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# An assessment of microstructure, hardness, tensile and impact strength of friction stir welded ferritic stainless steel joints

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ABSTRACT

Microstructure and mechanical characterization of friction stir welded 409M ferritic stainless steel joint were carried out. Single pass welds free of volumetric defects were produced at a welding speed of 50 mm/min and rotation speed of 1000 rpm. Optical microscopy, microhardness testing, transverse tensile, impact and bend tests were performed. The coarse ferrite grains in the base material are changed to very fine grains consisting duplex structure of ferrite and martensite due to the rapid cooling rate and high strain induced by severe plastic deformation caused by frictional stirring. Tensile testing indicates overmatching of the weld metal relative to the base metal. The joints are also exhibited acceptable ductility and impact toughness.

## 1. Introduction

409M grade ferritic stainless steels (FSS) widely used for the manufacture of coal wagons for transporting iron ore. The different parts made from 409M grade are box body (including the inner and outer walls, floor plate and wagon under-frame), vertical side stanchions and flab doors [1]. These steels generally conform in composition to grades S41003 (ASTM A240), 1.4003 (EN 10088-2 and EN 10028-7) and 3Cr12. The steel was developed from the ferritic stainless steel AISI 409 by careful balancing of ferrite (Cr, Si, Ti) and austenite (Ni, Mn, C, N) stabilising elements using Kaltenhauser's relationship presented in Eq. (1) [2]

$$\text{Kaltenhauser Ferrite Factor (KFF)} = \mathrm{Cr} + 6\mathrm{Si} + 8\mathrm{Ti} - 2\mathrm{Mn} - 4\mathrm{Ni} - 40(\mathrm{C} + \mathrm{N}) \qquad (1)$$

The 409M grade ferritic stainless steels are designed to transform partially to austenite on cooling, passing through the dual-phase austenitic–ferritic phase field on the Fe–Cr equilibrium phase diagram, (Fig. 1). This partial solid-state phase transformation of ferrite to austenite on cooling improves the weldability and as-welded toughness by restricting heat-affected zone (HAZ) grain growth [3]. In high purity Fe–Cr systems, the gamma loop extends as far as about 13.5% Cr, after which the structure is fully ferritic at all temperatures. Due to low alloying content, the steel used in the present study lies in the dual phase region, and the structure would therefore consist of a mixture of untransformed delta ferrite, alpha ferrite which transformed from austenite on cooling and martensite, depending on the cooling rate [3] and that is why it is variously described as "ferritic" or "ferritic–martensitic" 12% Cr stainless steel [4].

The 409M grade stainless steels are usually supplied in the fully annealed and desensitized condition. Final annealing is performed at temperatures below the A1 (normally between 700 °C and 750 °C) after air cooling or cold rolling [5]. Though the modified 12% Cr ferritic stainless steels are having better weldability than conventionally used ferritic stainless steels, the steel still suffers from grain growth in the heat-affected zone and weld metal region results in significant alterations in the mechanical properties [6].

Friction stir welding (FSW) is a novel solid-state joining process that was invented in 1991, it can avoid many problems associated with fusion welding processes, thereby defect-free welds having excellent properties can be produced even in some materials with poor fusion weldability [7]. Due to its many advantages, FSW attracts a great deal of attention in industrial fields, and is successfully applied to the joining of the various aluminum alloys, magnesium and copper alloys. In recent years, FSW of high melting temperature materials such as steels, nickel and titanium alloys has become a research hotspot [8]. The main obstacle to use FSW with these higher melting point materials is the development of tool materials capable of surviving the high temperatures and forces generated by the process [9]. Considerable advances have been made, mainly through improved materials selection and tool design [10–13]. Tool material development work has looked primarily at refractory metals (e.g., W–Re) [10,11], polycrystalline boron nitride (PCBN) [12] and WC [13].

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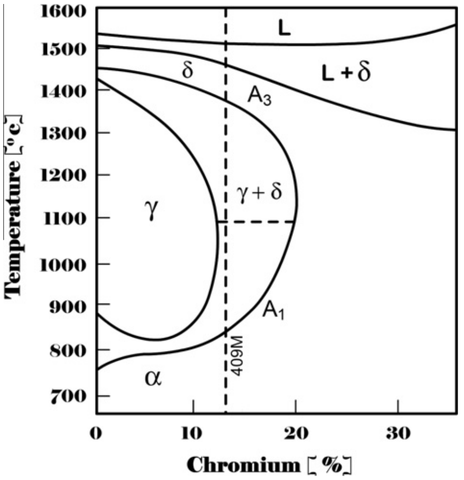

**Fig. 1.** Fe–Cr equilibrium phase diagram showing the position of 409M ferritic steel.

**Table 2**
Welding conditions and process parameters.

| Parameters | FSW |
|---|---|
| Welding machine | RV Machine Tools, India |
| Welding speed (mm/min) | 50 |
| Tool rotational speed (rpm) | 1000 |
| Axial force (kN) | 33.5 |
| Tool material | Tungsten alloy |
| Tool profile, shoulder and pin diameter (mm) | Taper cylindrical, 20 and 8–6 |
| Pin length (mm) | 3.7 |

Only three papers were reported on friction stir welding of ferritic stainless steels in the literature. Thomas et al. [14] reported a feasibility study on FSW of a ferritic–martensitic, low carbon, 12 wt.% Cr stainless alloys, and of low carbon mild steel. The welding speeds used were in the range of 102–240 mm/min to fabricate the joints. The author reported that the detailed weld parameters, dimensions of the tool, and the tool material are still being further optimized. They observed that the maximum weld temperatures of the order of 1100 °C and the hardness values of heat-affected zone are higher than the weld metal region. The reason for this difference is not clear from the limited microstructure presented by authors. Park et al. [15] examined the microstructural evolution and mechanical properties of friction stir welded 430 stainless steel. The joint was made using a welding speed and rotational speed of 80 mm/min and 550 rpm respectively and they found that the coarser elongated base material was changed to very fine duplex microstructure of ferrite and martensite resulted in significant improvement in mechanical properties. Thomas et al. [16] used bobbin tool design to join 8 mm thick 12 Cr ferritic stainless steel plates and reported that sound welds were produced using a rotational speed of 584 rpm and 75 mm/min. During tensile test the joints were found to fail in the plate away from the weld. FSW of ferritic stainless steels leads to improvement in mechanical properties by microstructural refinement compared to the fusion welding processes. However, details of microstructures and mechanical properties of friction stir welded 409M grade ferritic stainless steels are not yet reported in literature. In this paper, microstructure, microhardness, tensile, impact toughness and bend tests were carried out in order to evaluate the joint performance and the weld zone characteristics of friction stir welded 409M grade ferritic stainless steel joints.

## 2. Experimental

The as-received base material (BM) used in this study was 4 mm thick cold rolled, annealed and pickled AISI 409M grade ferritic stainless steel plates. The chemical composition of the base metal presented Table 1 was obtained using a vacuum spectrometer (ARL, model 3460). Sparks were ignited at various locations, and their spectrum was analysed for the estimation of alloying elements. Few welding trials were carried out and specimens were extracted from various locations of the joint and subjected to macrostructural analysis. The specimen free of volumetric defect and lack of penetration was considered as the optimized welding condition. Also care was taken to avoid the tool pin failure and control the heat input by controlling the combination of tool rotational speed and welding speed. The welding conditions and optimized process parameters presented in Table 2 were used to fabricate the joints for further investigation. An indigenously designed and developed CNC controlled friction stir welding machine was used in position control mode to fabricate the FSW joint. Argon gas shielding was employed to prevent the oxidation of the plate surface. Fig. 2 shows the photograph during friction stir welding of 409M joint and an example of weld bead appearance. The welded joints were sliced (as shown in Fig. 3) using abrasive cutting and then machined to the required dimensions for preparing tensile, impact test, bend and metallographic specimens.

Two different tensile specimens were prepared as shown in Fig. 4a and b, to evaluate the transverse tensile properties. Un-notched smooth tensile specimens were prepared to evaluate the transverse tensile properties of the joints such as yield strength, tensile strength and elongation. Notched specimens were prepared to evaluate notch tensile strength and notch strength ratio (notched tensile strength/un-notched tensile strength) of the joints. Small tensile specimens of which the gauge length was covered by the weld nugget shown in Fig. 4c, were used to characterize the tensile properties of the stir zone. Three replicates for tensile testing were prepared to minimize errors. Tensile testing was carried out using 100 kN, electromechanical controlled universal testing machine (FIE-Blue Star, India; model UNITEK-94100). ASTM E8M-04 guidelines [17] were followed for preparing and testing the tensile specimens.

Charpy impact specimens were prepared to the dimensions shown in Fig. 4d and e to evaluate the impact toughness of the weld metal and HAZ, and hence the notch was placed (machined) at the weld metal (weld centre) as well as in the HAZ. As the plate thickness is small, subsized specimens were prepared. Impact testing was conducted at room temperature using a pendulum-type impact testing machine (ENKAY, India) with a maximum capacity of 300 J. The amount of energy absorbed in fracture was recorded, and the absorbed energy is defined as the impact toughness of the material. ASTM E23-04 specifications [18] were followed for preparing and testing the impact specimens. Face and root three-point bend tests were performed as per ASTM E190-03 specifications [19]. A Vickers microhardness testing machine (SHIMADZU, Japan;

**Table 1**
Chemical composition of base metal used in this study (spectrometry results).

| C | Cr | Ni | Nb | Cu | Si | Mn | P | S | N | Al | Co | Ti | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.026 | 11.40 | 0.4 | 0.009 | 0.365 | 0.45 | 1.15 | 0.4 | 0.16 | 0.04 | 0.01 | 0.2 | 0.008 | 0.017 |