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Accessing collision welding process window for titanium/copper welds with vaporizing foil actuators and grooved targets

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ABSTRACT

A method for accurate, low-cost, lab-scale determination of the optimal collision angles and velocities for collision welding of a given combination of materials has been introduced. 0.508 mm thick grade 2 CP Ti sheets were launched at various velocities toward a Cu 110 target with grooves of angles ranging from 8° to 28°, machined on the collision side. Capacitor bank-driven aluminum vaporizing foil actuators operated at input energy levels up to 12 kJ and currents up to 140 kA were used to launch the flyer sheets. Velocity was measured with high temporal resolution using a photonic Doppler velocimetry (PDV) system. Collision velocities ranged from 440 m/s to 860 m/s. The welded assemblies were sectioned and the weld interfaces were observed via scanning electron microscopy. For each collision angle there were certain collision velocities which yielded a wavy interface. Welding velocity for transition from smooth to wavy interfaces for each collision angle was used to determine the corresponding transition Reynolds number and was compared to existing results in literature. The uniqueness of this process lies in its small scale and ease of implementation.

1. Introduction

Collision welding of a given pair of metals occurs only when the collision angles and velocities are within an optimum range, called the welding window. Successful collision welds are generally obtained when the collision velocity is in the range of 150–1500 m/s and the collision angle is between 5° and 20° as cited by Zhang et al. (2011). These ranges can be shown graphically in the form of a welding window. Fig. 1, which is based on the illustration from Akbari Mousavi and Farhadi Sartangi (2009), shows a generic welding window where all the possible outcomes of an attempt for collision welding are presented. Some of the earliest works on welding windows are from Wittman (1973) and Deribas et al. (1975), who studied the effect of explosive welding parameters on the strength and microstructure of welds.

The welding window only indicates the presence or absence of a good weld under a given set of input parameters; it does not quantify the strength of the weld. The shaded area in Fig. 1 denotes the parameters which lead to a wavy interface boundary with no melt zones. In this work, such weld interfaces will be identified and plotted in such graphs. The critical Reynolds number ($R_{transition}$) for laminar to turbulent flow is thought to determine this transition, and is given by the following relation developed by Cowan et al. (1971) who likened wave formation in explosive welding to fluid flow around an obstacle.

$$R_{transition} = \frac{(\rho_{flyer} + \rho_{target})V^2_{F\text{-}transition}}{2(H_{flyer} + H_{target})} = K_{E-P} \quad (1)$$

Here ρ (kg/m^3) stands for density and V_F (m/s) for velocity of flow of the flyer material into the collision point, which approximately equals welding velocity for low collision angles. H represents Vicker's hardness (N/m^2), and K_{E-P} represents the elastic–plastic constant, which varies with collision angle. For low collision angles, it can be shown that V_F and welding velocity (V_W) are almost equal. The relationship between V_W and the collision velocity, V_P, varies with the welding configuration, and will be derived for the present set up. As noted by Crossland (1982), the Karman vortex street analogy should be considered with caution since this is a transient and very local occurrence. This analogy also does not explain why the waves get initiated at a finite distance from the point of first impact. There are other mechanisms that can be considered for wave formation as well: Helmholtz instability, suggested by Hunt (1968), and the interaction of compression and relaxation waves traversing through the colliding plates predicted by Godunov et al. (1970). However, there are inherent problems with those analogies as well. It is possible that for different materials under different conditions,

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Nomenclature

$R_{transition}$ transition Reynolds number
K_{E-P} elastic plastic constant
β collision angle
V_F velocity of flow of flyer material into the welding front
V_W welding velocity
V_p collision velocity
ρ density (kg/m^3)
H Vicker's hardness (N/m^2)

one or more of the suggested mechanisms could be at work. The Karman vortex street analogy in conjunction with the Reynolds number is a simple option used by many researchers to mathematically understand the smooth to wavy transition. Due to its simplicity of application, it has been used in this work as well.

Jaramillo et al. (1987) used gas gun-driven experiments to develop the relationship between collision angles and elastic–plastic constants for Al–Al, Cu–Cu and Fe–Fe welds and showed that unlike the theory of Cowan et al., the transition curve is not a straight line but a compromise between Newtonian liquid and elastic–plastic behavior. As shown in the recent simulation work by Grignon et al. (2004) and the experimental work of Akbari Mousavi and Farhadi Sartangi (2009), those relations that depend exclusively on static metallic characteristics of the weld members are still valid. Grignon et al. (2004) also reported some successful finite element modeling work based on Johnson–Cook constitutive model of AA 6061 T0 for modeling the conditions for jetting and smooth-wavy transition criteria during explosive welding. However, a complete model-based solution to this problem, which includes multi-scaled detailed structures, phase transformations at very small levels, and shock physics, has not yet been demonstrated. For the foreseeable future, empirical verification of welding windows created by such numerical or analytical models will be required.

Here, a quick, low-cost method for developing collision welds with varied collision angle and velocity is described. This method can be executed in a typical laboratory. The authors (Vivek et al. (2013) have reported on a novel method for implementing collision welding at length scales similar to magnetic pulse welding (MPW). This method, which has been named Vaporizing Foil Actuator Welding (VFAW), uses the pressure created from electrically driven rapid vaporization of a thin aluminum foil to launch flyer plates of thickness on the order of 1 mm thick to velocities of

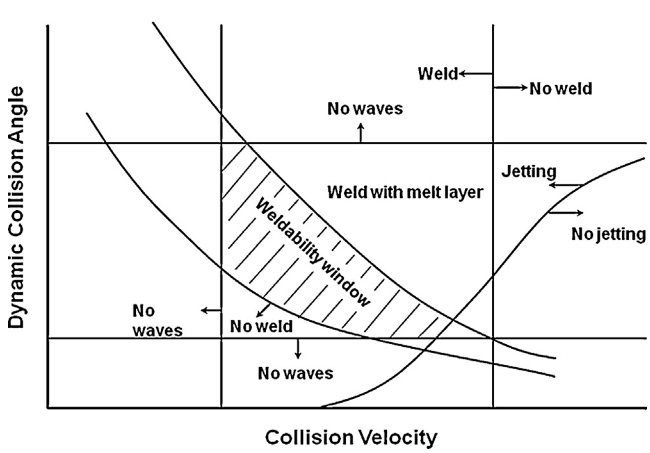

Fig. 1. Generic welding window based on Akbari Mousavi and Satrangi (2009).

1000 m/s or more. The issue of actuator longevity does not exist in this method because the foil actuator is disposable and can be easily replaced after every experiment at a low cost.

Besides explosive, magnetic pulse is also used for high speed flyer launch for collision welding. Daehn (2006) discussed the limitations of both of these methods. Explosive welding (EXW) runs into issues such as the inability to scale the process to thin sheets or small weld zones because explosives do not detonate reproducibly below a certain size known as the critical diameter, which is discussed by Cooper (1997). Furthermore, increasingly stringent safety regulations inhibit their use. The most significant drawback of MPW is that actuators tend to fail after decreasing numbers of cycles as the magnetic pressure increases. Laser-driven collision welding (Zhang et al., 2011) also has a niche, but because the delivered energies are typically on the order of several joules, this is not suitable for workpieces on the size scale of centimeters. Filling this gap has also been a motivation for developing VFAW.

The work presented here focuses on using VFAW for determination of the welding window of commercially pure titanium and copper. Following a brief description of the experimental procedure, the results are discussed and plotted on charts resembling welding windows from Jaramillo et al. (1987) and Akbari Mousavi and Farhadi Sartangi (2009). An empirical relation between K_{E-P} and β is also derived.

2. Experimental procedure

The Vicker's hardnesses of the copper and titanium to be welded were measured to be 90 HV and 170 HV, respectively. Specific angles (8°, 12°, 16°, 20°, 24°, and 28°) were machined into a 6.3-mm-thick copper target plate in the form of grooves. These angled grooves provide the collision angles required for collision welding. A piece of dogbone-shaped 0.0762-mm-thick aluminum foil was connected to the leads of a 426-μF capacitor bank, the characteristics of which are cited in Table 1.

The 0.5-mm-thick titanium flyer was placed against the foil actuator, with polyester and polyimide insulation in between, using procedures similar to those described by Vivek et al. (2013). The copper target plate with the angled grooves was placed parallel to the flyer, with a 1.6-mm stand-off gap in between. The whole assembly was clamped in a fixture made of heavy steel blocks. Fig. 2 shows different stages and views of the experimental assembly. The capacitor bank was charged to various energy levels (3, 4, 6, 8, 10, and 12 kJ) and then rapidly discharged through the foil. The foil was effectively and instantly vaporized by the high current and generated sufficient pressure to propel the flyer into a high-speed collision with the target plate. The experiment was repeated one extra time at 8 kJ to test reproducibility. The velocity of the flyer was measured in situ at each energy level by a photonic Doppler velocimetry (PDV) system (Johnson et al., 2009). The PDV probe looked at the flyer plate through concentric holes that were drilled in the steel backing block and the copper target plate to measure the normal sheet velocity, V_P. If the angle of collision is β, then from Fig. 3 it can be geometrically shown that

$$V_w = \frac{V_P}{\sin(\beta)} \approx V_F \quad (2)$$

The approximate equality between V_W and V_F holds true as long as β is small (<30°). Voltage was measured using a 1000:1 probe connected across the terminals of the capacitor bank, and current was measured by a 100kA:1 V Rogowski coil. The samples were then sectioned for metallography and mechanical testing.