Short Communication

Optimization of the tensile-shear strength of laser-welded lap joints of ultra-high strength abrasion resistance steel

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Abstract

The tensile-shear strength of laser-welded lap joints developed in abrasion resistance ultra-high strength ARS-600 steel was optimized by evaluating the joints achieved with different welding parameters and various configurations of weld patterns, including multiple continuous longitudinal and transverse weldments. The microstructural evolution of the fusion zone was characterized by electron backscatter diffraction (EBSD) after welding with different values of energy input (60–320 J/mm). Furthermore, in order to better comprehend the shear response of different weld patterns, stress analysis of various longitudinal and transverse lap joints was conducted by the finite element method (FEM). © 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Abrasion resistant steel (ARS) is a type of ultra-high strength martensitic steel, which is widely used in harsh working environments, such as in mining industry applications, crushers, agricultural machinery and conveyors, and the construction and cement industry. ARS experiences severe mechanical stresses and wear during application. Consequently, deleterious effects due to abrasion during drastic application induce failure [1,2]. The abrasion resistance property of ARS is mainly affected by the microstructure phase constituents and grain structure. Recently, it was reported that the martensitic microstructure and the small prior austenite grain size (PAGS) of ARS are favorable to inducing a high-performance wear resistance [3,4].

Researchers have studied how to enhance the wear performance of ARS by controlling the phase structure and the mechanical properties in order to increase the length of its service life [5–7].

Recently, bonded assemblies from multi-components structures are used in modern design structural...
applications. Thus, lap joints are widely used as mechanical fasteners in such structures. Furthermore, the structural integrity of these structures is mainly related to the strength properties and durability of the overlapping bond of the steel lap joints [8]. However, lap joints experience fragility at the interface between the sheets of the joints, as reported by our research group in a recent publication [9]. Thus, more research has been conducted to enhance the strength properties of the lap joints of ultra-high strength steel.

Laser welding technology is more efficacious than conventional welding methods due to the lesser width of the fusion zone (FZ) and smaller heat affected zone (HAZ) [10]. Furthermore, laser welding introduces limited heat transfer to the work piece, as well as reduced distortion, narrow weld bead and high welding speed [11]. The lap joints of ultra-high strength steel are processed by laser welding.

To the authors’ knowledge, the manufacturing of ARS lap joints by welding processes and the strength properties of such joints have not been reported in the literature. The present paper focuses on optimizing the shear-tensile strength of laser-welded ARS lap joints by controlling the welding process parameters and altering the weld pattern, that is, the multiple longitudinal and transverse welds configurations, at three different energy inputs. Comprehensive microstructure characterizations of the weld structures using electron microscopy were carefully conducted.

### 2. Experimental procedures

The base material (BM) in this study is an ultra-high strength steel grade (ARS-600) with microstructure composed of uniformly distributed grains of martensite. The studied steel was delivered by SSAB Europe Oy (Raah, Finland). The measured hardness of the BM is markedly high at 646 HV with yield and tensile strengths of 1770 and 2165 MPa, respectively, and a total elongation of 6.4%, as measured by using uniaxial tensile testing. The steel was supplied in the form of 3 mm thick sheets with a chemical composition (in wt. %) of 0.33 C, 0.5 Mn,
2.1 Ni, 0.81 Cr, 0.31 Si and 0.5 Mo. The geometry and dimensions of the single-lap joints with different weld patterns are schematically shown in Fig. 1. The dimensions of the two steel plates used for the lap joints are 150 × 50 × 3 mm. The overlap length in the lap joints is 50 mm. The distance between the multiple weld beads was equal to 10 mm.

Yb:YAG (Trumpf HDL 4002) disc-laser with a maximum power of 4 kW was used in the experimental setup of laser welding in this study. Laser-welding experiments were conducted at three different movement speeds and a constant power of 4 kW. The laser beam was focused by optics with a focal distance of 300 mm. The diameter of the focused laser beam was 0.3 mm and the laser focal position defocus was adjusted to 1 mm below the surface of the steel plate. The beam quality of the laser was 8 mm*mrad. The welding parameters and calculated laser energy inputs are presented in Table 1. A K-type thermocouple was utilized at a distance of 2 mm from the weld line center to measure the temperature and cooling rate.

The morphology and geometry of the welds were examined across the weld cross-section after polishing and etching the specimens with a 1 vol. % nitric acid solution. Electron backscattering diffraction (EBSD) was conducted at an acceleration voltage of 15 kV and step sizes of 0.1–0.2 μm to characterize the fine details of the weld microstructures. MATLAB software along with the MTEX texture and the crystallographic toolbox as well as EBSD data were used to reconstruct the original austenite grains as described in [12,13].

The tensile-shear strength of the laser-welded lap joints was evaluated according to the standard ASTM E8/8M by carrying out tensile strength tests at a constant loading rate of 1 mm/min using the Instron universal testing machine. The tensile tests were conducted three times for each laser energy input to validate the tensile-shear strength results. The Vickers hardness of the joints was measured in the weld cross-section by applying a 0.2 kg load.

Finite element simulation of the welded specimens was performed in order to analyze the shear stress state of the various weld patterns, that is, the single and triple longitudinal and transverse lap joints, achieved at the energy input of 160 J/mm, which led to full penetration with the smallest HAZ area. In this regard, three-dimensional models were constructed in the ANSYS 19 commercial software package based on the experimentally determined details of the weldments (micrographs in Fig. 2). The FEM model was divided into six zones in the vicinity of each weld line. The stress–strain relation for each zone was estimated from the average Vickers hardness value measured at the corresponding distance from the weld center line, as fully described in [14]. The whole model was meshed with 8-node 3-D solid185 hexagonal elements.

3. Results and discussion

The weld bead morphology and size of the laser-welded lap joints are shown in Fig. 2. The width of the weld bead at interface and welding penetration are mainly affected by the laser energy input (LEI). At the low LEI of 60 J/mm, the welding could not fully penetrate the ARS lap joint, as shown in Fig. 2(a), with weld penetration depth of ~4 mm. However, at a higher LEI of 160 and 320 J/mm, the welding was able to fully penetrate the lap joints, as shown in Fig. 2(b) and (c). Furthermore, the width of the weld bead at interface, highlighted in the yellow oval, is significantly affected by the LEI. It can be seen that the bead widths at interfaces are ~0.6, 1 and 1.6 mm for lap joints welded at LEI 60, 160 and 320 J/mm respectively. In addition, the size of the weld bead is significantly affected by the LEI. The bead width increases from 1.2 to 4.4 mm as heat input increases from 60 to 320 J/mm. As the
LEI is increased, more plasma forms on the upper of face plate, which results in further melting of the steel plates of the lap joint. In agreement, Meng et al. [15] found that the variation in weld bead geometry and size is significantly affected by the heat input during the laser welding of a high strength steel.

3.1. Hardness measurements

The hardness measurements of the fusion zones along the transverse cross section of the lap joints with changing laser energy inputs are shown in Fig. 3. It is observed that the hardness obtained at the low energy input of 60 J/mm is significantly high with the average value of 725 HV, which is higher than that of the BM 646 HV. As the energy input is increased to 320 J/mm, the hardness markedly decreases to 580 HV due to the softening of the fresh martensite in the FZ. The above observation could be explained by the fact that with increasing energy input, the cooling rate decreases. As a result, softer tempered martensite is formed.

A striking feature of the hardness measurements is the wider hardness profile at the higher energy input of 320 J/mm, as seen in Fig. 2. Thus, lesser heat energy input causes a smaller molten pool and a narrower FZ. Moreover, the size of the HAZ in laser-welded AR 600 lap joints is affected by energy input. Hence, it can be emphasized that the weld bead size at the interface of the lap joints and welding penetration vary significantly with the EI, as shown in Fig. 2. It is reasonable to assume that the hardness level is mainly related to the weld microstructure, which is affected by the EI. However, the hardness level is not correlated with weld bead morphology and size.

Recently, Wang et al. [16] succeeded to weld butt joints from ultra-high strength quenching and partitioning (Q&P) steel with a yield strength of ~1 GPa, applying a friction stir welding technique. They found that the hardness of the weld zone, that is, the stir zone, is enhanced due to the generation of martensite, which possesses high hardness and strength in steels. Similarly, the hardness of the weld zones in the lap joints of laser-welded AR 600 steel is significantly increased due to the formation of fresh lath martensite, as shown in Fig. 4(a) and (b). Furthermore, they reported that the hardness decreases in the HAZ due to the tempering-induced softening of martensite and increasing volume fraction of ferrite. In the present study, the ferrite phase was observed throughout the HAZ of the weld. Due to the relative slow cooling in the HAZ, the microstructures of the HAZ underwent phase transformation to form ferrite, as indicated by the yellow circles in Fig. 4(c). It is observed that the ferrite formation in the HAZ mainly depends on the EI. The higher EI, in turn, results in a considerably higher ferrite content, as seen in Fig. 4(d). For instance, the ratios of ferrite phase in the HAZs with EIs of 160 and 320 J/mm are 7% and 18% ferrite, respectively. Consequently, the hardness of the HAZ in the lap joint welded at the higher EI of 320 J/mm is lower than the corresponding HAZs at lower EIs, as illustrated in Fig. 3.

3.2. Microstructure characteristics

The microstructural characteristics of the martensitic structure in the FZ are shown in Figs. 5 and 6. It can be observed from Fig. 5 that the size and morphology of the prior austenite grain (PAG) is significantly affected by the energy input during welding. The PAGs are mainly columnar with the average size...
of 34 and 52 μm at energy inputs of 60 and 160 J/mm, respectively. This is attributed to the directional solidification from the edges of the weld pool toward its center [17]. However, a mixture of columnar and equiaxed grains can be seen in the FZ structure at 320 J/mm. Columnar grains are seen toward the BM and equiaxed grains in the middle of the FZ ahead of the columnar front. The mixed columnar-equiaxed solidification, which has for years fascinated researchers, was studied and modeled in different materials by several authors, for example, [18–20]. They emphasized that the solidification rate and temperature gradients in the melt pool have a remarkable effect on the size and morphology of the grain structure. According to the weld morphology, as seen in Fig. 2, at the low energy input of 60 mm/J, the heat flux is unidirectional. Consequently, the resulting grain morphology is columnar. However, when increasing the energy input to 320 J/mm, a columnar structure first incepts while the rest of the weld pool solidifies in equiaxed grains, which then randomly nucleate ahead of the columnar grains and begin to grow. Hence, the growth of the columnar grains is blocked. Grain boundaries with a misorientation greater than 15° are known to be high-angle grain boundaries, which are expected to be the boundaries of the blocks or packets that determine effective grain size [21].

The calculated results of the effective grain size at 90% of the cumulative grain size distribution (D_{90%}) are shown in Fig. 6. Whereas the D_{90%} increases from 3.7 to 4.4 μm with the increase of the energy input from 60 to 160 J/mm, the D_{90%} decreases to 3.9 μm at the higher energy input of 320 J/mm. This can presumably be attributed to the promotion of tempered martensite at high energy input. A higher heat energy input requires more holding time at the tempering temperature, that is, it has a slower cooling rate during the welding thermal cycle [22]. Consequently, tempered martensite with precipitated carbides and partial recovery of martensite is formed at the higher energy input. This agrees with the hardness measurements in Section 3.2. The lower the energy input, the higher the hardness achieved. Recently, Barrick and DuPont [23] measured the effective grain size of the martensitic structure in the FZ of 10 wt.% Ni steel welded by two different techniques, gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). They reported that the effective grain sizes achieved during GTAW and GMAW techniques at heat inputs of 1770 and 1580 J/mm are 9.9 ± 1.0 μm and 6.4 ± 0.4 μm, respectively. In the same context, Feng et al. [24] studied the morphology and the crystallographic characteristics of the fine components of the martensitic structure, such as the lath, block and packet, in the weld metal of high strength steel.

As can be inferred from the microstructure analysis of the weld structures by EBSD, as seen in Figs. 5 and 6, the grain sizes of the prior austenite and the fresh martensite gradually increase with the laser EI. The microstructure of the weld metal at the higher EI of 320 J/mm is characterized by
tempered martensite with coarse prior austenite grains. This is in agreement with the hardness measurements in Fig. 3, which displayed the highest hardness at the low EI of 60 J/mm as compared to the other welds at higher energy inputs.

3.3. Shear-tensile strength of the lap joints

During uniaxial tensile testing of the laser-welded lap joints, the loading direction on the lap joint varies with the weld pattern. The applied load is along the longitudinal axis of the weld and perpendicular to the weld axis of the longitudinal and transverse lap joints, respectively.

The results of the shear-tensile strength tests of lap joints are shown as shear strength–number of welds plots in Fig. 7. It is well known that the strength property of the welded joints is related to the weld bead geometry, mainly bead width at the interface [15]. Hence, it is expected that with increasing the LEI from 60 to 320 J/mm, the strength increases. For instance, the shear strengths are 200, 370 and 525 MPa for the single transverse welds in the lap joints welded at LEIs of 60, 160 and 320 J/mm, respectively. Moreover, the weld pattern, represented by the number of welds and welding orientation, displays a significant effect on the mechanical behavior. Clearly, as seen from the shear-tensile strength results in Fig. 7, with the increasing number of welds from single to multiple, the shear strength of the lap joint significantly increases at the same energy input. The shear strength–number of welds plots display the striking feature of the transverse weld.
patterns exhibiting higher shear strengths than those of the longitudinal weld patterns at LEIs 60 and 160 J/mm. For example, at LEI 160 J/mm, the shear strengths of the longitudinal lap joints are 275 and 1110 MPa for single and five longitudinal welds, respectively. The corresponding shear strengths of the transverse lap joints for single and five the transverse welds are 370 and 1170 MPa. This is attributed to the higher deformation capacity of the transverse weld pattern [25].

Anijdan et al. [26] achieved a shear-tensile strength of 334 MPa for a dissimilar joint of dual phase steel DP600 and AISI 304 stainless steel when applying spot welding. However, their welding technique is neither economically nor in regards to the time consumed relative to the present work. They optimized the welding parameters as follows: current density of 8 kA/m, 16 cycle (1 cycle = 50 s) welding time and 40 cycle holding time after welding (1 cycle = 50 s). Recently, Gu et al. [27] reported a maximum tensile-shear force of 24.46 kN for laser-welded lap-filet joints in SUS301L austenitic stainless steel plates with an EI of ~70 J/mm. However, its counterpart welded at 60 J/mm in the present work showed a higher tensile-shear strength of 30.6 kN.

3.4. Finite element simulation of the joints

The shear stress distribution on the mid-plane (interface) of different lap joints achieved with various configurations, that is, with single and triple longitudinal and transverse welds, are presented in Fig. 8. All the contours are plotted at certain instances of time with the same maximum von-mises strain reached in the specimens.

A striking observation is that the shear stress on the interfacial plane is highly concentrated at the corners of the longitudinal welds, as seen in Fig. 8(a) and (b). However, in the specimens with transverse welds, the shear stresses are evenly distributed over the whole length of the weld lines, as seen in Fig. 8(c) and (d). As a result, while the maximum shear stresses of over 1100 MPa were reached in longitudinal welds, smaller values of ~900 and 1050 MPa were observed for triple and single transverse welds, respectively. Moreover, in the case of the lap joints with triple transverse welds, the middle weld experiences a shear stress of ~420 MPa, that is, less than half of the stress of the two leading welds. It is also worth mentioning that the maximum elongations (x-displacement) in transversely welded specimens were nearly double those of the longitudinally welded lap joints.

4. Conclusions

Lap joints of 3 mm thick plates of abrasion resistance ultra-high strength steel AR 600 were laser-welded at different energy inputs of 160 and 320 J/mm and different configurations of weld patterns, that is, with multiple continuous longitudinal and transverse weldments, to optimize the tensile-shear strength. The following conclusions are drawn based on the experimental results from this research work:

1. The fine microstructure characteristics of the weld structure, such as prior austenite grains and the fresh martensite, were found to be affected by the energy input (EI). The effective grain size of the fresh martensite, $D_{90\%}$,
increased from 3.7 to 4.4 μm with increasing the EI from 60 to 160 J/mm. With the higher energy input of 320 J/mm, the D_EAI decreased to 3.9 μm.

2. The combination of laser EI parameter and weld pattern configuration (weld orientation and number of welds) was found to have a significant effect on the tensile-shear strength of the lap joint. For instance, the tensile-shear strengths of the lap joints with single transverse welds markedly increased from 200 to 525 MPa with increasing the EI from 60 to 320 J/mm. The corresponding strengths of lap joints with five transverse welds are 425 and 1205 MPa at EI of 60 and 320 MPa, respectively.

3. The FEM simulation of lap joints with the energy input of 160 J/mm showed a more homogenous distribution of shear stress along the transverse weld lines compared to the longitudinal welds. The localized maximum shear stress in the longitudinal weld was ~200 MPa higher than that reached in the transverse counterpart. This could considerably reduce the deformation capacity (elongation) of the former specimen.

Declaration of Competing Interest

The corresponding author confirms on behalf of all authors that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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