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Characterization of resistance spot welded transformation induced plasticity (TRIP) steels with different silicon and carbon contents

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ABSTRACT

This research work examines the influence of chemical composition and microstructure of 6 different transformation induced plasticity (TRIP) steels on the mechanical behavior of resistance spot weldments. The microstructure of the spot welds was characterized by means of scanning electron microscopy and X-ray diffraction techniques. The mechanical properties were assessed under lap-shear tensile and hardness testing. Results indicated that the nugget width is strongly correlated with the type of failure mode of the spot welds. The mechanical properties exhibited by the spot weldments are related with the partitioning behavior of chemical elements specially Si and C present in the steels during the cooling stage of the resistance spot welding process. X-ray diffraction study indicated traces of retained austenite in the heat affected zones of the spot welds of those steels with Si-enriched chemical composition where intercritical annealing temperatures were closer to Ac_1.

1. Introduction

High levels of pollution generated by CO_2 emissions have led the automotive industry to get involved in the production of fuel-efficient vehicles. Among the main proposed solutions, net weight reduction of vehicles is a promising one. This purpose is properly achieved by the introduction of advanced high-strength steels (AHSS), which are lighter owe to thinning of gauge sheet. Additionally, AHSS offer enhanced mechanical properties if compared to their predecessors (i.e. HSLA), in a way that the passengers safety is not compromised. Transformation Induced Plasticity (TRIP) steels highlight among AHSS due to the carefully designed microstructure composed of a ferritic matrix, bainite, fine islands of retained austenite (RA) and additions of martensite. TRIP steels offer an excellent combination of strength and ductility owe to transformation of RA into martensite (hardening rate) at elevated strain level. The stability of RA depends on the carbon enrichment during austempering because presence of Si acts as a carbide growth suppressor during bainitic transformation, thus, carbon enrichment increases the thermal stability of austenite that is to be retained upon cooling to room temperature [1].

Resistance Spot Welding (RSW) is the predominant welding process by which TRIP steels are joined for auto-body construction, RSW develops rapid weld thermal cycles (i.e. elevated heating rate followed by extremely high cooling rates), which causes the original steel microstructure to be locally transformed. Further microstructure transformation is strongly dependent on the steel chemistry and cooling rate [2]. For this reason, the resultant mechanical properties are of vital importance and must be assessed with the purpose of obtaining sound joints.

According to AWS D8.1M [3], failures in welded joints joined by RSW can occur in three modes: i) interfacial, ii) partial-interfacial, and iii) button failure. Each of these failures occur in different zones of the joint, either in the heat affected zone, which causes the complete detachment of the nugget as in the case of plug failure (button) or the partial detachment of the nugget as in the case of partial plug failure (partial-interfacial), a detachment along the nugget is characteristic of an interfacial failure. There are some factors associated with the failure modes in AHSS steels, in which the influence of the geometry, hardness and metallurgical phenomena generated by the welding process are highlighted. The size of the nugget directly influences the failure mode that the weld joint experiences, so the area available to support loads is a function of the nugget width, for this reason interfacial failure will occur more easily in small diameters, while larger nuggets involve partial or plug failures [4,5]. The metallurgical factors, as well as the hardness, both are intrinsically related to the chemical composition of TRIP steels, high percentages of alloying elements will cause the welded joint to be more susceptible to the segregation of harmful elements in the initially formed austenitic grain boundary, which will generate an

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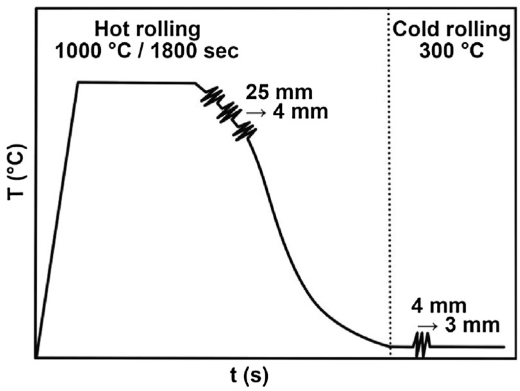

Fig. 1. Hot and cold rolling of studied steels.

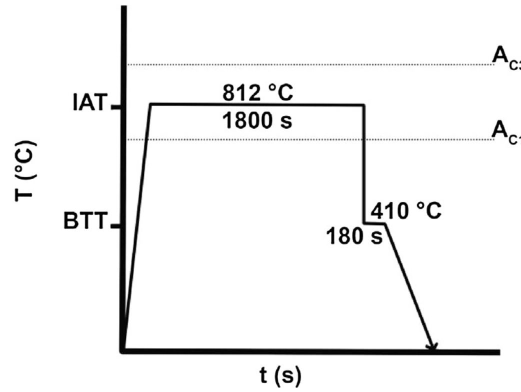

Fig. 2. TRIP heat treatment of studied steels.

intergranular failure along the grain boundaries [6]. Similarly, high carbon contents result in welded zones with sufficiently high hardness levels to fail in a brittle mode [7]. Thus, an increase in post-weld hardness also increases the percentage of brittle microstructure. It should be emphasized that the amount of absorbed energy or percentage of strain supported by systems joined by RSW are directly related to the failure mode they present, for this reason plug failure is the desired failure mode in automobile industry because it reflects high energy absorption levels, which are reached due the transformation or retained austenite to martensite and depend on the stability of retained austenite.

There are investigations that detail the microstructure and mechanical properties of AHSS steels, including TRIP steels, however, fails to compare the relationship between microstructure and mechanical properties of spot weldments in TRIP steels with different amounts of Si and C.

The objective of the present study is to analyze the microstructure and phase transformation of in lab casting and cold-rolled TRIP steels having different percentages of Si and C and assess their influence on quasi-static uniaxial tensile mechanical properties.

2. Materials and methods

Six experimental TRIP steels, with different alloying contents were fabricated in the Foundry Lab of the Metallurgical Research Institute of UMSNH (México), by using high purity raw materials, in a 25 kg capacity induction furnace. The alloying elements were added directly into the crucible, the steels were cast into 50 mm × 50 mm × 150 mm square section metal molds. The chemical composition of the TRIP steels was obtained via atomic emission spectroscopy (AES) and is shown in Table 1, where Ac_1, Ac_3 and M_s transformation temperatures were calculated using JMatPro^{TM} software, while the equivalent carbon (CE) content was calculated by means of Yurioka's formula [8]. The ingots were first heat treated at 1100 °C and held for 2 h, and then air cooled. After homogenization heat treatment, the ingots were cut in rectangular sections of 25 mm × 25 mm × 150 mm and then heated up to 1000 °C, kept at this temperature for 30 min, and then hot rolled to a thickness of 4 mm, once the materials were cooled down to 300 °C, they were cold rolled to a thickness of 3 mm, as shown in Fig. 1. After cold rolled, each steel was cut in longitudinal sections of 150 mm in gauge length and 30 mm in gauge width, and then mechanical rectified to a final thickness of 1.7 mm.

Heat treatment consisted of intercritical annealing carried out at 812 °C for 1800 s, and then rapidly cooling in salt bath directly from the annealing temperature to the bainite transformation temperature range and then isothermally held at 410 °C for 3 min followed by air cooling to room temperature, as shown in Fig. 2. Each of the

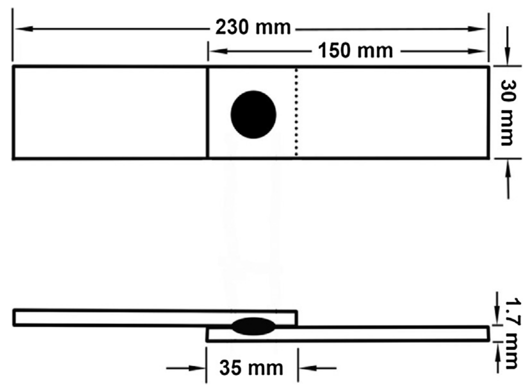

Fig. 3. Geometry and dimensions of lap-shear tensile test specimens.

heat treatments were monitored through a program developed in LabView using a K-type thermocouple.

Resistance spot welds were conducted in a CenterLine Ltd. 250-kVA single phase AC resistance spot welding machine, and a truncated class 2 electrode with 6.0 mm face diameter was used. The weld current was 8.3 kA, the weld force was 3.5 kN and the weld time was 30 cycles for each material. Weld nugget width was measured by the metallographic technique. Specimens were sectioned across the weld joint, covering the fusion zone (FZ), heat affected zone (HAZ) and base metal (BM), and then polished followed by etching in 2% Vilella's solution. Minimum of four specimens were considered to measure the nugget width and averages values were reported. Microstructures of the TRIP steels and their spot welds were identified by scanning electron microscopy (SEM) and X-ray diffraction (XRD) measurements. The specimens were ground in emery paper and diamond-polished to a 0.25 μm finishing, and then chemically etched in a 2% Nital solution. XRD analysis was done in sections containing the FZ, HAZ and BM polished samples, using Cu-Kα radiation (λ = 1.5402 Å), data conditioning and analysis was processed using TOPAS software package. The retained austenite content was calculated from the X-ray intensities using the Rietveld method. Lap-shear tensile tests were carried out using a Zwick test machine with a cross head speed of 1 mm /min that is nearly quasi-static. Fig. 3 shows the tensile specimen dimensions under study. Microhardness (HV) measurements were performed on the cross section of welded joints according to AWS D8.9M: 2012 [3], with 200 g load and hold time of 12 s maintaining a distance of 200 μm between indentations, these were conducted in a Zwick/Roell ZHV^{TM} testing machine.