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Effects of processing time on strengths and failure modes of dissimilar spot friction welds between aluminum 5754-O and 7075-T6 sheets

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ABSTRACT

The effects of the processing time on the strengths and failure modes of two types of dissimilar spot friction welds between aluminum 5754-O and 7075-T6 sheets are investigated by experiments. Dissimilar 5754/7075 and 7075/5754 spot friction welds made at different processing conditions were tested under lap-shear loading conditions. The experimental results indicate that the failure loads of both types of welds in lap-shear specimens increase when the processing time increases for the given ranges of the processing time. The optimal processing times to maximize the failure loads of the 5754/7075 and 7075/5754 welds under lap-shear loading conditions are identified. The maximum failure load of the 7075/5754 welds is about 40% larger than that of the 5754/7075 welds. Selected optical and scanning electron micrographs of both types of welds made at different processing times before and after failure are examined. The micrographs show different weld geometries and different failure modes of the welds made at different processing times. The failure modes of the dissimilar 5754/7075 and 7075/5754 spot friction welds are quite complex and appear to strongly depend on the geometry and strength of the interfacial surface between the two deformed sheet materials.

1. Introduction

Resistance spot welding is the most commonly used joining method for body-in-white parts made of steel sheets. However, resistance spot welding of aluminum sheets is likely to produce poor welds as reported by Thornton et al. (1996) and Gean et al. (1999). Recently, a spot friction welding technology to join aluminum sheets has been developed by Mazda Motor Corporation (Sakano et al., 2001) and Kawasaki Heavy Industry (Iwashita, 2003). The most significant advantage of the spot friction welding process comparing to the conventional welding processes is that the joint can be made without melting the base metal.

A schematic illustration of the spot friction welding process is shown in Fig. 1. The process is applied to join the two metal sheets as shown. A rotating tool with a probe pin is first plunged into the upper sheet. When the rotating tool contacts the upper sheet, a tool downward force is applied. A backing tool beneath the lower sheet is used to support the tool downward force. The tool downward force and the tool rotational speed are maintained for an appropriate time to generate frictional heat. Then, heated and softened material adjacent to the tool deforms plastically, and a solid-state bond is made between the surfaces of the upper and lower sheets. Finally, the tool is drawn out of the sheets as shown.

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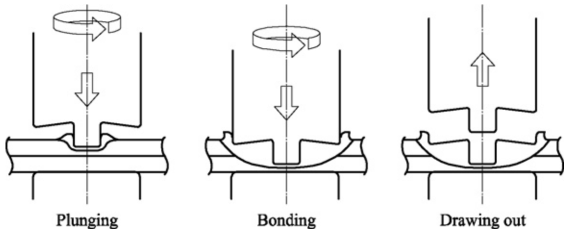

Fig. 1 – A schematic illustration of the spot friction welding process.

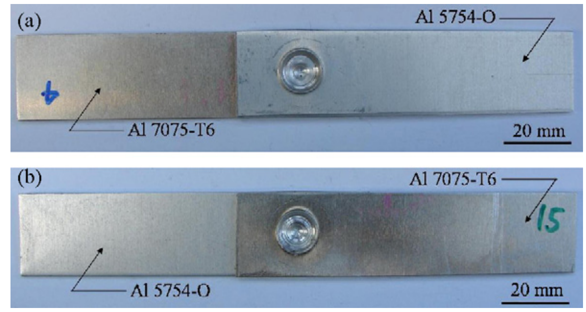

Fig. 2 – Lap-shear specimens with a 5754/7075 spot friction weld and (b) a 7075/5754 spot friction weld.

The mechanical behavior of aluminum spot friction welds under quasi-static loading conditions was studied, for example, see Fujimoto et al. (2004a,b), Hinrichs et al. (2004), Lin et al. (2004) and Pan et al. (2004). The metallurgical aspects of aluminum 6111-T4 spot friction welds were investigated by Mitlin et al. (2006). Tran et al. (2007) investigated the failure loads of spot friction welds in aluminum 6111-T4 lap-shear specimens under quasi-static and dynamic loading conditions. Recently, Lin et al. (2005, 2006, 2008a,b) and Tran et al. (2008) investigated the fatigue behaviors of spot friction welds in aluminum 6111-T4 and 5754-O sheets based on experimental observations, fracture mechanics, and the structural stress approach. A comprehensive literature review for spot friction welds can be found in Pan (2007). Note that most of the literature is for spot friction welds between similar aluminum sheets. However, dissimilar spot friction welds between aluminum 2017-T6 and 5052 sheets, and between aluminum 7075-T6 and 2024-T3 sheets were investigated by Tozaki et al. (2007) and Tweedy et al. (2008), respectively. Also, Su et al. (2007) investigated the intermixing of dissimilar spot friction welds between aluminum 5754 and 6111 sheets by experiments and numerical simulations.

It should also be noted that many types of aluminum alloys are currently used to make different components of vehicles in the automotive industry. For example, the aluminum alloys are widely employed to produce different parts such as internal door stiffeners, entire body-in-white, and inner body panels as reported in Kaufman (2000). An efficient joining method is needed to join different components made of different types of aluminum alloys. Therefore, dissimilar spot friction welds between different aluminum sheets need to be explored.

In this paper, the effects of the processing time on the strengths and failure modes of two types of dissimilar spot friction welds between aluminum 5754-O and 7075-T6 sheets are investigated by experiments. In this investigation, dissimilar spot friction welds were first made at different processing conditions. During the spot friction welding process of the two aluminum sheets, the tool contacts the upper sheet and penetrates the upper sheet to weld together the upper and lower sheets. The dissimilar spot friction welds are denoted as 5754/7075 when aluminum alloys 5754-O and 7075-T6 were used as the upper and lower sheets, respectively, and as 7075/5754 when aluminum alloys 7075-T6 and 5754-O were used as the upper and lower sheets, respectively. The failure loads of the 5754/7075 and 7075/5754 welds in lap-shear specimens under quasi-static loading conditions are obtained from the experiments. The optimal processing times to maximize the failure loads of the 5754/7075 and 7075/5754 welds under lap-shear loading conditions are identified. Selected optical and scanning electron micrographs of the 5754/7075 and 7075/5754 welds made at different processing times before and after failure are examined to investigate the weld geometries and the failure modes. Finally, the mechanical behaviors and failure modes of the 5754/7075 and 7075/5754 welds made at the optimal processing times are compared and discussed.

2. Experiments

Lap-shear specimens were used to investigate the mechanical behavior of spot friction welds under shear dominant loading conditions. The materials used in this investigation are aluminum 5754-O and 7075-T6 sheets. Table 1 lists the mechanical properties of the aluminum 5754-O and 7075-T6 sheets. As listed in Table 1, the yield and tensile strengths of the aluminum 7075-T6 sheets are about five and three times of those of the aluminum 5754-O sheets, respectively. Also, the elongation of the aluminum 5754-O sheets is about twice of that of the aluminum 7075-T6 sheets as listed in Table 1. The lap-shear specimens were made by using two 25.4 mm × 101.6 mm aluminum sheets with a 38.1 mm × 25.4 mm overlap area. The thicknesses of the aluminum 5754-O and 7075-T6 sheets are 2.0 mm and 1.6 mm, respectively. Fig. 2(a) and (b) show a lap-shear specimen with a 5754/7075 spot friction weld and a lap-shear specimen

Table 1 – The mechanical properties of the aluminum 5754-O and 7075-T6 sheets

	Young modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Al 5754-O	69	97	207	26
Al 7075-T6	71	469	578	11

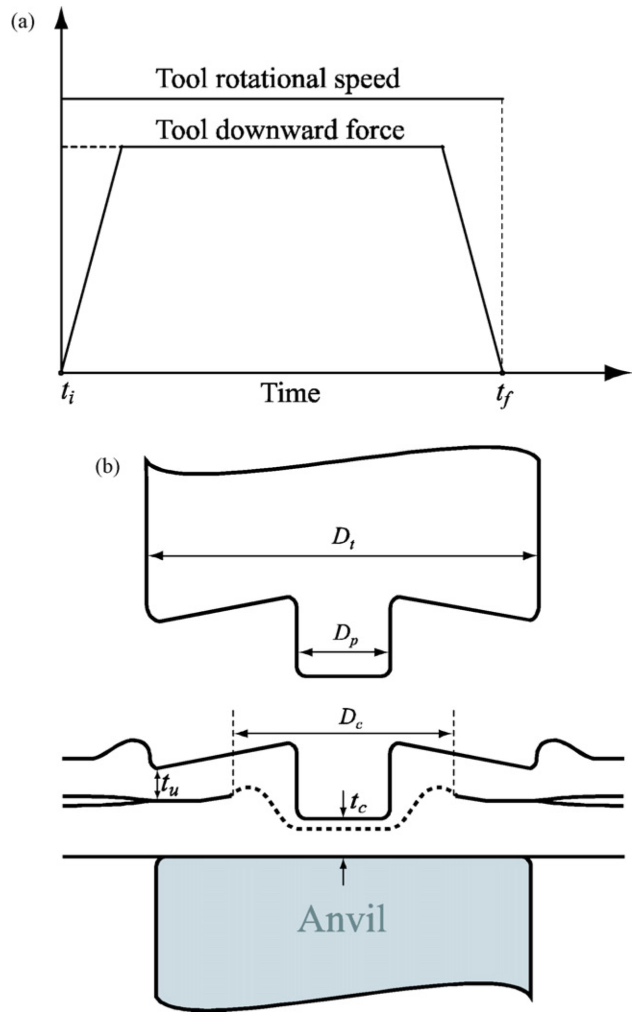

Fig. 3 – Schematic plots of (a) the tool rotational speed and the tool downward force as functions of the time and (b) an extracted tool and two welded sheets after spot friction welding.

with a 7075/5754 spot friction weld, respectively. One doubler made of the upper sheet and another doubler made of the lower sheet with a dimension of 25.4 mm × 25.4 mm are attached to the ends of the upper and lower sheets, respectively, of the lap-shear specimens during testing. Note that the doublers are used to align the applied load to avoid the initial realignment of the specimen under lap-shear loading conditions. The welds were made by using a spot friction welding gun manufactured by Kawasaki Robotics, USA.

For the spot friction welding process under load-controlled conditions, the important processing parameters are the tool geometry, the tool rotational speed, the tool downward force and the tool holding time. Fig. 3(a) shows a schematic plot of the tool rotational speed and the tool downward force as functions of the time. As schematically shown in Fig. 3(a), during the spot friction welding process, the tool rotational speed is kept constant. Initially, the tool downward force increases linearly for a period of time. Then the tool downward force is kept constant for another period of time and finally decreases linearly to zero. The rise and fall times of the tool downward force are about a fraction of a second based on a recent research investigation at Ford Motor Company. As shown in the figure, t_i represents the time that the tool contacts the top surface of the upper sheet and t_f represents the time that the tool extracts from the top surface of the upper sheet. The time interval between t_i and t_f represents the total tool holding time or the processing time.

Fig. 3(b) shows a schematic plot of an extracted tool and two welded sheets after spot friction welding. As shown in the figure, the anvil is used to support the tool downward force during the welding process. As shown in Fig. 3(b), the diameters of the tool shoulder and the tool probe pin are denoted as D_t and D_p, respectively. The actual bonding diameter for the weld or the weld diameter is denoted as D_c. The weld diameter D_c is determined as the distance between the locations of the two crack tips identified by the optical and scanning electron micrographs of the welds before testing. In this figure, the thick dashed line represents the interfacial surface between the two deformed sheet materials. It should be noted that the interfacial surface was well bonded as discussed later. In the figure, the reduced thickness of the central part of the nugget due to the tool probe pin penetration at the bottom of the central hole is denoted as t_c. The thinnest thickness of the upper sheet outside the weld nugget due to the indentation of the concave tool shoulder geometry is denoted as t_u. The weld diameter D_c and the thicknesses t_c and t_u depend upon the processing parameters, and the thicknesses and mechanical properties of the upper and lower sheets.

3. Micrographs of spot friction welds before testing

In this investigation, a tool with a concave shoulder and a threaded probe pin was used to make dissimilar 5754/7075 and 7075/5754 spot friction welds. A tool rotational speed of 3000 rpm and a tool downward force of 5.88 kN were specified to make both types of welds used in this investigation. The 5754/7075 welds were made at the processing time ranged from 1.6 s to 4.0 s with a time increment of 0.2 s. The 7075/5754 welds were made at the processing time ranged from 1.0 s to 8.0 s with a time increment of 0.5 s. For both types of welds, at least two samples are made at each processing time. One sample is reserved for cross-sectioning before testing and the other samples are tested under lap-shear loading conditions. Note that the weld made at the processing time shorter than the minimum processing time of the range was not bonded while the weld made at the processing time longer than the maximum processing time of the range had a hole in the central portion of the weld due to the excessive tool penetration. Only the experimental results within the ranges were considered and investigated since there was no bonding between two sheets when the processing time was shorter than the minimum processing time, while a welded sample with a hole should be rejected from the manufacturing viewpoint when the processing time was longer than the maximum processing time. In the following, some optical and scanning electron micrographs of the cross sections along the symmetry planes of the 5754/7075 and 7075/5754 spot friction welds made at