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Microstructural and mechanical characterisation of laser-welded lap joints with linear and circular beads in thin low carbon steel sheets

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ABSTRACT

This paper presents a microstructural and mechanical characterisation of laser-welded lap joints in low carbon steel thin sheets. Different combinations of steel types (DC05, S355MC) and thickness values are used to assemble welded specimens with linear and circular weld bead. Metallurgical observations and micro-hardness tests are used to characterise the weld microstructure. Mechanical response in tensile test is then used to evaluate the static strength, rotation angle of weld bead and failure mode of welded specimens. Lap-joints with circular weld showed a lower rotation angle compared to linear welds. The fracture in all tested specimens occurred at the base metal, far away from the weld. A simplified mechanical model is finally proposed to derive theoretical formulae for estimating the tensile strength of welded joints as a function of material properties and weld geometry. The analytical results are in good agreement with experimental findings and they estimate an increased strength for circular welds, compared to linear weld with same lateral width. A design chart is also derived to allow a design of laser-welded joints with virtually equal strength of base metal and weld zone.

1. Introduction

Laser welding is becoming an attractive and economically advantageous joining technique in several engineering fields. The main advantages are low process cost, high welding speed and concentrated heat power, which gives reduced distortions and narrow weld bead with limited microstructure changes in the heat-affected zone. Laser welding has largely been applied, for example, in the automotive industry to manufacture parts of car such as doors, front and side panels, side beams and wheel arches [1]. Applications of laser welding are partly documented also in railway industry, as possible replacement of resistance spot welding to increase surface quality of welded assembly on rail vehicle side panels [2].

A lap joint is a geometry commonly adopted in various welded assemblies and its characteristics have been investigated in the literature. Experimental studies of laser-welded lap joints, with various combinations of metals and alloys, have been focused on microstructural and metallurgical characteristics [3–5], as well as on mechanical strength under static [6–13] and fatigue loadings [5,14,15]. For example, Sokolov et al. [3] presented an experimental study on laser welds in S355 steel with high thickness values (20 and 25 mm). Microstructure and hardness profiles were used to characterise welded joints and to suggest preferable welding parameters. Hardness trends were use to identify microstructural changes in the joint. They found an increase of hardness in welded region, compared to base metal. An increase in welding speed also induces an overall increase in hardness and a reduction in the width of heat-affected zone. Yilbas et al. [4] investigated laser welds of low carbon steel plates with numerical simulations and experimental tests. Finite element analyses were used to compute the temperature distribution and the residual stresses in weld zones, which were in good agreement with measurements. The metallurgical and morphological modifications in the weld were also examined. Farabi et al. [5] characterised the microstructure and mechanical properties of laser joints in dual phase steel DP600. They found a considerable increase of hardness in the fusion zone, due to the large amount of martensitic structure promoted by rapid cooling during welding. On the other hand, a softer zone was observed at the outer heat-affected zone (HAZ), due to tempering of the pre-existing martensite. This soft zone was the position where all specimens fractured in tensile tests. In fatigue tests, welded joints showed a slightly lower fatigue limit compared to base metal. At high stress amplitudes, however, they showed comparable fatigue strength within the experimental scatter.

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The strength of welded joints has been investigated by theoretical and numerical approaches, as well as by experimental studies. For example, Ha and Huh [6] carried out experimental tests to formulate an analytical failure criterion for laser weld under combined normal and shear loading. Their study pointed out also the change in failure mechanism (from base metal to interfacial failure), as a function of the loading angle. Ono et al. [7] presented an experimental characterisation of static and fatigue strength of laser-welded lap joints in thin steel sheet. They also proposed a simple analytical model to estimate the strength and fracture position, based on weld joint properties. Miyazaki and Furusako [8,9] developed a similar model to estimate static failure evaluation, which also included the failure in the portion adjacent to the weld.

Numerical simulations with finite elements were also attempted to evaluate the weld strength under tensile loading. For example, Terasaki and Kitamura [10] adopted an elastic–plastic finite element model to check whether the equivalent plastic strain can be used to estimate the static tensile strength of lap joints. Comparison with experimental results showed that the equivalent plastic strain is only suitable to estimate base metal failure, while weld shear failure has to be assessed by conventional failure theories that assume a constant shear stress. Pan and co-workers [11,12,15] proposed a non-homogeneous elastic–plastic model to simulate the mechanical response and failure mode of lap joints in high strength low alloy (HSLA) steel. Results from finite elements analysis were in good agreement with experimental observations. The main limitation of finite elements modelling, however, is that numerical simulation can continue until numerical instability occurs. Therefore, the simulated load–displacement curves are monotonically increasing, without any maximum load that can be used to define the joint strength.

In the context of previous literature studies, this work presents the preliminary results of a research project aimed to characterise the microstructure and the mechanical strength of laser-welded lap joints in steel sheets, to assess their possible application in railway industry. The interest is focused on laser welds made of thin low carbon steel sheets with different thickness and chemical composition. A deep drawing DC05 steel and S355MC high strength structural steel, with thickness values in the range of 1.0–1.5 mm, are considered. Two different weld geometries (linear and circular) are also compared, see Fig. 1. The linear weld has a straight weld bead, perpendicular to specimen longitudinal axis. A circular weld, instead, has a weld bead that forms a circumference located at the specimen centre.

Metallurgical analyses, micro-hardness measurements and mechanical tensile tests were carried out to characterise the microstructure and mechanical properties of laser-welded lap joints with different weld geometry. The proposed experimental characterisation suggests that laser welding of dissimilar low carbon thin steel sheets could be a suitable joining technique for structural applications in railway industry.

2. Materials and experimental procedure

Microstructure and mechanical properties of laser-welded lap joints are investigated. Microstructure is characterised by metallurgical analysis and micro-hardness measurements. Mechanical behaviour is studied by tension tests, which provide the tensile strength, longitudinal deformation and rotation angle of the weld bead, as well as typical failure mechanisms.

2.1. Base materials and laser-welded lap joints

Two types of steel (DC05, S355MC) are used in welded joints. The DC05 material (EN 10130:2006 [16]) is a cold rolled, non-ageing low carbon steel especially suited for deep drawing and other demanding forming applications. The S355MC steel (material n. 1.0976) (EN 10149-2:2013 [17]) is a thermo-mechanically rolled steel with high yield stress and high impact strength properties. Table 1 lists the nominal mechanical properties and chemical compositions of DC05 and S355 steels used in this study.

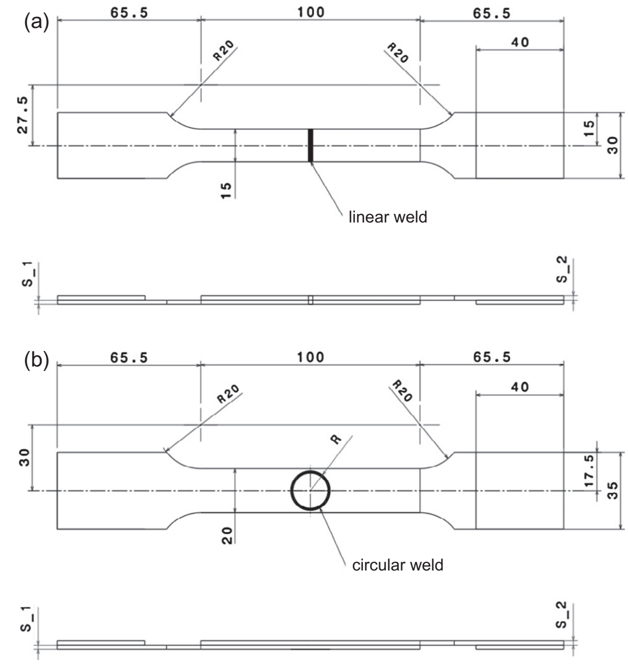

Fig. 1. Geometry of laser-welded lap joint with (a) linear and (b) circular weld geometry.

The laser-welded lap joints were obtained by welding two overlapping thin sheets with a fibre laser. The welding parameters are summarised in Table 2. No post-weld heat treatment was applied after welding.

Several preliminary tests were performed to arrive at the optimised welding parameters given in Table 2. In fact, previous parameters [18] gave unsatisfactory welded specimens, characterised by incomplete penetration, inhomogeneous microstructure and insufficient mechanical strength compared to base metal (e.g. failure occurred at weld bead). On the other hand, it is not the aim of the present work to further investigate the correlation between welding parameters and weld properties.

Fig. 1 shows the geometry and Fig. 2 a top-view of the welded specimens considered in this study. Different combinations of sheet thickness and metal types were used (see Table 3): a thickness of 1.0 and 1.2 mm for DC05 steel, 1.5 mm thickness for S355MC steel.

Specimens were shaped by laser cutting after welding. The overlapped welded sheets prior to laser cutting had a rectangular geometry, with same width and length as final welded specimens: length 231 mm, width 30 mm (linear weld) and 35 mm (circular weld). Two different weld geometries (linear and circular) were considered, both positioned at the overlap centre. The central straight portion of the specimen with reduced cross section has a length of 100 mm, while the width is 15 mm (for linear weld) and 20 mm (for circular weld). The linear weld has a length equal to the sheet width and is positioned transversely to the longitudinal specimen axis. Instead, the diameter of circular weld (15 mm) is lower than sheet width, which assures that the weld is completely inside the metal sheet and it is not cut during specimen shaping by laser cutting. The overlap length is 100 mm. Two doublers, 40 mm long, were positioned at both ends of the welded