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Material flow and intermixing during friction stir spot welding of steel

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ABSTRACT

Tracer materials as inserts have been used to study the material flow during Friction stir spot welding (FSSW) of DP590 steel of 1.6 mm thickness. A PCBN tool with convex scrolled shoulder was used for welding. The progressive development of the material flow with tool penetration has been investigated by tracking the tracer distribution. When flow conditions are established, the shoulder scrolls provide the driving force for material flow by dragging the plasticized materials towards the pin and releasing them there. The released material flow outwards and upwards towards the shoulder periphery along different sub-surface flow routes. Successive flows in this fashion builds up the material circulation within the flow zone. The bonding ligament is created by intermixing of material between the overlapping sheets. The flow zone size and ligament width increases with increasing tool penetration. The flow zone encompasses the pin and a large area below the tool shoulder. Material flow during FSSW can be subdivided in two components, namely rotational flow and through thickness flow. A combination of the two components results in the spiraling motion of plasticized material within the flow zone. A material transport model is developed on the basis of experimental observations, illustrating the material flow during FSSW and the formation of bonding ligament.

1. Introduction

In FSSW a cylindrical rotating tool with a protruding pin plunges at a specific rate to a predetermined depth in overlapping sheets. It is then retracted rapidly either immediately or after a dwell period. The frictional heat softens the metal and the rotating pin causes material flow in both circumferential and axial directions. The forging pressure applied by the tool and the material intermixing between the overlapping sheets create an annular solid state bond around the pin. The welding parameters like rotational speed (rpm), plunge depth, plunge speed, dwell time and tool design influence the temporal conditions, and hence the material flow. These effectively define the microstructure and bond area, which in turn determines the joint strength and failure mode. The plastic flow during welding and the forces that drive it are critical to the formation of a sound joint.

Intermixing of candidate metals and their flow pattern during FSW has been keenly pursued over the last decade through experimental and modelling approaches. Guerra et al. investigated the material flow around the tool by 'stop-action' technique during FSW of dissimilar aluminium alloys (Guerra et al., 2003). They reported that during welding, the tool was surrounded by a zone of plasticized material that rotated and advanced with the tool. They defined different flow zones; namely the rotational flow zone adherent to the tool contour (bounded by a critical shear stress), surrounded by the shear flow dominated transitional flow zone and finally the deflection zone suffering minimum deformation. Within the rotational flow zone, the material underwent a helical motion; rotating, advancing and descending in the wash of the threads on the pin and rising on the outer part of the rotational zone. They observed that the material flow near the top of the weld was dominated by the shoulder, while the threads on the pin created a secondary vortex within the rotational zone, enabling the vertical transport of material. Similar observations were reported by Schmidt et al., who investigated the material flow in FSW by metallography, X-ray and computer tomography (CT) (Schmidt et al., 2006). Schneider and Nunes, used orientation image mapping (OIM) to investigate the genesis of onion ring patterns observed on the cross section of FSW joints (Schneider and Nunes, 2004). Schneider et al. studied the material flow paths around the tool using a tracer embedded along the weld seam (Schneider et al., 2006). They proposed that the onion rings were caused by the interaction of different flow currents (straight-through current and maelstrom current) with different time-temperature and shear strain histories. Reynolds proposed that the periodic variation in contact conditions

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Table 1
Chemical composition (wt%) and mechanical properties of base materials.

Material	C	Mn	Si	S	P	UTS (MPa)	YS (MPa)	Elongation (%)
DP 590	0.009	0.98	0.31	0.01	0.012	617	365	25

(sliding/sticking to partial sliding/sticking) during the course of one revolution of the tool, resulted in a periodic interleaving of the residues of two currents, manifested as the onion ring pattern (Reynolds, 2008). The fluctuations in contact conditions were correlated to the periodic in-phase fluctuation of process responses such as torque and *x*-force. Murr et al. observed various swirls and vortex like circulations near the workpiece/weld zone interface during FSW of Al-6061 to Cu, characterized by dynamically recrystallized grains (Murr et al., 1998). He proposed that these intercalations were generated to accommodate extreme plastic flow followed by dynamic recrystallization and static grain growth. Li et al. studied the FSW of dissimilar aluminium alloys and reported that for a range of tool rotation speeds, the weld temperature was sufficient to cause dynamic recrystallization even with modest strains. They observed that the plastic flow was significantly affected by the tool rotation speed and even small variations in the tool axis geometry (Li et al., 1999). A 3D finite element simulation of the FSW process by Zhang et al. indicated good correlation between the distribution of equivalent plastic strain across the weld cross section and the corresponding microstructure (Zhang et al., 2007). Their simulations suggested that the nugget region experienced the highest strains while the HAZ experienced the minimum. The equivalent plastic strain was observed to be higher near the top surface than the bottom surface, due to larger plastic flow induced by the rotating shoulder. Texture patterns on transverse, longitudinal and horizontal cross-sections in Al 6061-T6 friction stir welds and their variations with different welding parameter combinations were experimentally investigated by Xu and Deng (Xu and Deng, 2008). They reported that the spacing between the bands in the onion ring equalled the distance travelled by the welding tool in one revolution. The texture patterns were consistent with the equivalent plastic strain contours obtained by numerical simulation, and the authors concluded that the variation in texture patterns resulted from different levels of plastic deformation experienced by different regions within the weld.

The material flow during FSSW has also been investigated by several researchers. Su et al. investigated material flow during FSSW of Al 5754 and Al 6111 by a combination of experimentation and numerical modelling (Su et al., 2007). They reported that the material flow consisted of a combination of rotational, horizontal and vertical motion of the plasticized material around the tool and concluded that a threaded pin and a dwell period were essential for intermixing of candidate metals. They concluded that the intermixing was caused by the incorporation of upper and lower sheet material at the top of the pin threads and their subsequent release at the pin tip. The movement of the intermixed materials down the pin threads formed the intrinsic driving force for the material flow. Fujimoto et al. analyzed the plastic flow of Al alloy joint produced by FSSW and observed that plastic flow was prevalent across a large area below the tool (Fujimoto et al., 2009). They observed that the flow zone size increased with increase in weld time. The rotational speed of the tool had a major effect on the rotational flow of material around the tool axis, while the threads on the pin were responsible for the material transport in plate thickness direction. Yang et al. studied the material flow during FSSW of Mg by using copper tracers and reported that the shoulder contact initiated a combination of rotational, horizontal and vertical motions of the plasticized material creating three distinct regions in the weld, namely flow transition zone, stirred zone, and torsion zone (Yang et al., 2010). An incorporation of the upper and lower sheet materials occurred in the flow transition zone under the shoulder, and the intermixed materials subsequently moved down the pin threads and were released into the stirred zone. They reported that the release of intermixed materials at the end of the rotating pin through an outward-spinning motion formed the intrinsic driving force for the material flow. Tozaki et al. studied the plastic flow during FSSW of Al 6061-T4 sheets using a scrolled shoulder tool without probe and reported that sound welding could be achieved with a probe-less tool (Tozaki et al., 2010). The scrolled shoulder played a significant role in the rotational and through-thickness flow of plasticized material.

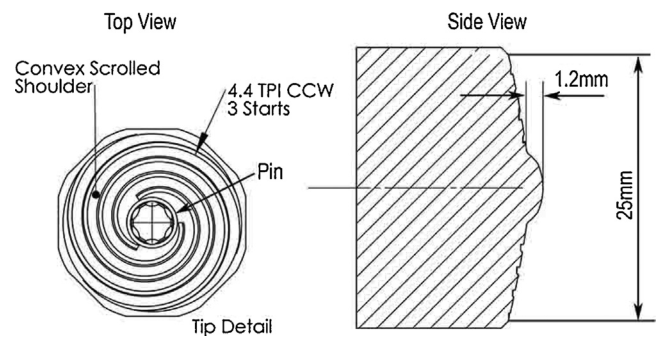

Fig. 1. Detail of the PCBN tool used for welding.

The material intermixing between the overlapping sheets creates the bonding ligament. A thin film of oxide is often present on the surface of metallic materials. During the formation of the bonding ligament, material flow within the stirred zone disintegrates the oxide layer on the interface and complete metallurgical bonding takes place between the overlapping sheets. Immediately adjacent to this location, the strain is not sufficient to disintegrate the oxide layer, which exists as an array of discontinuous particles. According to Hovanski et al. this discontinuous array prevents intimate bonding (Hovanski et al., 2007). In context to the current work, this represents the partially bonded interface.

The flow mechanisms discussed previously are predominantly observed in non-ferrous metals where the flow stress is of much lower order, and hence the extent of mixing is greater. The same has not been studied elaborately in steels. The effect of material viscosity, plasticity at high temperatures and limited flowability in steels are expected to provide new understandings along with commercial implications. Hence it was felt necessary to understand the mechanism in steel assemblies, given the growing importance of FSSW in the automotive industry. This study has intended to cast light on the nature of the flow process occurring around the tool during FSSW of advanced high strength (AHS) steel.

2. Experimental procedure

The welding experiments were carried out on a FSW machine operated in position control mode, with the response (*x, y and z*) forces and torque data being recorded during welding. A PCBN tool featuring a convex scrolled shoulder (diameter 25 mm) and a hexagonal flat faceted pin (height 1.2 mm) (Fig. 1) was used for