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INVESTIGATION OF FRICTION STIR WELDING OF Al METAL MATRIX COMPOSITE MATERIALS

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Introduction

The innovative process of Friction Stir Welding (FSW) has generated tremendous interest since its inception about a decade or so ago since the first patent in 1991 by TWI of Cambridge, England. This interest has been seen in many recent international conferences and publications on the subject and relevant published literature [1-3]. Still the process needs both intensive basic study of deformation mechanisms during this FSW process and analysis and feasibility study to evaluate production methods that will yield high quality strong welds from the stirring action of the appropriate pin tool into the weld plate materials. Development of production processes is a complex task that involves effects of material thickness, materials weldability, pin tool design, pin height, and pin shoulder diameter and related control conditions. The frictional heating with rotational speeds of the pin tool as it plunges into the material and the ensuing plastic flow arising during the traverse of the welding faying surfaces provide the known special advantages of the FSW process in the area of this new advanced joining technology.

This research study will analyze the development of the FSW process in production of long welds of up to 4 foot length of functionally graded Al metal matrix materials (Al-MMC) materials. These materials possess high stiffness and other potential benefits for extreme conditions of space applications. The FSW process is now a reality and has been adopted by shipbuilding and marine industries and finds applications for aerospace applications. The present study should advance understanding in applications of the advanced Al-MMC materials. Developments of discontinuous reinforced Al-MMCs have found applications in space applications as seen in the special advantages of the solid state FSW process over conventional welding such as: the absence of a melt zone, reduced distortion, strong welds, no need for shielding gases, ease of automation and success seen in longitudinal butt welds and circumferential lap welds. Other industrial sectors can also realize benefits from this process. Development of the FSW process for Al-MMCs is relatively new and the process [4] promises advantages of no reaction and no need for joint preparation as mandated in conventional fusion welding. Microstructures should provide better evolution as no dendritic or inhomogeneous structures would result during the process. Some of the reported related work [5] has pointed out the difficulty in fusion welding of particulate reinforced MMCs where liquid Al will react with SiC to precipitate aluminum carbide (Al_4C_3). Advantages of the process are clearly seen and need to be realized in optimum processing conditions.

Al-MMCs, 4 in x 12 in plates of 0.25 in. (6.35mm) thickness, procured from MMCC, Inc. were butt welded using FSW process at MSFC NASA using prior set of operating conditions. These materials are of the same composition as studied in the previous analysis [6]. MSFC is developing the FSW process for several projects [7]. There is interest in advancing the FSW technology for production of long welds in Al-MMC materials and in comparison of the wear behavior of selected pin tool materials. Based on the pin tools behavior of the monolithic design and a two-piece pin tool design as utilized in the previous study, and wear characteristics encountered, in this study all welds were made using a modified design for a monolithic pin tool. ferro-tic, stellite, and tool steel T-15 pin tool materials were investigated for selected operating and material weld conditions. Details of welding history, pin tool wear performance and weld quality were investigated.

Weld quality was evaluated using radiography and standard metallography techniques. Mechanical behavior of these plate materials upon friction stir welding of these plates is to be analyzed with increasing volume fraction of ceramic particles in the composites. The weldability of the Al-MMC materials and the pin tool wear behavior is analyzed and reported in this work. Such studies are essential if Al-MMCs are to find their wide spread use in space applications.

Experimental Process Results

Al-MMC plates as procured from MMCC, Inc.,4 in x 12 in plates of 0.25 in. (6.35mm) thickness with 40 vol. % SiC and 55 vol. % SiC, (17μ+3μ), 3 DP +sintered + 0.25 in. layer with ceramic edge of 5%, 20% and 30% Al_2O_3 saffil edges were friction stir welded to study the weldability and pin tool wear behavior. The five categories of Al-MMC materials that are investigated in this study included:
Category 1-40% SiC bulk, 0.25" 5% saffil Al_2O_3 layer at plate edges
Category 1-40% SiC bulk, 0.25" 20% saffil Al_2O_3 layer at plate edges
Category 1-40% SiC bulk, 0.25" 30% saffil Al_2O_3 layer at plate edges
Category 4-40% SiC bulk and at plate edges
Category 5-55% SiC bulk and at plate edges.

In the earlier FSW studies the two piece ferro-tic pin tool shoulder had indicated fracture in some of the welding, and one of the goals of the present study has been to investigate the behavior of the new monolithic design of the pin tool materials for the five selected categories of the Al-MMC materials. The study included analysis of 3 different monolithic pin tools namely, of ferro-tic, stellite and T-15 tool steel, F 1-4, S 1-4, and T 1-4 pin tools.

The FSW process in this research work was performed using the MSFC vertical weld tool friction stir weld system in the Productivity Enhancement Complex. The welds of up to 4 foot length were produced in selected process conditions. All welds were single pass butt welded in comparative similar conditions. The study included the pin tool characterization prior to and post welding under similar FSW process conditions. All pin tools had the same standard design for comparison purposes. The welding operating conditions were selected similar to as in prior studies. A typical horizontal travel speed of about 3 inches per minute, a plunge depth of about 0.01 inch and a rotating spindle speed of about 650 rpm was considered appropriate from these studies.

In initial welds, the welding was done in a satisfactory manner using T-1 pin tool from category 1 to 4 MMC materials. However in welding of the category 4 MMC material with no saffil edges and 40 vol. % SiC material welding, the pin tool had been heavily worn out and threads were mostly gone. In the next category 5 MMC plates with no saffil edges and 55 vol. % SiC material weld, the welding was carried out with S-1 pin tool. However, this weld could not be completed, and the plates cracked into pieces at about 3-3/8 inch location into the weld. Category 5 MMC material indicated difficulties in welding of these plates and appears to be unweldable. All the other four category materials were then subsequently utilized in the FSW study of long welds up to 4 foot length. The test welds and the material weldability were evaluated further with radiographic inspection, and macroevaluations and microscopic examinations.

In production of the long MMC welds, plates from each category 1 to 4 MMC materials were utilized. The selected category plates were stacked in sequence on each other along the short edges and tack welded. Two sets of 4 tack welded plates were then used for producing 4 foot long welds that were butt joint and tack welded along the length at the beginning, end and selected locations for stability and keeping a straight edge during welding. These first 4 foot long welds were completed using ferro-tic and T 15 tool steel pin tool materials in similar process conditions. In the welding of category 4 material with 40% SiC edge and no saffil, the pin tool broke during welding at about 1-1/3 foot location indicating difficulty in long welds for this material. Welded panel photos were taken and radiography was performed for weldability evaluations.

The evaluation of the Stellite pin tools was performed by welding of the remainder plates of the materials in category 1, 3, and 4 that were available for this study. With the remaining MMC plates, for this evaluation, 3 foot long welds were completed using similar previous process conditions. The Stellite pin tools S-2, S-3 and S-4 were evaluated in this part of the study. .

From the weld panels after completing the first 4 foot long welds of category 1 to 4 MMC materials, these welds were then cut out and these plates were then used to re weld using outside second edges. There was ,however, difficulty in cutting of the first weld of category 4 materials, and for this only two foot long weld was produced. Evaluation of ferro-tic and tool steel pin tools was carried out in this analysis. Based on evaluation of the processing of the first 4 foot long welds, and to reduce any distortion on welding at the junctions in long welds, tack welds along the short edges in these second 4 foot long welds were done across the two sides in stacking the plates to nearly cover the width of the two plates along their short edges. These second weld panels were earmarked for further evaluation of weld properties at room temperature and cryogenic temperatures and any joint efficiency and related studies. All welding history data and process results for the above 3 foot and 4 foot long welds are available and submitted separately. All weld panels were photographed after the FSW process and evaluated by radiography. The wear of the ferro-tic, stellite and T 15 tool steel pin tools was evaluated using micrometer, and profile measurements and details of measurements are provided separately.

Large optical macroscans of the FSW weld regions of selected specimens showed a typical weld and stir zone structure as seen in a typical onion type structure in the center enclosed by the surrounding HAZ, and the unaffected parent metal structure. The composite base plate with saffil edges have the structure gradient and interactions of the Al_2O_3 and the SiC particulates in category 1-3 materials, and the variation of SiC particulates in the materials with out the saffil edges. The Al_2O_3 particles appear as lighter elongated particles and the SiC as the angular, darker particulates in the FSW weld microstrutures.

FSW in welding panels of functionally graded Al-MMC materials of categories 1-4 has been accomplished for up to 4 foot length welds using selected ferro-tic, stellite and T 15 tool steel pin tools. Category 5 material due to 55 vol% SiC reinforcement was unweldable. In some cases lack of consolidation and possible worm holes are seen and quality improvements in such cases can be made based on data generated and welding experience in these cases. Material push through can be seen in some cases due to soft saffil edges, and for this a backing plate has then been used to avoid any effect on the anvil material. In some cases, flash has been accumulated possibly due to too hot a weld. In these productions of long welds, the pin tool history has indicated that T 15 tool steel pins provided larger cumulative weld lengths of up to about 72 inches, and the ferro-tic pin tools provided cumulative weld lengths of about 54 inches in producing 4 foot long welds. The stellite pin tools provided cumulative weld lengths of about 36 inches in producing 3 foot long welds. Continuing mechanical property evaluations are to be carried out of the second 4 foot long welds. The welded plate specimens and all weld data are available to further fine tune the processing conditions for producing long welds.

Summary

The selected FSW weld evaluations of up to 4 foot long welds have analyzed the behavior of ferro-tic, stellite and tool steel pin tool materials for welding of functionally graded Al-MMC materials. Category 1-4 MMC materials are weldable using the FSW process. The weld defects could be reduced further upon optimization of weld parameters. However, in producing long welds it is seen that a related problem is seen in the alignment of the plates and distortion that affects the weld quality. Having long plates will remove this issue arising from having small size plates. In the previous study and from the current work, it is seen that monolithic pin tools have fared better than the two piece pin tool shoulder assembly used in prior studies. Ferro-tic, stellite and T 15 tool steel all appear to be suitable for welding of Al-MMCs. The pin tool life and wear is seen to be dependent on the volume % reinforcement. The FSW process using the monolithic design pin tool holds good promise for welding and development of MMC materials.

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References

[1] TWI, Proceedings of the 1st Friction Stir Welding Symposium, Thousand Oaks, CA, 1999.
[2] TWI, Proceedings of the 2nd Friction Stir Welding Symposium, Gothenburg, Sweden, 2000.
[3] TWI, Proceedings of the 3rd Friction Stir Welding Symposium, Kobe, Japan, Sep. 2001.
[4] Stellwag Jr. W.L. and Lienert, T. J., “Friction Stir Welding of Aluminum Metal-Matrix Composites”, AEROMAT Conference, June2001.
[5] Lee, J.A., Carter, R.W. and Ding, J: Friction Stir Welding for Aluminum Metal Matrix Composites (MMC’s), NASA/TM – 1999-209876.
[6] R.M. Diwan, “Investigation of Friction Stir Welding and Laser Engineered Net Shaping of Metal Matrix Composite Materials”, NASA SFFP Report 2001.
[7] B.N. Bhat, R.W. Carter, R.J. Ding, K.G. Lawless, A.V. Nunes, C.K. Russell and S.R. Shah., “Friction Stir Welding Development at NASA” - Friction Stir Welding and Processing, edited by K.V. Jata, M.W. Mahoney, R.S. Mishra, S.I. Semiatin, and D.P. Field, TMS (The Minerals, Metals & Materials Society), 2001.