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Failure analysis of tungsten based tool materials used in friction stir welding of high strength low alloy steels

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ABSTRACT

A non-consumable tool is a vital requirement for friction stir welding (FSW) of high melting point alloys such as steel and titanium. In this investigation, an attempt was made to understand the pre-weld and post-weld microstructural characteristics of three tungsten based alloy FSW tools viz. 90%W, 95%W and 99%W. High strength low alloy (HSLA) steel plates of 5 mm thickness were welded using the above tools with a tool rotational speed of 600 rpm and welding speed of 30 mm/min. Microstructural characteristics of the FSW tools, before and after welding, were analyzed using optical microscopy (OM), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) techniques. From this investigation, it is found that the tool made of 99%W doped with 1% La_2O_3 exhibited microstructural stability due to absence of Fe–Co–Ni phase formation at elevated temperatures during FSW process.

1. Introduction

Friction stir welding (FSW) is a promising solid state joining technique for welding of high melting point alloys such as steel, titanium and nickel based alloys. FSW is known for green, high productive welding technology with lower emission of harmful gases as compared to fusion welding process [1]. Mechanical action in the form of frictional stirring on the base material modifies the coarse grain microstructures into fine grains due to plastic deformation and fast cooling rate [2]. Welding of steels will be affected by both the temperature and composition which extensively affects the microstructure evolution. Tool wear and plastic deformation are the two major problems encountered during FSW of high melting point alloys (L80 steel) [3]. The tool wear is either due to mechanical damage or chemical affinity of the tool and work piece; however, the plastic deformation is associated with the variation in stress, strain rate and temperature during FSW. Therefore, the tool must withstand high frictional and resultant forces experienced by the pin during initial plunge stage [4].

Most of the tool failures are reported during plunge stage, thus resulting in poor stirring and non-uniform grain refinement of the parent material in stir zone and thereby, violating the primary advantage of the FSW process itself. However, the tool should withstand and counter various forces generated at the initial plunge stage along with other factors while tool is allowed to traverse in the weld direction. The tool pin is responsible for plasticizing the stir zone, excavating the softened material from advancing side to retreating side and consolidating beneath it so as to begin the next cycle [5]. Selection of tool material and its configuration is the key features to avoid interaction gap between consecutive cycles, which eliminates defects like wormholes, pin hole and tunnel defect at the advancing side [6].

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Jiye et al. [4] explained the tool wear mechanism of W–La tool and advocated the use of conical pin with large pin length as compared to smaller one for better stability [7]. Hence, the taper conical larger pin was mostly recommended. During the tool transverse motion, the tool shoulder should support the pin by generating optimum heat to plasticize the parent material which in-turn reduce the flow stresses. This supportive heat generation should be uniform throughout the weld length. The variation in flow stresses during welding will lead to pin damage resulting in poor weld quality. Consolidations of the material extruded are secondary function of the shoulder [8,9].

The tool distortion such as expansion or contraction, rubbing wear and if any one of the situation prevails will lead to poor weld quality, loss of tool pin, and severe plastic deformation [10]. Much of the tool degradation may be attributed to the high heat (temperature around 1200 °C) and stresses generated during FSW of steel. The brittle tendency of the poly-cubic boron nitride (PCBN) tool used for FSW of steel and titanium alloys can cause tool breakage due to sudden spike in load or vibration during tool plunging and traversing [11]. Apart from the tool material selection, researchers had also investigated other possibilities to reduce tool wear and breakage such as pilot-hole and partial penetration. However, the problems are not solved yet completely. Recent developments in the tool material, tool design and processing strategies fetters feasibility of friction stir welding of high melting temperature materials.

Tool cost is also considered as an important factor, which restricts the application of FSW technology for steels. However, the tungsten base alloys are cheaper than W–Re/W–Re–HfC/PCBN tools. Therefore, tough tungsten base alloys were selected as FSW tool materials for this investigation. Tungsten has a high energy threshold for physical sputtering and offer distractive physical properties which include the highest melting point of all metal, the lowest vapor pressure, good thermal conductivity and high temperature strength and toughness [12–14]. Also, these alloys contain a small amount of impurities which are known to increase the high temperature creep resistance. As the tool experiences high temperature and large forces during FSW, it is appropriate to investigate the microstructural characteristics of tools before and after welding to quantify the tool degradation. Hence, in this investigation, high strength low alloy (HSLA) steel was friction stir welded using tungsten based tool materials to check the feasibility and employability.

2. Experimental

The rolled plates of 5 mm thick high strength low alloy (HSLA) steel were used as the base material. The microstructural features of the base metal are shown in Fig. 1 and it primarily consists of ferrite with a small amount of pearlite. The three different grades of tungsten based alloy were used as the tool materials in the present investigation to weld HSLA steel. The tool was produced by powder metallurgy route and supplied by M/s. Heavy Alloys Penetrator Project (HAPP), Tiruchirappalli, India. The chemical composition and the mechanical properties of base metal and tool materials are presented in Tables 1a, 1b and 2, respectively. Tool materials are designated as W90, W95 and W99 for the purpose of convenience.

The tools were machined to the dimensions and configuration as shown in Fig. 2. Using these three tools, HSLA steel plates were joined by FSW process. The process was done in "worst-case set-up" that is, without using shielding gas and without pre-heating the base metal. Tool rotational speed of 600 rpm, welding speed of 30 mm/min, plunge rate of 2.5 mm/min and with an axial force of 15 kN welding parameters were used to fabricate the joints. To measure the temperature fields, four K-type thermocouples of 1 mm diameter were embedded on the advancing side of the plate at a depth of approximately 1.5 mm from the surface. Thermocouples were placed at 14 mm from the weld center as shown in Fig. 4. Six thermocouples were connected to the first six channels of the DAQ to collect temperature. Thermocouples were attached to a DAQ system which could measure the data at 15 Hz. Data collection was done with DAQ system that was attached to the computer running Lab VIEW software.

After 1 m length of welding, the tools were sliced for post-weld metallographic examination. Specimens were extracted and sectioned to the required sizes from the tool materials before and after the weld and then polished using different grades of emery papers. Final polishing was done using the diamond compound (0.1 μm of particle size) in the disc polishing machine.

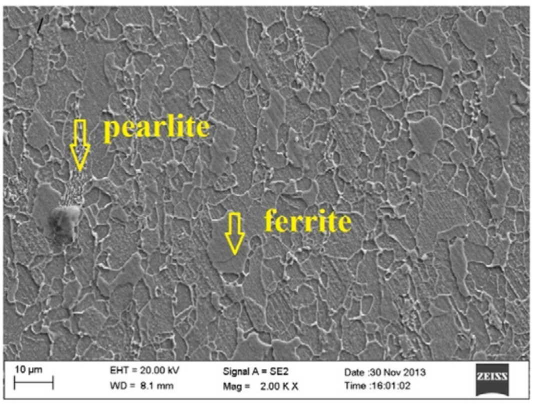

Fig. 1. SEM micrograph of base metal.