Top surface microstructure of Base metal and FSPed mild steel at 200X magnification at 450 rpm and 100 mm/min feed rate.

Figure 5. Cross sectional microstructure of Base metal and FSPed mild steel at 200X magnification at 450 rpm and 100 mm/min feed rate.
• Temperature in the stir zone is sufficient to convert the base material ferrite into austenite region of phase diagram. Since the recovery is slow in austenite, dynamic recrystallization occurs. The amount of deformation in friction stir processing is very large, therefore the critical condition for discontinuous dynamic recrystallization are met. This leads to very fine austenite grain formation.
• These fine recrystallized grains of austenite transform back into ferrite when the temperature falls down.
• These fine grains of austenite transform back into ferrite when the temperature falls down differently near the top of friction stir processed surface and near the center and bottom of parent metal as well as flanks of stirred zone.

3.1.1.2 Partially Transformed Zone (PTZ)

The temperature in the partially transformed zone is not as high as in stir zone and it reaches just about α+γ region of phase diagram. It has a partially transformed grain structure from fine to coarse.

3.1.1.3 Thermo Mechanically Affected Zone (TMAZ)

The temperature was sufficiently high and dynamic recrystallization takes place in majority of the regions where the grains are subjected to plastic deformation. The region slightly away from the partially transformed zone showed some grains with distorted structure as some grains could not get recrystallized. This is a consequence of not achieving sufficient temperature due to heat losses to the surroundings. Stir Zone (SZ), Thermo Mechanically Affected Zone (TMAZ) and Partially Transformed Zone (PTZ) of top surface and cross section of friction processed mild steel at 100 X magnification are shown in Figure 8.
3.2 Hardness Test

Macro hardness test was done using the Vickers hardness test and protocol adopted was IS: 1501-2002 was used to measure the macro hardness of the different samples. During making indentation on samples, load was taken 10kg. Indentations were taken on polished surface so that the indentions are very clear for accurate measurements of the diagonals. Two set of specimens were taken for finding out the hardness of processed specimens produced under various process parameters. One set were taken from the transverse section of the specimen while the second set was taken as top surface of the specimen. On traverse section indentations for hardness measurement were made 1mm apart starting from top surface to bottom of specimen and for the top surface it was from the middle portion i.e. stir zone towards the flank i.e. unaffected base metal.

It was found that the average hardness has increased to more than 3 to 4 times in the processed zone as compared to the parent metal i.e. mild steel. Average hardness value of about 371 HV10 has been attained from base metal with average hardness of about 116 HV10 as shown in Figure 9. It shows that there is an increase in the hardness value, which also indicates the presence of $B_4C$ particles in the grains of mild steel. $B_4C$ reinforcement affects the hardness value in many ways. Firstly $B_4C$ powder is the hard nature. Secondly crushing effect of FSP decreases the size of the $B_4C$ particles and in turn presents extra refinement of ferrite grains through grain boundary pinning. Overall the increase in hardness is attributed to the grain refinement. At times it was very high i.e. 610 HV10 due to high concentration of $B_4C$ particles at localized pockets.

4. Conclusion

Friction stir processing of mild steel as a reinforcement of $B_4C$ particles has been successfully carried out and it has been established that friction stir processing of mild steel with $B_4C$ Nano particles enhance its mechanical and metallurgical properties. Micrographs and hardness graphs discussed in this paper also shows that temperature plays a vital role to validate the process capability. It is also found that by varying the processed parameter it is very easy to control the mechanical properties of processed zone.
5. References

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