Joining Metals by Combining Mechanical Stirring and Thermomechanical Treatment to Form a Globular Weld Structure

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Abstract. A method for joining metals in the semisolid state is presented. A model alloy Sn-15\%Pb was used to demonstrate the concept. By presented process, dendritic microstructure of the weld zone can be avoided. Moreover, near-weld zone of the cold worked substrates which is affected by heat would have a globular structure due to a thermomechanical treatment. The two substrates were heated up locally in the joint line to the semisolid temperature range. At this point a stirrer was introduced into the weld seam in order to mix the two sides into a single uniform joint. Localized mechanical properties of different zones were examined using Shear Punch Test (SPT), showing a good strength in the weld zone and thermomechanically affected zone.

1. Introduction

The most commonly used welding methods consist of a local heating of the substrate above the liquidus temperature (e.g., GTAW, GMAW, LBW, EBW). The liquid metal generally solidifies with a dendritic microstructure. This effect is not desirable from a metallurgical point of view because of the lack of control of the microstructure. Also, the high temperatures necessary to completely melt parts of the substrate induce a heat affected zone. In this zone the material undergoes a thermal history that makes its properties different and generally worse than those of the rest of the bulk material in the substrate, often deteriorate fracture toughness, corrosion resistance and yield strength [1].

During the solidification of castings in the partially solidified state, the formation and growth of dendrites is common, whether columnar or equiaxed. As the solid fraction increases past a characteristic value during cooling, the deformation resistance of the partially solidified metal increases dramatically. However, the deformation resistance is drastically reduced if this same alloy composition is sheared sufficiently during cooling to break up dendrites and form spheroidal solid-phase particles [2].

Semisolid metal forming technology aims to produce metals with globular microstructure free from dendrites. Many methods are used to produce globular microstructure, most of them consists a stir process to break dendrites and make them globular. However thermomechanical processes such as SIMA (Strain Induced Melt Activated) and RAP (Recrystallization and Partial Remelting), produce globular structure by deforming, followed by heating in the mushy zone [7]. Vieira et al. gave these processes the general term “TTM” (Thermomechanical Treatment Mechanism) [8]. TTM is simple and does not need complicated equipments, compared to the stirring method. A uniform and fine globular microstructure is obtained by TTM.

A little effort has been done to use semisolid processing in joining of materials. Mendez used Sn-15\%Pb slurry as filler and applied it on the joint groove, to join bars of this alloy [1]. While in other studies, joining is carried out using semisolid properties in combination with forming in a single process [3, 4, 5, 6].

Changing dendritic microstructure of the weld zone to globular microstructure, offers the potential of avoiding the problems mentioned above, because the solidification and heat transfer processes
are radically different than those of welding using a purely liquid phase. Semisolid welding also dramatically decreases welding distortions. The temperature difference between the weld pool and the bulk substrate is much smaller than in common welding since the welding temperature is below the liquidus temperature [1].

Shear punch test (SPT) was used for assessment of mechanical properties. SPT is based on exerting shear force on a slice of material via a punch with an appropriate diameter. Through this process, the small zone between punch and die experiences shear force. Results are exhibited through a load-displacement diagram similar to those acquired from uniaxial tension test. Shear force can be converted to an equivalent shear stress, of which tensile stresses can be simply derived by equations which are given elsewhere [9, 10, 11, 12].

Experimental Methods

Plates of Sn-15wt%Pb were cut to 17x35x10 mm and rolled from 10 to 8mm of thickness. In order to heat the weld seam to semisolid temperature range locally, a heating system as shown schematically in Figure 1a was designed. N₂ gas was used as the heating medium. A pair of bars was mounted on a small trolley under a nozzle, and the whole arrangement was then mounted on a moving table which moves at a constant speed to move the bars to be joined under the nozzle. A 1.5mm drill coated by TiC was used as a stirrer. After a sufficient area under the nozzle had become semisolid in a way that the stirrer could start revolving with ease, it penetrated into the semisolid area. At this stage, the moving table under the nozzle started to move at a constant speed. The stirrer mixed the material from both bars into a uniform weld metal; moreover, mechanical stirring by the stirrer was used to break the dendrites and make a globular weld zone. A schematic illustration of the joining process is given in Figure 1b.

The stirrer revolved at approximately 150 rpm. The best results were obtained with a gas temperature of 450°C where the mushy weld zone had an approximate temperature of 195°C, corresponding to the volume solid fraction of 42%. The substrate (heated approximately 3 min to reach the target temperature in the localized area) did not deform because the heating system was so designed that the mushy weld zone was limited to a rather small area. The displacement velocity used was 1.7 cm/min. After optimum range for welding parameters were obtained, 4 welds were produced with parameters given in Table 1 for further evaluation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial state</th>
<th>Thickness [mm]</th>
<th>Gas flow [l/min]</th>
<th>Welding speed [cm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rolled</td>
<td>8</td>
<td>5.5</td>
<td>1.66</td>
</tr>
<tr>
<td>2</td>
<td>rolled</td>
<td>8</td>
<td>4</td>
<td>1.66</td>
</tr>
<tr>
<td>3</td>
<td>rolled</td>
<td>8</td>
<td>3</td>
<td>1.66</td>
</tr>
<tr>
<td>4</td>
<td>as-cast</td>
<td>10</td>
<td>3.5</td>
<td>1</td>
</tr>
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</table>
A SPT system for evaluation of localized mechanical properties was designed (Figure 2a) and assembled on a tensile test equipment (Hounsfield model H10KS). SPT was done on the weld or stir zone (WM or SZ), near weld zone (NWZ), and BM (Figure 2b) in order to obtain tensile properties from shear properties using conversion equations.

Results and Discussion

The cross section of the joint made by semisolid stir joining (SSSJ) is shown in Figure 2b, macro-etched to show the contrast between SZ and NWZ. Figure 3 shows SEM micrographs of the joint. In figure 3a and 3b, the smooth boundary between SZ and NWZ is shown, taken from lower parts of the joint. It can be seen in Figure 3a and 3b that both microstructures are not significantly different, and there is a smooth transition, within 100 microns, from one to the other without the presence of an interface or an oxide layer. There is neither microcracking nor porosity, and the appearance of the joint is very smooth and not corrugated. In upper parts of the welds, no clear boundary was distinguishable, indicating a perfect bounding in the weld.

In the near weld zone (NWZ), mechanical work prior to the heating regime produces a globular structure as well, due to TTM which causes recrystallization in grains. The thermomechanically affected zone (TMAZ) is limited to the area which has reached the semisolid temperature. The stir zone has a globular microstructure due to mechanical stirring, where the globules are the solid particles that grew and coarsened during cooling the welds. Sn-Pb eutectic is located between the globules.
Image analysis results illustrated in Figure 4a, indicates a reasonably good sphericity in SZ. In NWZ grains are not as globular as SZ, but results still imply a degree of globularization due to TTM in these regions. Surprisingly, the as-cast specimen shows the best value of sphericity in SZ (0.8), it may be referred to the better action of the stirrer in this substrate.

![Image](image-url)

**Fig. 4** (a) Sphericity in various areas of different samples. (b) Volume fraction solid for different areas of samples mentioned in Table 2.

Probably due to density differences between the liquid phase (Pb rich) and solid phase (Sn rich), some separation of both phases occurred in the weld zone. This separation resulted in a concentration of the liquid phase in the bottom of welds as shown in Figure 3a and 3b. Image analysis for volume fraction solid in different areas of the welds indicates the same criterion (Figure 4b). This diagram also implies that having less heat input by decreasing the gas flow, the separation of phases may be avoided. The separation may also be a result of the stirrer shape and its action. As the stirrer is treaded, it may act similar to a drill and bring the broken solid globules to the top.

Several stages can be distinguished on typical SPT curves shown in Figure 5a, similar to tensile curves. Such curves were used to extract tensile properties from shear data. Ultimate tensile strength of both rolled and as-cast specimens were very similar in SZ and NWZ. Although SPT data show stronger SZ and NWZ for the as-cast specimen, micrographs indicate smoother joints in rolled substrates. Model alloy used in this study can not show the differences well, owing to its having a very ductile nature. It seems that the modification brought by TTM may have more significant effects on industrial metals, where it may be able to prevent problems connected with HAZ. Figure 5b shows the tensile ultimate strength values for current samples. There is no significant difference between SZ, NWZ and BM; although, in almost all samples, BM is stronger.

![Image](image-url)

**Fig. 5** (a) A typical SPT curve for different zones of a semisolid stir joined substrate. (b) Ultimate strength for various zones of different samples.

**Conclusions**

It may be possible to join metals by semisolid stir joining (SSSJ); the advantage of this process is a globular microstructure of the joint and near weld zone, and possibility of joining thick plates
autogenously. The weld zone is thin and the boundary between WM and NWZ is smooth and free of oxides, microcracking and porosity. The critical parameters for obtaining a desirable joint are the gas flow and temperature along with welding speed. In addition, operating temperatures are lower than in fusion welding. SPT is an appropriate means to evaluate mechanical properties locally. The ultimate tensile strength of BM, NWZ and SZ are very similar.

The process has limitations in its current implementation. The first one is that the optimum parameters are changed with the specimen size. It is not possible to maintain the same parameters for a long distance of welding as the temperature of the whole specimen increases; a more sophisticated process monitoring system which changes the parameters with time is necessary for industrial scale. Moreover tool design should be modify in terms of better and smoother mixing of the substrates and prevent forming of pores. Friction stir welding tools may be considered in designing tools for SSSJ. Another limitation is that the heating medium used in this study is limited in its capabilities to low melting point alloys. Possible heating media could involve plasma impinging on the joint seam. These methods would also provide a protective atmosphere and absence of slag.

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References