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Micro–macro-characterisation and modelling of mechanical properties of gas metal arc welded (GMAW) DP600 steel

A. Ramazani [a,*], K. Mukherjee [a], A. Abdurakhmanov [b], U. Prahl [a], M. Schleser [b], U. Reisgen [b], W. Bleck [a]

[a] Department of Ferrous Metallurgy, RWTH Aachen University, D-52072 Aachen, Germany
[b] Welding and Joining Institute, RWTH Aachen University, D-52072 Aachen, Germany

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ABSTRACT

Dual-phase (DP) steels show combined high strength and adequate formability. However, during welding, their microstructural feature of dispersion of hard martensite islands in the soft ferrite matrix is lost and the properties deteriorate. The current research aims to study the mechanical properties of the welded joint, taking into account the effect of features of all regions, such as microstructure, chemical composition and the area fraction, on the macroscopic mechanical properties of the welded joint. Hot rolled DP 600 steel was gas metal arc welded (GMAW) and tensile specimens were made with a welded joint. In the heat-affected zone (HAZ), the microstructure varied from bainite to coarse grained ferrite and tempered martensite. Chemical composition of every quantified region in the welded specimen was also identified using electron probe microanalysis (EPMA). Macromechanical FE modelling was employed to simulate the mechanical properties of the welded tensile specimen. 2D representative volume elements (RVE) for different parts of the welded region were constructed from real microstructure. 2D simulated flow curves were corrected to 3Ds using a developed correlation factor. Finally, the tensile test of welded material with inhomogeneous morphology was simulated and good agreement between experimental and predicted flow curve was achieved.

1. Introduction

Currently, dual-phase (DP) steels are considered an attractive choice for the automotive industry, thanks to their good mechanical properties, which include low yield strength to tensile strength ratio, continuous yielding, high initial work hardening rate and superior crash performance [1–5]. These properties derive from the special microstructure of the DP steel, which contains 5–20% hard martensite phase in a soft ferrite matrix. This special microstructure is obtained through proper alloying and suitable thermomechanical treatment [6,7]. However, welding plays a destructive role in the final mechanical properties of the DP steels. As a large temperature gradient is induced on the work piece during welding, the microstructure is locally destroyed and hence the mechanical properties of DP steel are downgraded. It is therefore essential to quantify the microstructure evolution in the welded zone and its influence on the final mechanical properties of DP steels.

Gas metal arc welding (GMAW) is widespread for plastically deformed or closed parts of the auto body and is frequently engaged where the part geometry inhibits the use of resistance spot welding (RSW) or when the design requires supplementary joint strength and stiffness. The application of arc welding and flash butt welding processes for DP steel welding has also been reported [8,9]. The joined parts using GMAW typically experience a higher heat input and lower heating and cooling rates than other welding techniques in automotive applications. During GMA welding, the microstructure is exposed to a thermal path different from that used for its production. Local heat input of the welding heat source that induces a large temperature gradient on the work piece will destroy the microstructure, and hence the mechanical properties, of DP steel [10,11].

Recently, micromechanical modelling through representative volume element (RVE) is being applied to obtain the flow curves of composite phases [6,12–16]. In this approach, a proper RVE has first to be selected from the real microstructure. The constitutive equations of different phases can be obtained using dislocation-based strengthening models [13,17]. The flow behaviour of DP steels depends on the properties of ferrite and martensite and on the volume fraction and morphology of the martensite islands [17–21]. The strength of ferrite is determined by its composition

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[*] Corresponding author. Tel.: +49 241 80 95841; fax: +49 241 80 92253.
E-mail address: ali.ramazani@iehk.rwth-aachen.de (A. Ramazani).

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and grain size [22–26]. In addition, in the case of dual-phase steel, the ferrite gets extra strength from the initial dislocation density, formed due to the compatibility stresses and strains when austenite transforms into martensite during cooling [27–30]. The strength of martensite depends mainly on its carbon content [18,31,32]. Leslie has shown that the yield strength of martensite increases linearly with its carbon content [31]. The substitutional alloying elements Mn, Si, etc., also strengthen the martensite; however, their effect is minor compared to the effect of carbon.

The aim of this study is to quantify the microstructure at different parts of the welded joint and make a qualitative correlation between the microstructure and the tensile strength of the welded joint. Until now, few studies have been done to investigate the different characterizations of the zones of the welded samples, especially the softened zone [33,34]. Some scientists have observed that the softening is caused by the coarsening of ferrite grain size in the heat-affected zone (HAZ) [35], while others attribute it to the tempered martensite in the HAZ [36–38]. Since the softened zone is important for the material mechanical properties, therefore, it is meaningful to investigate the microstructure in the HAZ. Finally, the RVE approach is used to predict the flow behaviour of different microstructural regions observed in the welded joint. Next, all these different zones are aggregated (fusion zone+HAZ+base metal) and put into a macromodel. A numerical test is performed on this macromodel.

2. Experimental approach

2.1. Description of base material

The material used in this research was supplied by Thyssen Krupp Steel AG Division Auto as hot rolled sheets of 2.5 mm thickness. It was designed to be a 600 MPa (ultimate tensile strength) grade, high-strength, dual-phase steel. The material was galvanized. The microstructure of DP steel consists of 90% ferrite and 10% martensite. As can be observed from the chemical composition listed in Table 1, this was a low carbon steel, with additions of Si and Cr to facilitate the formation of the dual-phase microstructure.

2.2. Welding details

For welding, a 6-axis weld robot (OTC Daihen Almega AX-V6) was used. The arc source used for the experiments was an OTC DP 400 with a power input of 22 kW for pulse process.

G3Si1 (SG2) wire of 0.9 mm diameter was used as filler wire for welding of DP steel. According to the norm EN ISO 14341, this filler material is well suited to welding of low carbon steel. The chemical composition of the filler material is shown in Table 2. Moreover, the filler material has a tensile strength of 560 MPa (EN ISO 14341), so that the weld seam is approximately 5–10% less, guaranteeing tensile strength as the base metal (600 MPa).

For welding experiments, a pulsed arc welding process under inert gas was used. The pulse rate used during the welding in pulsed mode was 84 Hz and the shape of the pulse is schematically depicted in Fig. 1. So, as shown in the figure, pulse rise time is $t_1=0.5$ ms, pulse peak time is $t_2=0.8$ ms, pulse fall time is $t_3=0.8$ ms, so that the distance travelled during each pulse is 2.1 ms and the distance between two pulses is $t_4=9.7$ ms.

Table 1
The chemical composition of the steel investigated.

C	Si	Mn	P	Cr	Mo	Al	Cu	Ni	N
0.06	0.08	0.88	0.015	0.44	0.009	0.029	0.005	0.039	0.003

Table 2
The chemical composition of the filler material (in wt%).

C	Si	Mn	P	S	Cr	Mo	Al
0.06–0.14	0.3–0.5	0.95	0.015	0.025	0.17	0.005	0.029

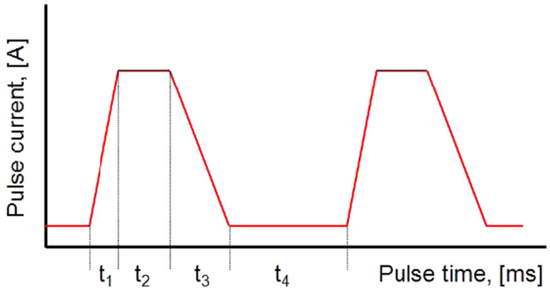

Fig. 1. Pulse shape during GMAW of DP steel.

Table 3
Operating conditions for sheet welding.

v_d, m/min	v_s (m/min)	U (V)	I (A)	P (kW)	E (kJ/m)
4.85	0.25	20.5	72.9	2.05	504.0

The gas used for the investigations consisted of 80% argon and 20% CO_2, with a flow rate of 15 l/min. The contact tip-to-work distance was 15 mm.

Welding samples with the dimensions $200\times50\times2.5$ mm^3 were machined from hot rolled sheet. The welding direction was perpendicular to the rolling direction. The welding conditions used in this study are summarized in Table 3. The parameter v_d is the feeding speed of the consumable electrode, v_s is the speed of the electrode (or arc), U is the operating voltage, I is the operating current, P is the power of the welding process and E is the energy input per unit length.

2.3. Microstructural analysis

2.3.1. Metallography and hardness mapping of GMAW joints

The microstructural analysis was also performed using optical microscopy on a ground, polished and etched specimen (etchant is 2% Nital). To quantify the microstructure of the welded sample, the following areas were selected for microstructural analysis (Fig. 2).

For the hardness mapping of the welded samples, UCI hardness equipment designed by IEHK, RWTH Aachen was used [39]. Using this equipment, the Vickers hardness of the whole surface of the sample can be quantified at 0.3 mm intervals automatically, using an exerted force of 1.0 Kg.

2.3.2. Electron probe microanalysis (EPMA)

EPMA measurements were also carried out in order to identify the chemical composition of single phases in any quantified zones in the GMAW sample. The measurements were made in a CAMEBAX SX 50 Electron Probe Micro Analyzer equipped with four wavelength-dispersive (WD) spectrometers. A focused electron beam of 15 keV with a current of 100 nA was used. The characteristic X-ray intensities were calibrated according to the following standards: Fe3C, GaP and pure metallic elements. The calibrated intensities (k-ratios) were transferred into elemental concentrations with the help of a matrix correction procedure