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Parametric optimization of friction stir welding parameters of marine grade aluminium alloy using response surface methodology

S. SHANAVAS[1], J. EDWIN RAJA DHAS[2]

1. Department of Mechanical Engineering, Noorul Islam University, Tamil Nadu, India;
2. Department of Automobile Engineering, Noorul Islam University, Tamil Nadu, India

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Abstract: Friction stir welding between AA5052-H32 aluminium plates is performed by central composite design technique of response surface methodology. It is found that the welding parameters such as tool pin profile, tool rotational speed, welding speed, and tool tilt angle play a major role in deciding the joint characteristics. The joints fabricated using tapered square pin profile tool with a tool rotational speed of 600 r/min, welding speed of 65 mm/min, and tool tilt angle of 1.5° result in an unexpected weld efficiency of 93.51%. Mathematical models are developed to map the correlation between the parameters and responses (ultimate tensile strength and elongation) and these models are optimized to maximize the ultimate tensile strength of the friction stir welded joint. Response plots generated from the mathematical models are used to interpret the interaction effects of the welding parameters on the response variables. Adequacy of the developed models is validated using analysis of variance (ANOVA) technique. Results from the confirmatory experiments plotted in scatter diagram show a good agreement with predicted models. Different grain structures in various zones of the weld are examined by observing the micro and macro structures of the weld.

Key words: aluminum alloy 5052; friction stir welding; response surface method; tensile strength; microstructure

1 Introduction

High specific strength and corrosion resistance necessitate the use of aluminium alloy in making lighter, faster, and stronger high-performance vessels. Aluminum alloys widely used for marine applications are 5xxx series in which the principal alloying element is magnesium. These alloys are now used as an alternative to steel in many applications because of their light weight, good weldability, good formability, high strength, and high corrosion resistance [1,2]. Among the AA5xxx series of aluminium alloys, AA5052-H32 aluminium alloys are excellent in corrosion resistance and therefore are particularly suited for applications in the industrial and marine environment. Welds of these alloys are normally as corrosion resistant as the parent material. Till 1991, the welding of aluminium and its alloys was a great challenge for researchers and technologists. Friction stir welding (FSW) is relatively new solid state joining process patented in 1991 [1]. The process is used in various industries like aerospace, marine and automobile, due to its high-quality joints [3].

Weld parameters such as tool pin profile, rotational speed, welding speed, and tool tilt angle, are key factors that govern the heat generation and stirring required to join the material effectively [4−6]. Influence of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium alloy [7], AA6061 aluminium alloy [8] and AA7075 aluminium alloy [9] is investigated. It is found that the tapered pin profile exhibited superior tensile properties compared to straight pin profile for AA7039 aluminium [10]. AA5052-H32 aluminium alloy is highly corrosion resistance stabilized aluminium alloy used for automotive and marine structural applications. Limited works are carried out on friction stir welding between AA5052-O aluminium alloy plates [11−13]. Studies were done on the effect of tool shoulder diameter on heat input during FSW of AA5052-H32 alloy [14]. The effect of tool rotational speed and tool tilt angle on the mechanical properties and metallographs of the dissimilar friction stir butt joint between Al alloy AA5052-H32 and HSLA steel [15] were investigated.

Various experimental design methods are available to predict the response under a given set of operating

Corresponding author: S. SHANAVAS; Tel: +91-9400529829; E-mail: shanavas.in@gmail.com
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parameters accurately and efficiently. Taguchi method is such a method, which uses an orthogonal array to cut down the number of experiments. The major drawback of this method is a few interactions with variables, and this can be overcome by the response surface method [16]. Nowadays, researchers prefer response surface design to develop an empirical relationship to predict the responses [17−19]. Therefore, in this work, an attempt has been made to optimize the FSW process parameters to maximize the tensile strength of AA5052-H32 aluminium alloy joints using the central composite design technique of response surface methodology. Mathematical models are developed to predict the response. Microstructures are examined on the welded specimen and the reports are presented.

2 Experimental

It is very difficult to form a mathematical equation for higher tensile strength values so that we consider the range of friction stir parameters. The predominant factors that influence the joint properties and the working ranges of those factors of AA5052-H32 aluminium alloy are presented in Table 1. Due to wide range of influencing factors, it is decided to design four significant factors, five levels and a central composite response surface method design matrix with 31 runs. So, many trial welds were carried out to fix the working ranges of all selected parameters. The upper limit of these factors was coded as +2 and the lower limit as −2. The intermediate values are calculated using the relationship:

$$X_i=2[2X-(X_{max}+X_{min})]/(X_{max}-X_{min}) \quad (1)$$

where X_i is the required coded value of variable X, X is any value of the variable from X_{min} to X_{max}, X_{min} is the lowest level of the variable and X_{max} is the highest.

The 31 sets of coded conditions comprise a half replication of 2^4=16 factorial design with 7 center points and 8 axial/start points. All the welding parameters at the middle level (0) constitute center points, whereas the combinations of each welding parameter at its lower value (−2) or higher value (+2) with the other four parameters at the middle level constitute the star points. Thus, the 31 experimental runs allowed the estimation of linear, quadratic and two-way interactive effects of the welding parameters on the ultimate tensile strength.

In the present work, 150 mm × 50 mm × 6 mm cold rolled plates of high strength aluminium magnesium alloy AA5052-H32 were used for friction stir welding experiments. The chemical composition of the metal is given in Table 2. Wire brushing is employed for cleaning the abutting surfaces for welding. The welding direction was parallel to the rolling direction of the plate. The plates were welded in a single pass, using tapered tool pin profiles such as cylindrical tapered, hexagon tapered, pentagon tapered, square tapered, and triangular tapered having a taper angle of 10° and pin length of 5.7 mm (Fig. 1). Considering the weld quality of AA5052-H32 aluminium plates and tool wear rate, H13 steel was selected for this work [20−22]. As prescribed by the design matrix, totally 31 joints of each alloy were fabricated. Photographs of the fabricated joints are displayed in Fig. 2.

Table 1 Identified significant factors and their levels

No.	Parameter	Level				
		−2	−1	0	+1	+2
1	Tool profile (tapered), P	Hexagon	Pentagon	Square	Cylindrical	Triangular
2	Rotational speed, N/(r·min^{-1})	400	500	600	700	800
3	Welding speed, S/(mm·min^{-1})	45	55	65	75	85
4	Tool tilt angle, A/(°)	0.5	1	1.5	2	2.5

Table 2 Chemical compositions of Al5052-H32 alloy (mass fraction, %)

Cu	Mn	Mg	Si	Cr	Fe	Ti	Al
0.01	0.08	2.33	0.14	0.18	0.29	0.02	Bal.

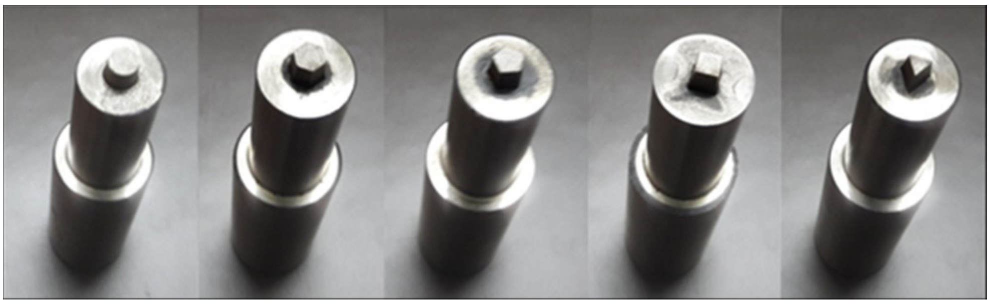

Fig. 1 Various tool pin profiles used for welding study