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Full Length Article

Design of experiment study on hardness variations in friction stir welding of AM60 Mg alloy

S. Richmire[a], K. Hall[b], M. Haghshenas[a,*]

[a] *Department of Mechanical Engineering, University of North Dakota, Grand Forks, ND 58202, USA*
[b] *Department of Chemical Engineering, University of North Dakota, Grand Forks, ND 58202, USA*

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Abstract

Identification of process parameters, their effects and contributions to the outcomes of the system using experimental approach could be a daunting, time consuming, and costly course. Using proper statistical methods, i.e., Taguchi method, could significantly reduce the number of required experiments and statistical significance of the parameter can be identified. Friction stir welding is one of those welding techniques with many parameters which have different effects on the quality of the welds. In friction stir welding the tool rotational speed (RPM) and transverse speed (mm/min) influence the strength (i.e., hardness distribution) of the stirred zone. In this study, these two factors are investigated to determine the effect they will have on the hardness in the stirred zone of the friction stir welds and how the two factors are related to one another for as-cast magnesium alloy AM60 with nominal chemical composition of Mg- (5.5–6.5) Al- (0.24–0.6) Mn-0.22Zn–0.1Si. Experimental data was taken at three different tool rotational speeds and three different transverse speeds. The data obtained was then analyzed using a 3^2 factorial design to find the contribution of these parameters. It was determined that both tool rotational speed and transverse speed possess significant effects on the stir zone hardness. Also, the interactions between the two factors were statistically assessed.
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Keywords: AM60 Mg alloy; Design of experiment (DOE); Statistical method; Friction stir welding.

1. Introduction

1.1. Friction stir welding parameters and DOE

Friction Stir Welding (FSW) is considered a solid state joining process because the heat generated by the process does not reach the melting temperature of the materials being joined. Developed in 1991 [1], FSW allows for the joining of materials that, by traditional welding technologies, are considered to be non-weldable (i.e., dissimilar material, Mg alloys, some aluminum alloys, etc.) [2]. In the FSW process, a non-consumable cylindrical tool with a shoulder and pin is used as a stirrer. In this study, the FSW tool is fixed to a displacement controlled milling machine chuck and is rotated clockwise along the longitudinal axis. It is worth mentioning that the FSW is not always performed on a milling machine. The work pieces to be welded are butted up (or overlapped) to one another and clamped in order to stay stationary and withstand the large applied forces. The rotating tool pin is then inserted into the work piece at the faying surface, and the shoulder is forced into contact with the work piece surface. The tool is then moved transversely along the faying surface. As the tool rotates and moves along the joint, the material is softened and stirred together forming a weld without reaching the melting point of the base materials [1,3]. At the end of the joint the tool is retracted out of the work piece. Four steps of the FSW have been shown in Fig. 1.

Complex physical processes like FSW usually involve large number of inter-related variables that directly or indirectly affect the weld quality and the performance. These

* Corresponding author.
E-mail addresses: meysam.haghshenas@engr.und.edu, mhaghshe@alumni.uwo.ca (M. Haghshenas).

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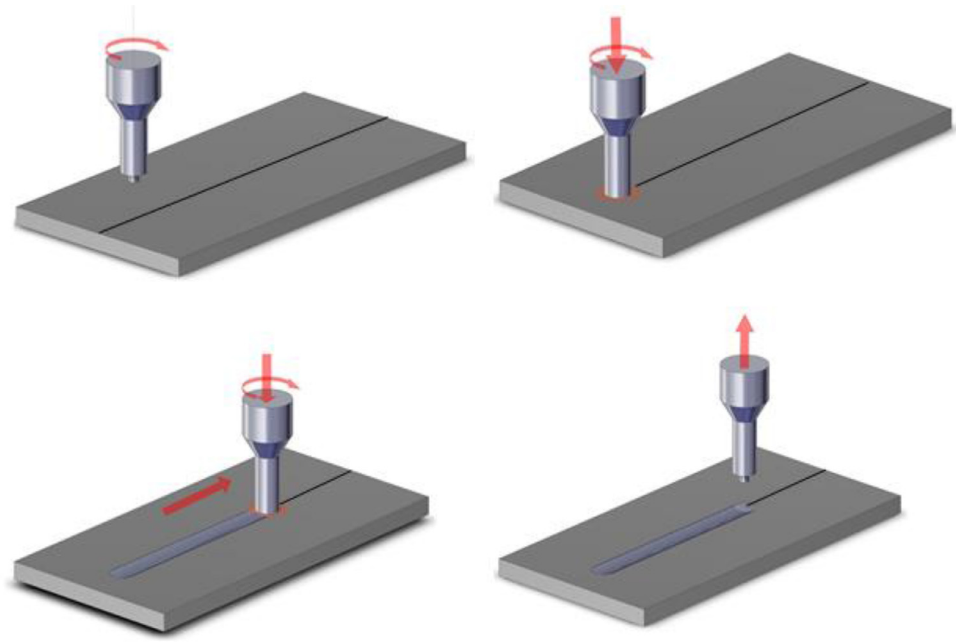

Fig. 1. Four steps of the FSW including initial set up, tool plunging, traverse, and tool withdrawal.

variables, in the FSW process, are classified as tool related, joint design related, and machine (welding) related parameters as well as a few others, which do not fall into any of these categories. Tool related parameters include the tool geometry and material type of the tool. Joint design includes the joint type (butt, lap, or fillet). Machine parameters include tool rotation speed (ω, rpm), transverse speed (V, mm/min), axial force (insertion depth), tool tilt (angle of the spindle), and the offset from the center of the joint. Other factors that could influence the weld quality include the initial temperature of the material (pre-heat or cooling), as well as the cooling rate. It is literally impossible to study the effect of these parameters all together or one by one considering inter-relation among them since an unusually large number of tests must be performed while the overall contributions of the interrelating parameters may not be necessarily detectable. According to engineering logic, one should be able to extract as much information as possible form a process (system) like FSW based on fewest number of essential experiments.

Around 1920 a British scientist, Ronald A. Fisher, originated the concept of design of experiment (DOE) by proposing a systemic approach to extract as much information as possible from experimental tests [4,5]. His approach was welcomed by experimentalists around the world as, via employing an appropriate DOE approach, redundant tests and observations are eliminated and therefore time, investment and human power are saved largely. Beside this, the main parameters of the system, their relations, and their contributions toward outcome of the system can be systematically identified and recorded in a timely manner. In the next sections, we employ a DOE approach to assess the effect of two important FSW parameter, ω and V, on the local hardness measurements of an FSWed die-cast AM60 Mg alloy.

1.2. The alloy used in this study

The Mg alloy used in this study is AM60, a high-pressure die cast alloy which contains 6 wt% aluminum (Al) as the main alloying element and 0.5 wt% Mn. Al is soluble in Mg from 2.1 wt% at room temperature up to 12.6 wt% at the eutectic temperature of 437 °C (see Fig. 2) [6]. Al helps to improve the strength and the castability of the alloy. The microstructure of AM60 consists of course grains of alpha magnesium (α-Mg), and an intermetallic beta phase (β-phase) distributed along the grain boundaries (see Fig. 3) [7]. β-phase consists of $Mg_{17}Al_{12}$ and forms due to the fast cooling conditions, which are typical of the casting process. Non-equilibrium solidification occurs and the intermetallic β-phase, which possesses a higher Al concentration than the α-Mg phase, forms and is distributed along the grain boundaries which improves strength of the AM60 alloy [7]. Fig. 3 shows the microstructure of the as received AM60. The base material (BM) characteristically possesses large grains made up of α-Mg and β-phase. This alloy is commonly used for automotive die castings for safety components such as instrument panel structures and seat frames. This alloy offers excellent ductility, energy absorbing properties, strength and castability [8,9].

There are a handful of reported literatures on FSW of AM60 implying that the weld quality of AM60 is largely affected by tool rotational speed and tool transverse speed. According to the published reports, there is a narrow range of parameters that produces good quality welds [10–12]. Outside this narrow span, inner voids and/or lack of bonding are observed in the FSWed parts. According to the literature, higher tool rotational rates and lower transverse speeds show better quality welds [1,11].

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