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Original Article

Identification of optimum friction stir spot welding process parameters controlling the properties of low carbon automotive steel joints

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ABSTRACT

Friction stir spot welding is a novel solid state process that has recently received considerable attention from various industries including automotive sectors due to many advantages over the resistance spot welding. However to apply this technique, the process parameters must be optimized to obtain improved mechanical properties compared to resistance spot welding. To achieve this, in this investigation, design of experiments was used to conduct the experiments for exploring the interdependence of the process parameters. A second order quadratic model for predicting the lap shear tensile strength of friction stir spot welded low carbon automotive steel joints was developed from the experimental obtained data. It is found that dwell time plays a major role in deciding the joint properties, which is followed by rotational speed and plunge depth. Further optimum process parameters were identified for maximum lap shear tensile strength using numerical and graphical optimization techniques.

1. Introduction

To meet the challenges in the today's automobile requirements, such as durability, reliability and sustainability, new emerging technologies were developed in the field of welding, since it plays a major role in many automobile components. In this manner, in order to weld low carbon automotive steel, commonly used technique in the automotive industry sector is the resistance spot welding (RSW). RSW has many limitations such as high wear rate of electrode, which limits the electrode life during welding of welding of steels [1], high temperature and rapid cooling rate leads to formation of brittle microstructure [2]. In order to avoid these limitations, friction stir spot welding (FSSW) process is the competent solid state process to weld the low carbon steel automotive steel. FSSW is a single spot joining process, in which a solid-state joining is made between adjacent materials at overlap configuration. This process also eradicates the problems associated with other conventional spot welding processes such as mechanical riveting, clinching, and toggle lock [3,4].

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FSSW was initially limited to join aluminium alloy due to the difficulty in selecting the appropriate tool materials that can withstand the high temperature during friction stir spot welding of steels. However, with the development of new tool materials, now this process can be applied to weld steels. Aato et al. [5], used a probeless frictions stir spot welding tool to join low carbon steel plates. The rotating tool of 3.6 mm diameter, rotating at 18,000 rpm, was plunged into the upper plate at a rate of 0.2 mm/s, and then kept at a maximum plunged depth of 0.05–0.25 mm for 0–1 s (dwell time). In the weld obtained by this process, a hole due to the impression of the plunged tool probe was not formed.

Baek et al. [6], fabricated friction stir spot welded galvanized steel joints and reported that there was no mechanically mixed layer between the top and bottom plates at the weld nugget due to the limited tool penetration and the lower pin height of the welding tool than the steel plate thickness. Baek et al. [7], joined low carbon steel plates by friction stir spot welding (FSSW) with lap configuration and observed that the tool penetration depth exerted a strong effect on failure mode of joining samples and a weak effect on the joint shear strength. They also reported that, with increasing tool penetration depth, and consequently with increasing depth of the tool shoulder pressing into top sample, failure mode in a lap-shear test changed from brittle to ductile and concentrated near the pinhole located away from the weld towards base metal.

Sun et al. [8], investigated the microstructure and mechanical properties of mild steel joints prepared by a flat friction stir spot welding technique. The author observed that, during lap shear testing, when the weld failed through the interfacial mode, the load dropped to zero in a very short time after a failure. However, when the weld fracture through the plug failure mode, the applied load starts to drop as the crack initiates. Sun et al. [9] conducted a feasibility study on friction stir spot welding of low carbon steel plates with high frequency induction as an additional heat source and reported that with preheating, sound welds can be obtained with less amount of load and low rotational speed and also they observed that the shear tensile load also can reach a maximum value of 12.4 kN.

In FSSW, it is essential to understand the effect of process parameters such as rotational speed, dwell time and plunge depth on the weld quality characteristics [10–12]. In order to investigate the effect of these process parameters, most of the researchers follow the traditional experimental techniques by varying one parameter at a time while keeping the others constant. This conventional step-by step optimization approach involves a large number of independent runs and does not take into account the possible interactions between factors. To avoid these disadvantages, the use of design of experiment (DoE) is the most efficient means to reach conclusions with a minimum of trials. Though research work applying the design of experiments and response surface methodology on friction stir spot welding of aluminium alloys have been reported in literature [13–15], it appears that the empirical relationship between FSSW process parameters and quality characteristics (i.e. tensile shear failure load) of friction stir spot welded automotive steel has not been reported yet. Hence, in this investigation, design of experiments was used to conduct the experiments for exploring the interdependence of the process parameters and second order quadratic models for the prediction of tensile shear failure load of friction stir spot welded low carbon steel joints were developed from the data obtained by conducting the experiments.

Table 1 – Chemical composition of the base metal (measured).

Elements	C	Si	Mn	W	S	P	Fe
%	0.03	0.04	0.21	0.003	0.008	0.016	Remaining

2. Experimental work

2.1. *Identifying essential friction stir spot welding process parameters*

The base metal used in this investigation is low carbon automotive steels. The chemical composition and mechanical properties of the base metal are shown in Tables 1 and 2. From the feasibility study carried out in our laboratory, among many independently controllable primary and secondary process parameters affecting the tensile shear failure load, the process parameters of rotational speed (*N*), plunge depth (*P*), and dwell time (*D*), were selected for this study. These three are the parameters that decide the bonding characteristics and subsequently influencing the tensile shear failure load variations in the friction stir spot welded low carbon automotive sheets.

2.2. *Feasible limits of process parameters*

Trial runs were carried out using 0.8 mm-thick of low carbon automotive steel to find out the feasible working limits of FSSW process parameters. Different combinations of considered process parameters were used to carry out the trial runs. This was done by varying one of the factors from minimum to maximum, while keeping the rest of them at constant values. The feasible limits of the individual were identified by inspecting the flash formation, top surface of the weld, macrostructure (cross section of the weld) for a smooth appearance without any visible macro level defects such as pinhole and root defect. The chosen levels of the selected process parameters with their units and notations are presented in Table 3.

Table 2 – Mechanical properties of the base metal (Measured).

Property	Values
Ultimate tensile strength	365 MPa
Yield strength	305 MPa
Elongation	40%
Microhardness	105 $HV_{1.0}$