

# Selection of Welding Parameter during Friction Stir Spot Welding

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## ABSTRACT

The selection of parameters during friction stir spot welding of Al-alloys and Mg-alloys is discussed. The role of tool rotation speed, plunge rate, and dwell time is examined in relation to the tool heating rate, temperature, force, and torque that occur during spot welding. In order to reduce the cycle time and tool force during Al-alloy spot welding, it is necessary to increase the tool rotation speed >1500 RPM. The measured peak temperature in the stir zone is determined by the rotation speed and dwell time, and is ultimately limited by the solidus of the alloy. When tool rotation speeds > 1500 RPM are employed during AZ91 Mg-alloy spot welding, the tendency for melted film formation and cracking are greatly increased.

## INTRODUCTION

During friction stir spot welding the two overlapping sheets are joined at a single location and the rotating tool is then withdrawn leaving a keyhole depression. The cycle time during friction stir spot welding is typically in the range from 1 to 5 seconds while the selectable welding parameters comprise tool rotational speed, plunge rate and depth of penetration into the contacting sheets. Studies have already shown that the peak joint strength is typically found when tool rotation speeds of 1500 to 3000 RPM are used [1,2]. These speeds are much higher than those normally used in friction stir seam welding, however it is not fully understood why such high rotation speeds are necessitated.

The depth of penetration of the rotating tool into the contacting sheets is determined by the sheet thickness and the pin length. It has been observed that allowing the tool shoulder to penetrate into the surface of the upper sheet increases the load to failure of completed spot welds [2]. Axial force and the torque are outputs during any friction stir spot welding operation unless the welding equipment has a force-control capability.

The heating rate during the tool penetration stage in friction stir spot welding is remarkably high (from about 210 to 400°C/s) while the temperature attained in the stir zone is ultimately limited by either the solidus temperature of the alloy being fabricated or by spontaneous melting temperatures of second-phase particles contained in the as-received base material [3,4]. For example, the measured temperatures in the stir zones of Al 7075, Al 2024, Al 6111, Al 6061, Al 5754, AZ31, AZ91 and AM50 friction stir spot welds correspond with homologous temperatures ranging from 0.94 to 0.99 [4].

The microstructural features and mechanical properties of friction stir spot welds are markedly affected by welding parameter selection. For example, it has already been shown that the fracture load during overlap shear testing of Al 5754 and AM50 friction stir spot welds is increased when the bonded area or the energy input are increased [5]. With this in mind, the present paper examines the factors determining welding parameter selection when Al-alloy and Mg-alloy base materials are spot welded. A combination of previously published output and new testing output is presented. The tool consisted of a 10 mm diameter shoulder and a 4 mm diameter pin which was 2.2 mm in length. Unless stated otherwise, the pin had a threaded profile with three flats. The general objective is to highlight the different factors, which are involved when a decision is made concerning welding parameter selection during friction stir spot welding of Al-alloy and Mg-alloy base materials.

## ENERGY GENERATION AND UTILIZATION

The energy generated during friction stir spot welding is determined by the following relation:

$$Q_{\text{applied}} = \sum_{n=1}^{n=N} \text{Force}(n) (x_n - x_{n-1}) + \sum_{n=1}^{n=N} \text{Torque}(n) \omega(n) \Delta t \quad (1)$$

where  $x_n$  is the penetration depth at sample ( $n$ ),  $\omega$  is the angular velocity (rad/s),  $n$  is the sample number,  $N$  is the

final sample and  $\Delta t$  is the sampling time. The amount of energy generation resulting from tool rotation accounts for around 98% of the total energy, which is generated during friction stir spot welding [5]. In addition to facilitating stir zone formation, heat is dissipated into the adjoining heat sinks, e.g.

$$Q_{\text{generated}} = Q_{\text{stir zone}} + Q_{\text{tool assembly}} + Q_{\text{sample sheets}} + Q_{\text{atmosphere}} + Q_{\text{anvil support}} + Q_{\text{clamp}} \quad (2)$$

where,  $Q_{\text{generated}}$  is the total energy generated during spot welding,  $Q_{\text{tool assembly}}$  is the energy dissipated in the tool assembly,  $Q_{\text{clamp}}$  is the energy dissipated in the clamp,  $Q_{\text{anvil support}}$  is the energy dissipated in the anvil support and  $Q_{\text{atmosphere}}$  is the energy loss to the surrounding atmosphere.

A remarkably large proportion of the energy that is generated via tool rotation transfers into the adjoining sinks. For example, Su et al. [6] reported that 12.7% of the energy resulting from tool rotation dissipated in the adjoining Al-alloy sheet material, when a steel anvil and clamp were used during spot welding. When the heat losses through the clamp and the anvil were minimized by locating mica inserts between them and the sheet being spot welded, around 50% of the energy generated via tool rotation was dissipated in the adjoining Al-alloy sheet material. As a result, friction stir spot welding is quite different from conventional fusion welding, for example, since the energy generating source – the electric arc – does not of itself absorb a substantial amount of the energy, which is generated during joining. With this in mind, any attempt to view what is happening during friction stir spot welding based on the premise that it is in any way similar to an arc welding operations would prove fruitless.

Since energy dissipation into the adjoining heat sinks is a critical feature during friction stir spot welding, it is important to establish the relation between the total energy, which is generated during tool rotation and the energy requirement for stir zone creation and maintenance. The efficiency of energy utilization during spot welding  $\beta$  is determined by the following relations [5]:

$$\beta = \frac{Q_{\text{stir zone}}}{Q_{\text{applied}}} \quad (3)$$

$$= \frac{\rho C_p (T_s - T_0) V}{\sum_{n=1}^{n=N} \text{Force}(n) (x_n - x_{n-1}) + \sum_{n=1}^{n=N} \text{Torque}(n) \omega(n) \Delta t} \cdot 100 (\%) \quad (4)$$

where,  $Q_{\text{stir zone}} = \rho C_p (T_s - T_0) V$  is the energy (kJ) required to raise the stir zone temperature from room temperature ( $T_0$ ) to the peak temperature ( $0.95T_s$ ),  $\rho$  is the density,  $C_p$  is the heat capacity, and  $V$  is the volume of the stir zone formed during spot welding. It is assumed in Eq. 4 that a) all of the mechanical energy delivered to the stir zone results in heat generation, b) the solidus temperature is attained within the stir zone and c) the temperature is uniform across the width the stir zone. Experimental support for these requirements has been provided by the results of recently published

research on spot welding of Al-alloy and Mg-alloy friction stir spot welds [3,4].

The efficiency of energy utilization ( $\beta$ ) during spot welding was investigated during plunge testing of Al 6061 and Mg-alloy AM50 sheets using a smooth pinned tool and found to increase from 0.24 to 4.37% when higher plunge rates were employed [5]. The efficiency of energy utilization during friction stir spot welding is remarkably low and is negligibly affected when the tool rotational speed increases from 1000 to 3000 RPM, see Figure 1. It follows directly from Figure 1 that heat abstraction and not energy generation is the critical issue during any friction stir spot welding operation. Heating the tool assembly and insulating the anvil, for example, will have a dramatic influence on the amount of energy that is dissipated into the adjoining Al-alloy and Mg-alloy sheets. Also, the dimensions of the stir zone region formed during spot welding are not affected by the initial sheet temperature or the sheet thickness [5]. In this connection, Zettler [7] has recently suggested that heat abstraction during friction stir seam welding has a major influence on the development and selection of welding parameter settings, which produce joints having consistent mechanical properties.

The tool rotation speed and welding (cycle) time have a significant influence on the tool torque and the total energy input during friction stir spot welding, see Figure 2. A trend of decreasing torque with increasing tool rotation speed has also been observed during spot welding of AM50 magnesium alloy [5]. Incorporating a dwell period into the spot welding cycle will increase the amount of energy delivered during friction stir spot welding using high tool rotational speeds settings. Figure 2(b) shows that almost all of the energy generated during friction stir spot welding is produced during the dwell period and since low efficiency of utilization of energy values are an inherent feature during joining, much of the energy is dissipated into the adjoining sheets. Consequently, the width of the softened region produced when age-hardened Al-alloys are spot welded is markedly influenced by the tool RPM and dwell time settings.

Figure 3 shows the relation between the tool RPM, dwell time and the hardness of the softened region formed adjacent to the keyhole when Al 7075-T6 sheet is spot welded [8]. The width of the softened zone is marginally increased when the tool rotational speed increases from 1500 to 3000 RPM during Al 7075-T6 friction stir spot welding using a dwell time of 1 second. However, the width of the softened zone in Al 7075-T6 spot welds is significantly increased when the dwell time increases from 1 to 4 seconds when a tool rotational speed of 3000 RPM is used. In contrast, increasing the dwell time from 1 to 4 seconds has a negligible influence on the width and severity of the softened region when annealed Al 5754-O is spot welded using a tool rotational speed of 3000 RPM, see Figure 4. The hardness of material adjacent to Al 5754-O spot weld is not significantly altered since this particular Al-alloy is not heat-treatable.

## ROLE OF THE PIN THREAD

Figure 5 shows the relation between the stir zone width and the tool rotational speed during plunge testing using a smooth pin tool [5]. The width of the stir zone formed during welding increases when the tool rotational speed increases from 1000 to 1500 RPM. However, the stir zone width is negligibly affected by a change in tool rotational speed from 1500 to 3000 RPM since the torque (the calculated power) decreases when higher tool rotational speeds are applied; see Figure 2.

Machining a thread onto the rotating pin only marginally increases the amount of energy generated during friction stir spot welding [5]. However, the presence of a thread on the pin markedly affects the width of the stir zone produced during friction stir spot welding with a dwell period. For example, the stir zone width is increased when higher tool rotational speed settings are applied during spot welding using a dwell period, see Figure 6. The stir zone width increases since material is incorporated into the stir zone during the dwell period in friction stir spot welding [9,10]. Material is transferred from the locations beneath the tool shoulder and from the bottom of the rotating pin and is moved downwards via the thread on the rotating pin and into the stir zone (intermixed region) formed adjacent to the periphery of the rotating pin.

## INFLUENCE OF WELDING PARAMETERS ON STIR ZONE TEMPERATURE

The heating rate during the tool penetration stage in spot welding is remarkably high and is largely determined by the tool rotational speed setting. For example, the heating rate close to the tip of the rotating pin varies from about 210°C/s to >400°C/s during friction stir spot welding of Al-alloy base material [3]. In addition, the heating rate in the location immediately beneath the tool shoulder is as high as 1100°C/s during Al-alloy friction stir spot welding.

Higher stir zone temperatures are produced when high tool rotational speeds are employed during spot welding (for any given dwell time setting), see Figure 7. Also, when the measured temperature values found during spot welding using a dwell time of 4 seconds and different tool rotational speed settings are extrapolated to 10 seconds, the temperature in the stir zone approaches the solidus temperature of the base material being fabricated, assuming that heat generation is only limited by viscous dissipation. A dwell time of 10 seconds is typically used during friction stir seam welding prior to the traversing movement of the tool. As a result, the stir zone temperature is very high in spot welds made using low tool rotational speed settings, in spite of the lower heating rate produced during the tool penetration stage in friction stir spot welding.

Two quite distinct axial force peaks are produced during the tool penetration stage in friction stir spot welding, namely the axial force ( $F_1$ ), which occurs prior to melt wear formation in material located beneath the tip of the rotating pin and the axial force ( $F_2$ ), which

is produced when the base of the tool shoulder contacts the upper surface of the upper sheet [11]. It is important to minimize the axial force resulting during robotic friction stir spot welding operations. Figure 8(a) shows that the axial force ( $F_2$ ) decreases when higher tool rotational speed settings are employed. In contrast, the axial force ( $F_2$ ) increases when the plunge rate increases from 2.5 to 10 mm/s, see Figure 8(b) [12].

## CYCLE TIME

In a high production environment such as an automotive manufacturing plant it is important to minimize the cycle time during friction stir spot welding. Since the typical cycle time when resistance spot welding is used is around 2 seconds, this is the target that friction stir spot welding must meet when it is considered as a replacement for resistance spot welding. This limited cycle time precludes the application of a sizeable dwell period during any friction stir spot welding operation. For example, this is the case when 1.5 mm thick Al-alloy sheet is spot welded using a plunge rate of around 2.5 mm/s. When Al-alloy sheet is spot welded using a tool rotational speed around 1000 RPM the width of the stir zone formed during friction stir spot welding is < 100  $\mu\text{m}$  [4]. With this in mind, the combination of a high tool rotational speed setting (from 2000 to 3000 RPM) and a plunge rate of about 2.5 mm/s will fulfill the 2 second cycle time requirement and minimize the axial load ( $F_2$ ) when 1.5 mm thick overlapping sheets are spot welded, see Figure 8(a).

Both the cycle time during spot welding and the width of the softened zone formed adjacent to the spot weld are reduced when the plunge rate is increased from 2.5 to 10 mm/s [6]. However, these benefit features come at the expense of markedly increased axial force ( $F_2$ ) values; see Figure 8(b). It is also possible that the axial force may increase to a level where rotating tool might stall during friction stir spot welding when very high plunge rate settings are used.

When the permissible cycle time during component fabrication is around 5 seconds, a dwell period can be incorporated during friction stir spot welding. However, Figure 2(b) shows that a significant fraction of the energy generated during any spot welding operation is produced during the dwell period and therefore the width of the softened region formed during friction stir spot welding of age-strengthened Al-alloy sheet is much larger when a dwell time of 4 second is applied, see Figure 3. Of course, when a non-heat-treatable Al-alloy such as Al 5754-O is spot welded, the width of the softened region is negligibly affected when a long dwell times is applied, see Figure 4.

Higher fracture strength values are produced during overlap shear testing of Al-alloy and Mg-alloy spot welds when the bonded area and the energy input are increased [13]. The width of the stir zone formed adjacent to the periphery of the rotating pin during spot welding increases when longer dwell period times are applied [14-17]. During friction stir spot welding using a tool comprising a threaded pin, the amount of material