WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL,* SEPTEMBER 2002
Sponsored by the American Welding Society and the Welding Research Council

Joining Using Semisolid Metals

Semisolid metals can be used as filler metal to obtain joints as strong as the base material

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ABSTRACT. This paper explores the possibilities of joining metals using semisolid slurries. Experiments have been carried out using a model alloy of Sn-Pb to demonstrate the concept, and the results are extrapolated using scaling laws to the semisolid metal joining (SSMJ) of aluminum plates. The advantages of this process are an equiaxed microstructure of the joint, the deposition of large amounts of filler metal in one pass, and the absence of fumes and spatter. Cross-joint tensile tests have been performed showing joint strength comparable to that of bulk material. Key factors in this process are the substrate and slurry temperature, as well as the absence of superficial oxides or contaminants. A criterion for the production of a successful joint is proposed.

Introduction

The key to high-strength welds resides ultimately in the metallurgical properties of the welded region. For processes involving fusion of the base metal (*e.g.,* GTAW, GMAW, LBW, EBW), these properties are largely influenced by the microstructure of solidification. In these processes, the molten metal solidifies with a dendritic microstructure with mechanical properties inferior to equiaxed microstructures.

Joining with semisolid metal slurries — semisolid metal joining (SSMJ) — offers the potential of avoiding some of the problems of conventional fusion welding by using semisolid metallic slurry as the filler metal (Ref. 1). This slurry, which can involve the same base metal and alloying elements as the substrate, or not, is deposited along a locally preheated groove, as shown in Fig. 1, where the solidification and heat-transfer processes are radically different from those of typical welding. The microstructure of the metal deposited in this way is always equiaxed, as shown in Fig. 2, not columnar dendritic as in fusion welding. In this microstructure, solidification occurs at all solid particles simultaneously. Other advantages of this process are the absence of spatter and welding fumes. SSMJ also presents some limitations, such as the need to locally preheat the substrate to a semisolid temperature.

This study focuses on the process of using semisolid metal slurries joining and on the properties of the resulting joints. The production of the semisolid stream is described in detail elsewhere (Ref. 2).

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Semisolid Metal Processing

Semisolid metal processing was invented at Massachusetts Institute of Technology (M.I.T.) in the early 1970s (Ref. 3); a comprehensive description of its fundamentals is given elsewhere (Refs. 4, 5). The equilibrium phase diagrams of metal alloys show regions of temperature and composition where a liquid phase and solid phase can coexist. These regions are highlighted in the phase diagram of Fig. 3, corresponding to the model alloy used in our experiments (Sn 85%-Pb 15%). During the solidification of castings in this 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. Alloys with this spheroidal microstructure in the semisolid state are called semisolid metal slurries, or just semisolid slurries. Flemings illustrates a semisolid slurry created in this manner exhibits a shear strength three orders of magnitude lower than a dendritic system of equal solid fraction (Ref. 4). This permits slurries of significantly high solid fraction to flow easily. The flow properties of a slurry stream can be greatly modified by controlling both the solid fraction present in the stream and the degree of agglomeration of the solid particles. Deformation resistance, or apparent viscosity, can be changed many orders of magnitude by changing the solid fraction of the slurry. A typical aluminum alloy at a 10% fraction solid has an apparent viscosity of the order of 10^{-1} Pa s, similar to that of olive oil. The same alloy at a solid fraction above 50% can have an apparent viscosity of the order of 10^{2} Pa s, similar to that of toothpaste.

KEY WORDS

Metallic Slurry
Aluminum Plate
Semisolid Slurry
Heat Transfer
Viscosity
Scaling

Analysis of the Process

Semisolid slurries allow for control of apparent viscosity of deposition material in such a way that filler remains where it was applied and does not flow along the

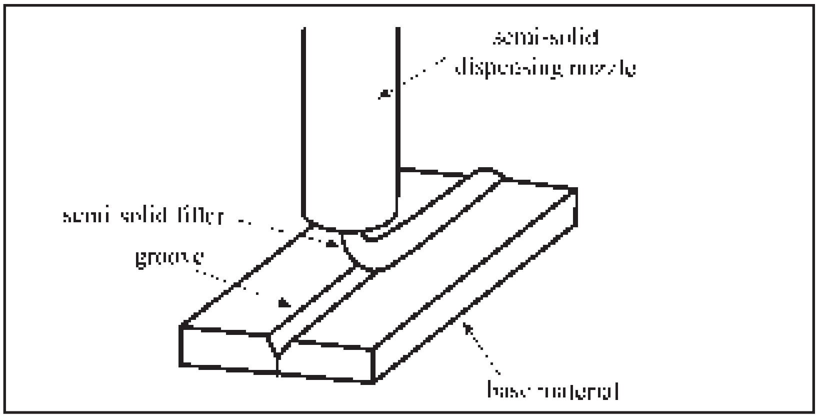

Fig. 1 — Joining using a semisolid metal slurry.

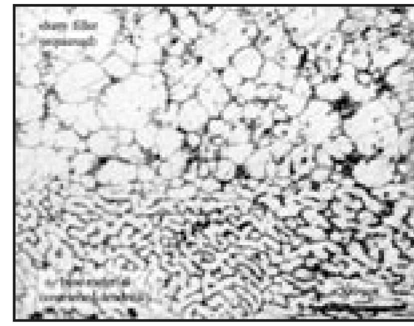

Fig. 2 — Joint between the semisolid slurry and the dendritic substrate.

Table 1 — Characteristic Height Corresponding to Fluid Flow Dominated by Surface Tension Effects (Bond number = 0.1)

Material	Surface Tension (σ) (N/m)	Density (ρ) (kg/m³)	Height (H) (mm)
Sn 85%-Pb 15%	0.6 (Ref. 13)	7200	0.922
Aluminum alloys	0.91 (Ref. 14)	2241 (Ref. 14)	2.035
Iron alloys	1.6 (Ref. 15)	6650 (Ref. 16)	1.566

Note: The characteristic height for surface tension-dominated flows is of the order of a millimeter.

joint groove, even for large filling cross sections. Because the substrate does not reach the liquidus temperature, dilution of the base metal in the filler metal is very small, allowing for joints in which filler alloy can have a very different composition from substrate. This capability of controlling deposition by varying the apparent viscosity is unique to this process, and it is not attainable with other technologies involving molten metal.

Surface tension is the dominant mechanism for holding liquid when molten metal is involved. Capillary effects are sufficiently strong when the bond number (Bo) is much smaller than one:

$$Bo = \frac{\rho_l H^2 g}{\sigma} << 1 \tag{1}$$

where ρ_l is the density of the liquid, H a characteristic height (Fig. 4), g the acceleration of gravity, σ the liquid surface tension. This need for strong capillary forces imposes an upper limit for the cross sections of passes for welding using fully molten metals (Ref. 6). This upper limit is of the order of a millimeter, as shown in Table 1. Different groove geometries can increase this upper limit to values closer to a centimeter in some cases.

Deposition and Deformation of a Semisolid Slurry

In SSMJ, a semisolid slurry is used as filler metal. It is deposited onto the substrate, where it deforms under the action of gravity and cools down simultaneously. As the slurry cools, its resistance to deformation increases, eventually reaching a solid fraction where deformation stops. The driving force for this deformation is the metallostatic pressure and the balancing force is the resistance to deformation of the slurry as a homogeneous material. Dimensional analysis of this process indicates it can be characterized by the following dimensionless group (Ref. 2):

$$Me = \frac{\rho_f g t_c H}{\mu} \tag{2}$$

where ρ_f and σ are the density and apparent viscosity of the slurry used as a filler metal, and t_C is the characteristic time during which the slurry deforms. This dimensionless group can be interpreted as a ratio of metallostatic pressure to viscous resistance to deformation. The larger this number, the more liquid-like the behavior of the semisolid; conversely, the lower this number, the more semisolid slurry will behave like a solid.

The apparent viscosity for a semisolid slurry has been studied in detail by Kumar (Refs. 5, 7). His experimental data for apparent viscosity at steady state for Sn-Pb and aluminum alloys can be summarized with the following formulas:

$$\mu = 0.085787\, f_l^{-4.642} \tag{3}$$

$$\mu = 0.037413\, f_l^{-5.0024} \tag{4}$$

where f_l is the volume fraction of the alloy. Equation 3 corresponds to a Sn85%-Pb15% alloy, and is valid for $0.55<f_l<0.7$ and shear rate below 250 1/s. Equation 4 corresponds to an aluminum alloy with 7% Si and 0.6% Mg. It is valid for $0.5<f_l<0.7$ and shear rate below 300 1/s.

The corresponding value of Me is 327 for the experiments performed. If the slurry had the viscosity of the liquid alloy (approximately 2 x 10^{-3} [Ref. 8]), Me would be three orders of magnitude larger. The characteristic time for this process is determined by the diffusion of heat from the slurry into the substrate; therefore, heat transfer in this system must be understood.

Heat Transfer

Heat transfer from the slurry into the substrate involves complexities such as multiphase transport with variable proportion of solid and liquid phases. These changes affect thermophysical properties of the semisolid. For simplicity, we assume one-dimensional heat conduction perpendicular to the direction of joining, constant properties, and a constant interface temperature. With these considerations, a characteristic time for the heat transfer process can be approximated as

$$t_C = \frac{1}{2}\frac{D^2}{\alpha_f}\frac{(T_f - T_p)}{(T_f - T_i)} \tag{5}$$

where D is a characteristic distance for heat conduction through the cross section of the joint, as indicated in Fig. 4; α_f is the thermal diffusivity of the slurry (semisolid filler); T_f is its temperature; T_i is temperature of the interface between the slurry and base metal; and T_p is the temperature at which the semisolid filler stops deform-

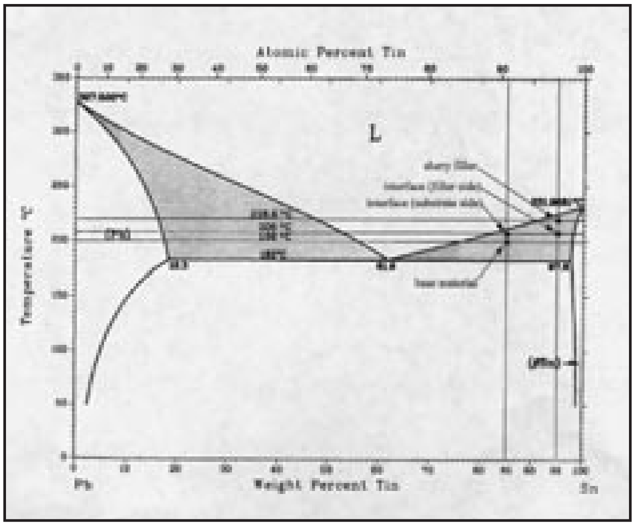

Fig. 3 — Phase diagram for the binary system Pb-Sn (Ref. 17). The shaded areas indicate the semisolid regions in this system.

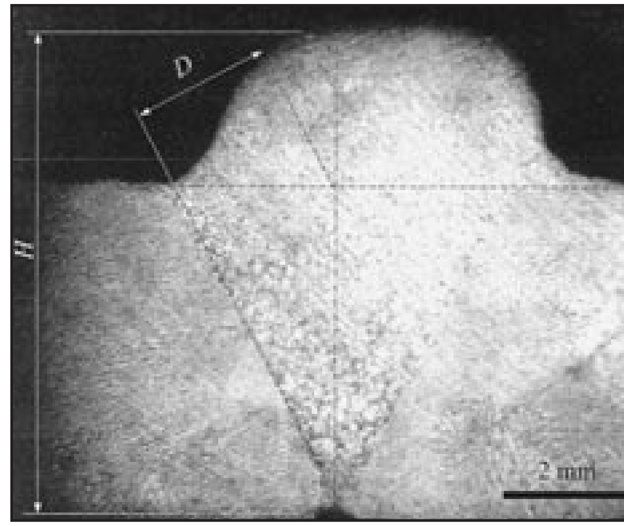

Fig. 4 — Cross section of a weld made by semisolid metal joining.

ing. This point is reached gradually and cannot be clearly defined. For simplicity in this analysis, it will be assumed the semisolid slurry stops deforming when it reaches a solid fraction equivalent to that of closed packed spheres (74%). For the experiments performed, t_C is 0.8 s.

The deduction of Equation 5 is presented in the Appendix. A more sophisticated expression based on the same simplifications of the physics can be found in Ref. 9. Given these simplifications, the use of more sophisticated expression adds little to the accuracy of the representation, yet the analysis becomes more difficult.

The dominant mode of heat transfer can be determined using the Peclet number (Pe); in this problem, this dimensionless group indicates how much heat is brought to the interface by the freshly laid slurry relative to heat carried away by the relative motion of the slurry under the nozzle.

$$Pe = VL / \alpha_f \qquad (6)$$

where V is the velocity of the substrate and L is a characteristic length in the longitudinal direction. The length L can be estimated as $L = Vt_C$. The value of the Peclet number for the experiments performed is 81, which is much greater than one, indicating conduction in the direction of motion is negligible, consistent with the hypothesis made above of one-dimensional conduction perpendicular to the direction of motion. The calculation of the equivalent heat diffusivity of the filler is based on the equivalent heat capacity of a semisolid slurry (c_{pss}).

$$c_{pss} = f_{s,w}c_{ps} + f_{l,w}c_{pl} + \Delta H_{sl}\frac{df_l}{dT_{ss}} \qquad (7)$$

where $f_{s,w}$ and $f_{l,w}$ are the solid and liquid fractions by weight, c_{ps} and c_{pl} are the specific heats of solid and liquid, ΔH_{sl} is the latent heat of change of phase (heat of melting minus thermal energy accumulated by the solid and liquid between the solidus and liquidus), and T_{ss} is the temperature of the semisolid. In this work, the liquid fraction of the Sn-Pb alloys was calculated using the lever rule. The liquid fraction for the aluminum alloy 6061 was obtained from Ref. 10.

The importance of heat losses at the surface can be evaluated using the Biot number (Bi)

$$Bi = \frac{h_e H}{k} \qquad (8)$$

where h_e is the equivalent surface heat transfer coefficient, which includes convection in still air and radiation. The expression for h_e is $h_e = h + \varepsilon\sigma_{SB}(T_f + T_0)(T_f^2 + T_0^2)$, where h is the convection coefficient for heat transfer in still air (approximately 20 W/m^{2}K), ε is the emissivity coefficient (approximately 0.06), σ_{SB} is the Stefan-Boltzmann constant, T_f is the absolute temperature of the surface of the slurry and T_0 is the absolute temperature of the surroundings. The convection term is dominant for the conditions of the experiments performed, and the corresponding Biot number is of the order of 10^{-3}, indicating surface heat losses are negligible.

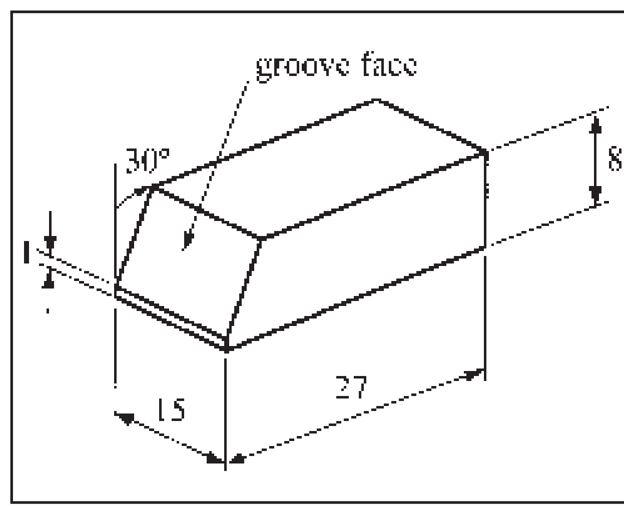

Fig. 5 — Dimensions of bars welded (mm).

Description of the Experiments

Bars of Sn 85%-Pb 15% (Fig. 5) were joined with semisolid slurry of composition Sn 95%-Pb 5%. The semisolid slurry was produced in a rheocaster, shown schematically in Fig. 6. Six pairs of bars were mounted on an aluminum plate, as shown in Fig. 7, and the whole arrangement was then mounted on a heating plate. The heating plate was on top of a computer-controlled x-y-z table, which moved the bars to be joined under the stationary slurry-dispensing nozzle. The bars were fitted with K-type thermocouples to record temperature histories. The bars

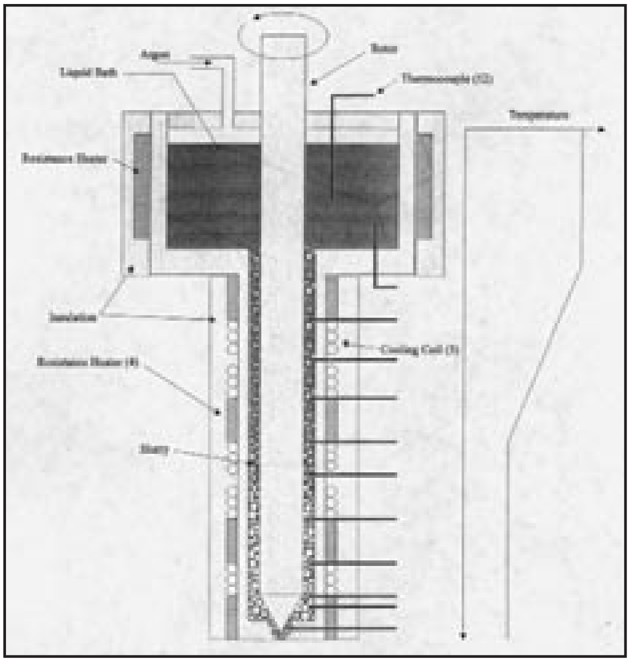

Fig. 6 — Rheocaster used to create the semisolid slurry (Ref. 2).

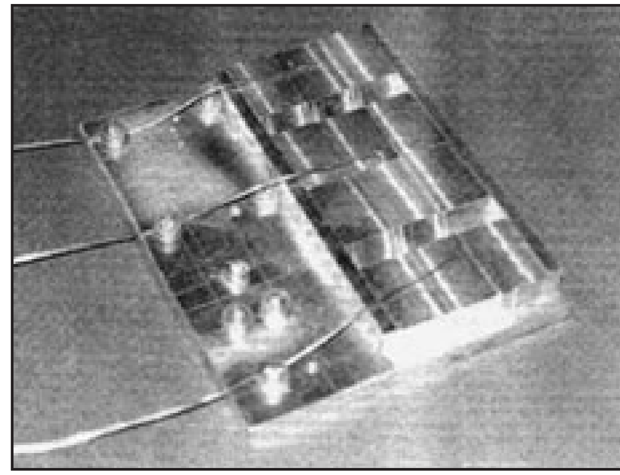

Fig. 7 — Setup of the bars to be welded.

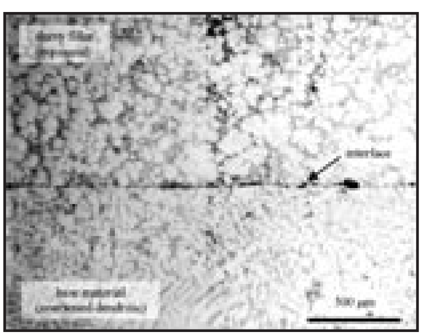

Fig. 8 — Interface of an inadequate weld. The microstructures of the filler and base metals are clearly separated by the interface, which acts as a path for crack propagation, significantly weakening the weld.

had an as-cast dendritic microstructure that coarsened slightly during the heating stage (approximately 35 min to reach the target temperature).

The slurry was produced with a shear rate of 200 1/s, and had a typical solid particle diameter of 100 microns. The best results were obtained with a substrate temperature of 198°C and a slurry temperature of 218.6°C, corresponding to volume solid fractions of 41.7% and 46.9%, respectively. Although the substrate was in a semisolid regime, it did not deform significantly because its dendritic microstructure had a high degree of interlocking, with the dendrites acting as a sort of skeleton preventing deformation (Ref. 5). For real-life applications outside the laboratory, having the whole substrate preheated to a semisolid temperature would be impractical, and the substrate should be locally heated.

The displacement velocity used was 20 mm/s, and the slurry flow rate was 1.6 cm^3/s. The experiments joined two sets of three pairs of bars for each run of the rheocaster. The joint was performed by depositing the semisolid slurry in a rectilinear path along the joint grooves.

The model filler metal employed, Sn 85%-Pb 15%, is the low-temperature system typically used for semisolid experiments (Refs. 5, 11, 12). The rheocaster was also loaded with an alloy of this composition. Due to density differences between the liquid phase (Pb rich) and solid phase (Sn rich), some separation of both phases occurred. This separation resulted in an initial liquid Pb-rich phase, followed by steady semisolid slurry of lower Pb fraction (Sn 95%-Pb 5%). The joining experiments were performed using this slurry. It will be shown later this difference in composition is beneficial for the joining process.

Criterion for a Strong Joint

The single most important factor for obtaining a good joint in SSMJ is the condition of the interface. The interface must be clean of oxides or contaminants that can prevent good contact between the deposited slurry and base metal. In addition to cleanliness, the interface has to reach a critical temperature that would enable a metallurgical joint between the slurry and the base metal. If the temperature is too low, a clear line-up of grain boundaries indicate the original location of the interface, as shown in Fig. 8. In this last case, the interface is significantly weaker.

In a good joint, there is no sharp microstructural transition at the interface, as shown in Fig. 2. This evidence suggests that for a good metallurgical joint, while the filler metal is being deposited, the semisolid interface must be soft enough to be deformed and permit the interlocking of the solid phase particles. Smaller solid particles of the slurry could potentially interlock into harder interfaces; however, this effect could be countered by the fact that at a given solid fraction, more solid particles need to be accommodated when their size decreases. The slurry solid particle size is determined by the slurry production machine, and it varies little for typical slurry-production machines, with values ranging between 100 and 200 microns, depending on the cooling and stirring rate for alloy systems comprising tin-lead, aluminum, and steel (Ref. 4).

Since resistance to deformation is strongly linked to solid fraction and temperature (Ref. 4), a heat balance at the interface is a useful tool to analyze a criterion for a strong joint.

Assuming the slurry-substrate interface as a one-dimensional conduction heat transfer process as suggested above, the interface temperature at the instant of contact can be calculated as suggested by Carslaw and Jaeger (Ref. 9)

$$T_i = \frac{T_f}{1 + \frac{k_b}{k_f}\sqrt{\frac{\alpha_f}{\alpha_b}}} + \frac{T_b}{1 + \frac{k_f}{k_b}\sqrt{\frac{\alpha_b}{\alpha_f}}} \qquad (9)$$

where T_i is the interface temperature, k_b and α_b are the thermal conductivity and diffusivity of the substrate, and k_f and α_f are the thermal conductivity and diffusivity of the semisolid slurry acting as a filler metal. Equation 9 shows the temperature

Table 2 — Parameters for the Experiments Performed and Their Extrapolation through Scaling

Base Metal	Filler Metal	Plate Thickness (mm)	H (Fig. 4) (mm)	D (Fig. 4) (mm)	Velocity (V) (mm/s)	Deposition Rate (lb/h)	Base Materials Temp. (T_b) (°C)	Filler Temp. (T_f) (°C)	Interface Temp. (T_i) (°C)
Sn 85%-Pb 15%	Sn 95%-Pb 5%	8	14.9	4.8	20.0	90	198.0	218.6	206.1
Sn 85%-Pb 15%	Sn 95%-Pb 5%	25.4	47.4	15.4	14.6	670	201.9	212.5	206.1
A356	6061	8	14.9	4.8	24.8	42	591.7	615.2	603.5
A356	6061	25.4	47.4	15.4	10.8	186	599.8	607.1	603.5

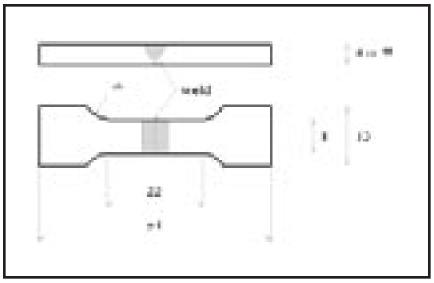

Fig. 9 — Dimensions of specimens used for tensile tests (mm).

Table 3 — Thermophysical Properties of Semisolid Sn-Pb Binary Alloys (Refs. 12, 13, 17, 18)

Sn (wt-%)	Pb (wt-%)	Temperature (°C)	Solid Fraction (f_s) (vol-%)	Thermal Conductivity (κ) (W/mK)	Density (ρ) (kg/m^3)	Specific Heat (c_p) (J/kgK)	Thermal Diffusivity (α) (m^2/s)	Viscosity (μ) (Pa s)
85	15	198.0	41.7	50	7430	984	6.84×10^{-6}	no flow
85	15	201.9	30.4	50	7410	1190	5.67×10^{-6}	no flow
85	15	206.1	14.8	50	7400	1520	4.45×10^{-6}	no flow
95	5	206.1	79.4	50	7180	647	10.8×10^{-6}	no flow
95	5	209.7	74.0	50	7170	785	8.88×10^{-6}	no flow
95	5	212.5	68.2	50	7160	950	7.35×10^{-6}	17.6
95	5	218.6	46.9	50	7140	1740	4.03×10^{-6}	1.62

Table 4 — Thermophysical Properties of Semi solid Aluminum Alloys (Refs. 10, 19)

Alloy	Temperature (°C)	Solid Fraction (f_s) (vol-%)	Thermal Conductivity (κ) (W/mK)	Density (ρ) (kg/m^3)	Specific Heat (c_p) (J/kgK)	Thermal Diffusivity (α) (m^2/s)	Viscosity (μ) (Pa s)
A356	591.7	30.9	160	2685	5860	10.2×10^{-6}	no flow
A356	599.8	19.9	160	2685	7210	8.26×10^{-6}	no flow
A356	603.5	14.8	160	2690	7760	7.68×10^{-6}	no flow
6061	603.5	77.3	180	2700	8530	7.82×10^{-6}	no flow
6061	604.8	74	180	2700	9200	7.25×10^{-6}	no flow
6061	607.1	67.8	180	2700	10300	6.50×10^{-6}	22.5
6061	615.2	41.6	180	2700	12000	5.57×10^{-6}	0.552

of the interface is a weighted average of the temperatures of the slurry and the substrate. If their properties are the same, the temperature of the interface is their arithmetic mean. For the experiments performed, the estimated temperature of the interface for good joints was 206°C, corresponding to a solid fraction of 14.8% for the substrate side of the interface. The inadequate joint of Fig. 8 was performed with a slurry temperature of 198.5°C and a substrate temperature of 111°C, which correspond to an interface temperature of approximately 150°C, below the eutectic temperature and well into the fully solid region. The fact that the slurry has a different composition from the base alloy is useful as the lower alloying content of the slurry allows for the deposition of hotter slurry at equivalent solid fractions, thereby remelting the interface with the substrate. The temperature and composition of the filler slurry and base metal are represented in the phase diagram of Fig. 3.

Based on experiments performed, one of the requirements for a strong joint is that interface temperature should correspond to a solid fraction of the substrate of 15%.

Scaling of the Process

An extrapolation of the experiments presented to other dimensions and materials systems can be performed with the help of similarity considerations. Similarity will be achieved by maintaining constant three dimensionless parameters: Me, Pe, and the solid fraction at the substrate side of the interface, f_{si}. Maintaining the value of these dimensionless parameters implies preserving the same slurry deformation conditions, same heat transfer conditions, and same joining conditions at the interface.

Table 2 presents the extrapolated conditions for the SSM joining of 1-in.-thick Pb-Sn plate, and 8-mm- and 1-in.-thick aluminum plate. The thermophysical properties for the alloys used in this work are listed in Tables 3 and 4. Aluminum alloy 356 is joined with aluminum alloy 6061 because the latter can be deposited at a higher temperature for equivalent solid fractions in a fashion similar to the deposition of a Sn-Pb slurry with lower Pb content than the base metal. The thicker plates need a filler metal deposited at temperatures close to the packing temperature, T_p. This temperature corresponds to the solid fraction of a closed-packed arrangement of spheres (74%). Accuracy in temperature control is more important

Table 5 — Results of the Tensile Tests

Test No.	UTS (MPa)	Elongation (%)	Thickness (mm)	Comments
1	56.0	41%	4	Joined specimens
2	55.4	36%	4	
3	54.9	35%	4	
4	55.3	36%	5	
5	52.9	39%	5	
6	48.4	23%	5	
7	58.5	57%	4	Control
8	59.5	61%	5	specimens,
9	49.2	30%	5	not joined
Average not Joined	55.7	49%		
Average joined	53.8	35%		

Note: Joined specimens have similar strength as the base material, but lower elongation.

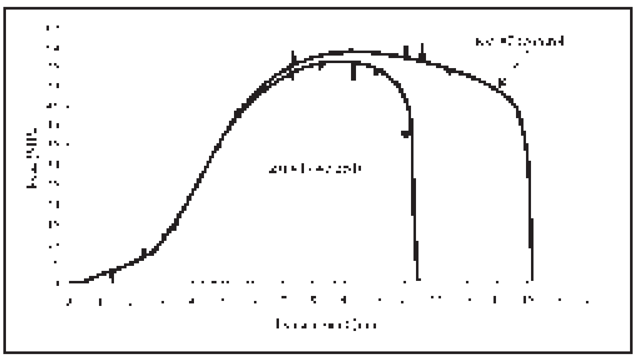

Fig. 10 — Load-displacement curves for welded and control specimens.

than for thinner plates because small temperature variations cause large variations in the characteristic time for deformation of the semisolid.

Results

Figure 4 shows a cross section of a joint made by SSMJ, etched to show the difference in microstructure between the bars and the filler metal. Figure 2 shows a micrograph of the joint between the substrate (bar) and filler metal (semisolid slurry). The substrate is in the bottom part of the picture and the semisolid filler metal on top. The solidified slurry that constitutes the filling has a globular microstructure where the globules are the solid particles that grew and coarsened during cooling in the rheocaster. Sn-Pb eutectic is located between the globules. The substrate has a coarsened dendritic microstructure, a product of the preheating process before the deposition of the slurry. It can be seen both microstructures are significantly different, and there is a fast transition, within 300 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.

Tensile tests have been performed on specimens (Fig. 9) joined with this process. A displacement-controlled tensile machine was used for the tensile tests. The displacement rate was 1 in./min, approximately equivalent to a strain rate of 1.9 x 10^{-2} in./in./s. This high strain rate was chosen to reduce rate-dependent effects since room temperature corresponds to a high homologous temperature for the alloy tested. The thickness of the specimen was 4 or 5 mm, depending on whether the slurry had completely filled the groove. Six joined specimens and three control specimens were tested. The control specimens were not joined, but had been subjected to the thermal cycle on the heating plate. Figure 10 shows superimposed typical load/displacement curves for a joined and a control specimen.

Table 5 summarizes the results of the tensile tests. The ultimate tensile strength of both the joined specimens and the control specimens are very similar, and in no case did the final specimen rupture occur in the joint zone. The elongation of the joined specimens is smaller than the control specimens, however.

Discussion

It was seen during the experiments that this process is very sensitive to the temperatures of the slurry and substrate and the corresponding liquid fractions. The exact mechanism of the metallurgical joint between the slurry and the substrate is not yet well understood. For the temperature and composition of the substrate (198°C, Pb 15%), the corresponding liquid fraction is 57% (Ref. 12). For the temperature and composition of the slurry (218°C, Pb 5%), the liquid fraction is 49%. Although the substrate has a higher liquid fraction than the slurry, it still keeps its shape during the time of the experiment while the slurry deforms significantly under its own weight. The slurry can flow more easily because it has a globular structure, whereas the substrate has higher deformation resistance because it has a dendritic structure that has to be disrupted before large deformations can occur (Ref. 5).

Some specimens exhibited pitting in the surface of the gauge length after machining. We discarded those specimens because of the sensitivity of the tensile test result to stress concentrations. It was observed cracks started in these surface pits at early stages of the tension test. This problem occurred in about one third of the specimens. One origin of this pitting was the porosity in the as-cast microstructure of the joined bars. Another source for pitting was surface contamination or oxidation on the face of the joint groove before the deposition of the slurry. Despite that, in Fig. 2 there is no contaminant or oxide film, there is a possibility some contamination of the exposed surfaces occurred. No protective atmosphere was used in the experiments. This effect would be reduced if the heating of the substrate was carried out in an inert atmosphere or a flux coating was used. An inert atmosphere might be necessary for other materials with greater affinity with oxygen.

The joined bars showed smaller elongation than the control specimens. One possible explanation for this reduction in ductility is the difference in composition between the base metal and filler alloys. The microstructure of the joined zone is also different from that of the base metal. The control specimens experienced the same thermal cycle of the joined specimens, including bulk temperature excursions into the semisolid regime. The reason for this was to compare the strength of the joints with all parameters being equal. Additional tensile tests of the control specimens before thermal cycling could offer a comparison of the strength of the joint and locally affected substrate with the strength of the substrate far from the joint.

Conclusions

It is possible to join metals with semisolid slurries; the advantage of this process is an equiaxed microstructure of the joint, the deposition of large amounts of filler metal in one pass, and the absence of fumes and spatter. The critical parameters for obtaining a good joint are the substrate and slurry temperature, as well as the absence of superficial oxides or contaminants.

Semisolid fillers provide the unique feature of having a controlled flow once deposited, even for deposition rates that cannot be contained by capillary forces. In addition, operating temperatures are smaller than in arc welding.

The process has limitations in its current implementation. The first one is that the heating of substrate is not localized, so the bulk of the bars to be joined is raised to a semisolid temperature. Another limitation is that our rheocaster for slurry production is limited in its capabilities to low-melting-point alloys such as the Sn-Pb alloy used in the experiments.

Future efforts include the application of this technology to alloys of commercial interest with higher liquidus temperatures and better structural qualities, such as the aluminum alloys studied theoretically above. Further work is also required to determine the best method for preheating the joint groove since the heat content of the slurry by itself is not enough to soften the interface adequately. A suitable preheating method should also prevent groove face oxidation or contamination. Possible preheating methods could involve hot inert gas or plasma impinging on the groove immediately before the deposition of the slurry; these methods would also provide a protective atmosphere and absence of slag. Practical considerations also remain to be addressed, especially from the point of view of design for ease of use of the semisolid slurry dispenser.

Acknowledgments

The authors would like to thank Prof. Tom Eagar and the reviewers for their helpful comments on the original manuscript.

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Appendix

Characteristic Time for Heat Transfer

Assuming one-dimensional heat conduction, the problem of heat diffusion from the slurry to the base metal can be formulated as the deposition of a layer of semisolid slurry (thickness D) deposited on top of the base metal. The goal is to estimate the characteristic time t_C in which the slurry reaches the solid fraction where fluid flow stops. The energy the slurry must release in order to reach this solid fraction is

$$E_f = \rho_f c_{pf} D\left(T_f - T_p\right) \qquad \text{(A1)}$$

where ρ_f, c_{pf}, and T_f are the density, specific heat, and temperature of the slurry, and T_p is the temperature at which the slurry stops flowing. This energy is transferred into the substrate by conduction and can be estimated as

$$E_b \approx k_f \frac{T_f - T_i}{D/2} t_c \qquad \text{(A2)}$$

where k_f is the thermal conductivity of the slurry and T_i is the temperature of the interface between the slurry and the base metal. Equation 5 is obtained by making $E_f = E_b$.