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Tensile and fatigue properties of laser-welded ultra-high-strength stainless spring steel lap joints

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Abstract

The study was performed to investigate the usability of thin 0.3 mm thick ultra-high-strength stainless spring steel in laser-welded simple panel structures. The mechanical properties of the laser welded joints in lap-shear specimens were investigated. The fatigue and shear strength of laser joints were experimentally investigated using continuous and intermittent lap joints that were welded using various energy inputs. The properties of separate laser welds were characterized by hardness testing and optical microscopy. Results of the hardness measurements showed that there was softened area at heat-affected-zone of the welds. Due to the weld mismatch, significant strain hardening took place at the weld seams. The shear strength of tested continuous lap joints was slightly lower compared to the yield strength of the base material. Fatigue strength of the studied lap joints was at acceptable level for dynamically loaded simple panel structures and the fatigue strength of the weld seams was in practice dependent on the weld area instead of weld type.

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Keywords: Laser-welding; lap joint; fatigue strength; ultra-high-strength steel; austenitic stainless steel

1. Introduction

There are great advantages in utilizing ultra-high-strength steels (UHSS) when designing lightweight structures. UHSS allows for example to use thinner sheets if the structures are designed with new approaches such as extended DFMA (design for manufacture and assembly) [1]. Structures can be even manufactured with sheet thicknesses that could not be utilized in load-carrying steel structures before. Even though the joining of thin (<0.5 mm) sheets is challenging due to distortions, laser welding can be successfully utilized to produce high quality joints [2,3].

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The weight of the metallic structures can be reduced using a specially designed simple panel structure [4]. Laser welding is basically only the welding method that can be used to manufacture these panels due to low distortion and very high welding speeds. Especially low distortions are a mandatory requirement for manufacturing of dimensionally accurate structures. Choosing the correct welding parameters and using shielding gas is very important in laser-welding of thin austenitic stainless steel [5-9]. Temper-rolled austenitic stainless steels have tendency to soften at heat-affected-zone (HAZ) and it must be considered when designing welded joints [10-13].

Lap joint is a very cost-effective joining method for simple panel structures. Positioning accuracy of the lap joint does not have such high requirements as e.g. butt joint. From the designer's point of view, the lap joint provides a lot of flexibility in the design of joints, because the lap joint is very easy to manufacture.

In this paper we have investigated the shear and fatigue strength of lap joints of thin ultra-high-strength stainless steel. The effect of welding energy input and weld type (continuous / intermittent) was determined to maximize the weld area to determine the optimal weld conditions for lap joints.

Nomenclature

DFMA	design for manufacture and assembly
HAZ	heat-affected-zone
HCF	high-cycle fatigue
HV	Vickers hardness
LCF	low-cycle fatigue
R	stress ratio
UHSS	ultra-high-strength steel
UTS	ultimate tensile strength
YS	yield strength

2. Experimental methods

2.1. Test material

Test material was temper-rolled 0.3 mm thick austenitic EN 1.4310 2H stainless steel (coded as UHSS). The EN 1.4310 2H stainless steel is typically used as spring steel or items subject to high mechanical loading. UHSS steel has very high mechanical strength through cold working and typical ultimate tensile strength (UTS) is 1500–1700 MPa (Table 1). The chemical composition (shown in Table 2) is typical for EN 1.4310. The grade has relatively high carbon content (sensitization risk), but it was selected because of its availability and strength.

Table 1. Guaranteed properties of the test material.

YS [MPa]	UTS [MPa]	A80%	Hardness [HV]
1270 - 1650	1500 - 1700	5	410 - 520

YS, yield strength; UTS, ultimate tensile strength

Table 2. Chemical composition (%) of EN 1.4310 stainless steel.

C	Si	Mn	P	S	Cr	Ni	Mo	N
0.096	1.05	1.07	0.032	0.001	16.94	6.42	0.71	0.062

2.2. Sample preparation

Specimens used in mechanical testing of the lap joints are shown in Fig. 1. Two 150 mm long and 50 mm wide steel sheets were overlapped in 50 mm distance. A lap joint was made in the middle of the overlap using either continuous (Fig. 1a) or intermittent (Fig. 1b) laser welding. In addition, 0.5 mm thick square 50 x 50 mm sheets were welded on both sides of both ends of the specimens for clamping (1 mm minimum thickness required for the testing machine). Specimen's edges were machined after welding. Machining was done to remove any notches or irregularities along the specimen's edges which may produce errors to fatigue tests.

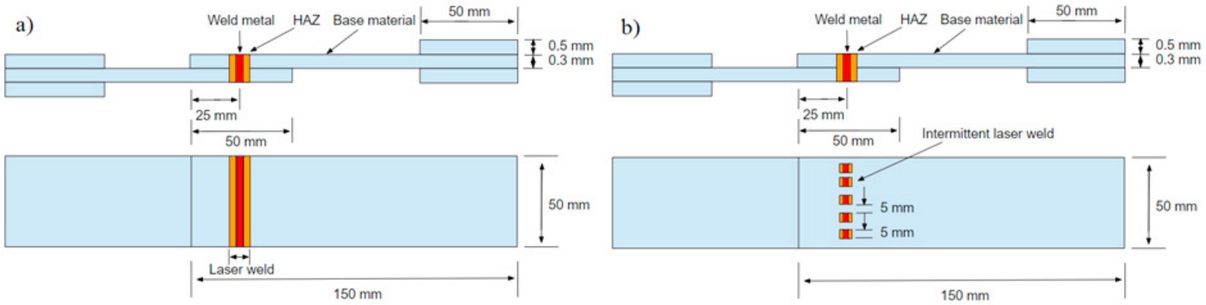

Fig. 1. Specimen geometry for (a) continuous and (b) intermittent lap joints.

The specimens were laser welded using a 4 kW diode pumped Yb:YAG disc-laser with 300 mm optics. The laser beam spot size was 0.3 mm and the focal point was adjusted 1 mm below the surface of the top sheet. The beam quality was 8 mm×mrad. The argon shielding gas was used on the backside of the laser-weld and flow rate was 30 l/min. The welding parameters for the weldments were chosen based on earlier experience of welding of UHSS steel [1,4]. Two sets of welding parameters were used for the continuous lap joints (W1, energy input of 6.67 J/mm and W2, energy input of 8 J/mm) as seen in Table 3. W1 welding parameters were used for the intermittent weld lap joints (I1). The intermittent weld was created using 5 mm long welds with 5 mm spacing as shown in Fig. 1b. Total length of intermittent welds was approximately 25 mm in contrast to 50 mm long continuous weld.

Table 3. Laser welding parameters.

Code	Weld type	Welding speed [m/min]	Power [kW]	Focus [mm]	Energy input [J/mm]	Total weld area [mm²]
W1	continuous	18	2	-1	6.67	23.5
W2	continuous	6	0.8	-1	8	23
I1	intermittent	18	2	-1	6.67	11.75

2.3. Mechanical testing

Two different loading machines were used to determine the stress-lifetime curves for the laser welded lap joints with stress ratio (R) of 0.05 using various load amplitudes. A servo-hydraulic loading machine was employed to determine the fatigue strength in the low-cycle fatigue (LCF < 10 000 cycles) regime. In this case, the loading frequency was 2 Hz. An electro-magnetically dynamic testing machine was employed to determine the high-cycle fatigue properties (HCF > 100 000 cycles) with loading frequency of 45 Hz.

Monotonic strength properties for the base materials were determined using the same servo-hydraulic loading machine. Tensile tests were carried out according to the standard ASTM E8/8M and lap joint specimens were used for shear strength measurements. The hardness of the joints was measured from the weld cross-section using Vickers indenter with 0.2 kg load. The distance between the measurement points was 0.2 mm.

3. Results and discussion

3.1. Initial properties of the test material

The base metal mechanical properties were determined before welding. The measured tensile properties (Table 4) of the UHSS were in range of the guaranteed values. The result showed the very high yield (YS) and ultimate tensile (UTS) strength of 1526 and 1644 MPa, respectively. The total elongation was low (5%). The martensite fraction of 23.3% was measured using a Feritscope instrument. The rest of the microstructure was work-hardened austenite. The heat input was not calculated in this study.

Table 4. Measured tensile properties of the test material.

Code	YS [MPa]	S.D. [MPa]	UTS [MPa]	S.D. [MPa]	A80 [%]	S.D. [%]	Hardness [HV0.2]	S.D. [HV0.2]
UHSS	1526	16	1644	23	5.0	0.2	511	14

YS, yield strength; UTS, ultimate tensile strength; A80, elongation A80%; S.D., standard deviation

3.2. The shape and hardness of the lap joint laser welds

Fig. 2 shows the hardness profiles of the joints. The hardness of the weld metal was approximately 50% lower than the temper-rolled base material reaching the hardness of annealed 301 steel (200-250 HV). This is in agreement with another study [14] on 301LN steel showing that the hardness of the weld metal is approximately 250 HV and the hardness is not depended on the initial strength (deformation state and/or grain size).

The metallography (Fig. 3) showed that the HAZ between the base material and weld metal consisted of new refined austenite grains. In the temper-rolled 301 steel, the deformation-induced martensite (fraction of 23%) transforms to new ultrafine grained austenite below the recrystallization temperature (~600-900 °C) by reversion and the new austenite grains then grow via diffusion as explained in Ref. 14. The deformed austenite (fraction of 77%) recrystallizes and grows in the temperature regime of approximately 900-1400 °C [13]. The coarse-grained region showed similar hardness with the weld metal and a steep increase in hardness to the base material level can be seen in Fig. 2. The total width of the softened area was approximately 15% wider in the W2 that was welded using higher energy input. Increased energy increases the energy for grain growth reversed and recrystallized grains, but the grain sizes and their distributions in HAZ were not determined in this study.

The shapes of the laser welds were very different as shown in Fig. 3. W1 (Fig. 3a) was an ″I‶ shape weld and the W2 (Fig. 3b) was a ″W‶ shaped weld. There was a small underfill at face and root side of the W2. The quality level of the welds was not defined because the standard ISO 13919-1 does not apply to materials under 0.5 mm thickness. The width of the lap joint weld was 0.47 and 0.46 mm for the W1 and W2, respectively.

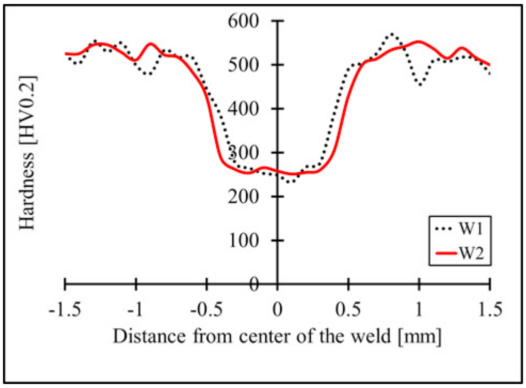

Fig 2. Hardness profiles of W1 and W2.

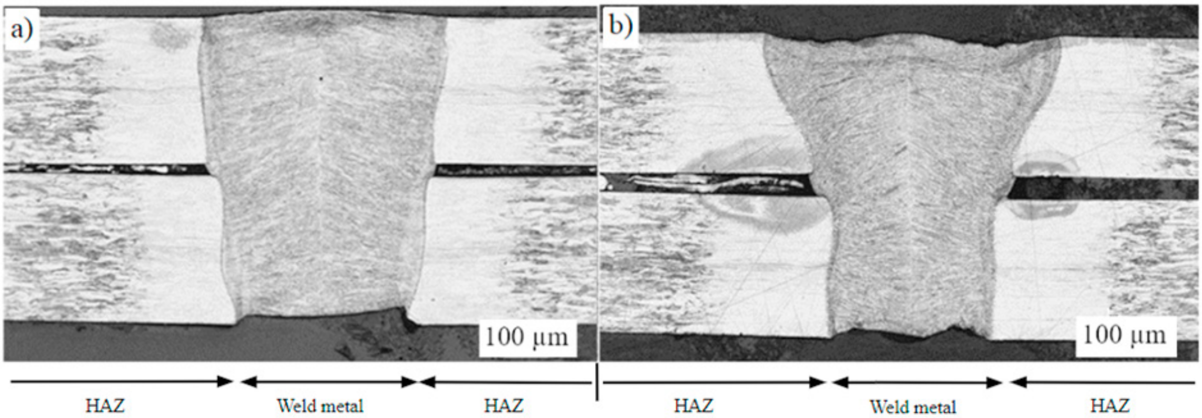

Fig. 3. (a) Cross-section of W1; (b) cross-section of W2.

3.3. Shear strength of the lap joints

The shear stresses of the specimens were determined using tensile testing. The average shear stress (Fig. 4a) was calculated from the load data (Fig. 4b) using the area of the whole cross-section of the specimen. The shear stress at yielding point was 7% higher for the W1 than for the W2. The shear stress and shear load of the intermittent joint I1 was approximately half of the values measured for continuous welds due to the smaller weld area.

Shear stresses of the W1 and W2 were slightly lower compared to the yield strength of the base material. Width of the lap joint laser weld is typically smaller than the thickness of welded sheet. However, when welding of very thin sheets, the width of the lap joint laser weld can be bigger than thickness of the sheet. In comparison to area of the cross-section of the welded sheet, the area of the lap joint welds was approximately 57% bigger. It can be assumed that the softened area at the HAZ has reduced shear strength of the UHSS steel lap joints. I1 was 51.5% weaker than W1, which was also the difference of the areas of the I1 and W1 welds.

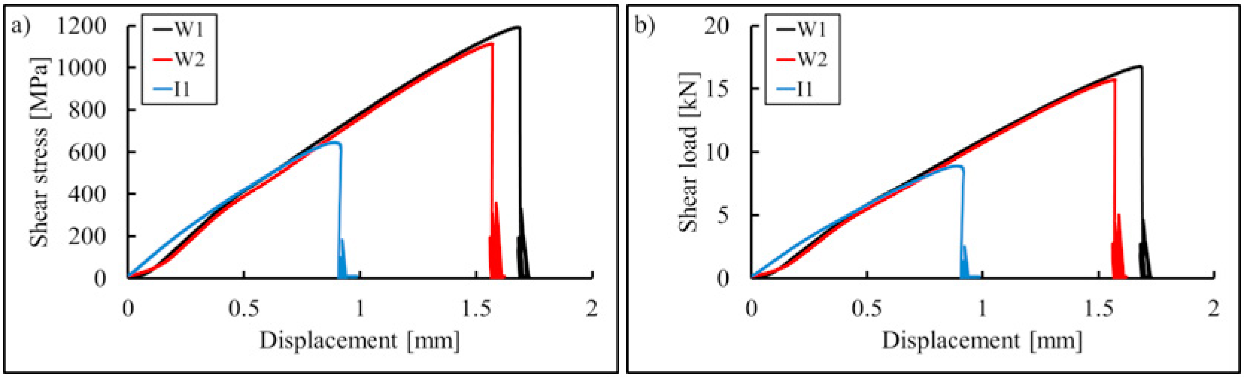

Fig 4. (a) Shear stress of W1, W2 and I1; (b) shear load of W1, W2 and I1.

3.4. Fatigue strength of the lap joints

The effect of the energy input on fatigue strength can be seen in Fig. 5. The comparison was made similarly than in previous Section to distinct the difference between the load resistance of the joint (Fig. 5a) and relative stresses in the material (Fig. 5b). Results showed that the fatigue strength was very similar between the lap joints W1 and W2, although the W1 was slightly weaker than the W2 at stress amplitudes of approximately 50–60 MPa. Based on the hardness measurements (Fig. 6), there was significantly higher strain hardening occurring in the W2 (+40%) weld seam than in W1 (+20%) or I1 (32%) at stress amplitude of 95 MPa. This could be related to the strength mismatch between the base material and weld metal, more stress is localized on wider W2 causing higher strain hardening without impairing the fatigue resistance.

The fatigue limit (10e6 cycle cut-off value) of W1 and W2 was approximately 40 MPa. Intermittent lap joint I1 had significantly lower fatigue strength (Fig. 5a) due to the smaller weld area. Interestingly, the I1 weld showed also clearly lower stress amplitudes (relative load in the weld metal) indicating that the intermittent weld is more vulnerably for fatigue than the continuous counterpart. It can be assumed that the stress distribution is more uniform in the continuous weld and that the stress peaks in intermittent weld impairs the fatigue resistance of the joint. Intermittent weld contains several start and end points of welding where occur sharp transitions from base metal to weld. These transition points are possible crack initiation spots.

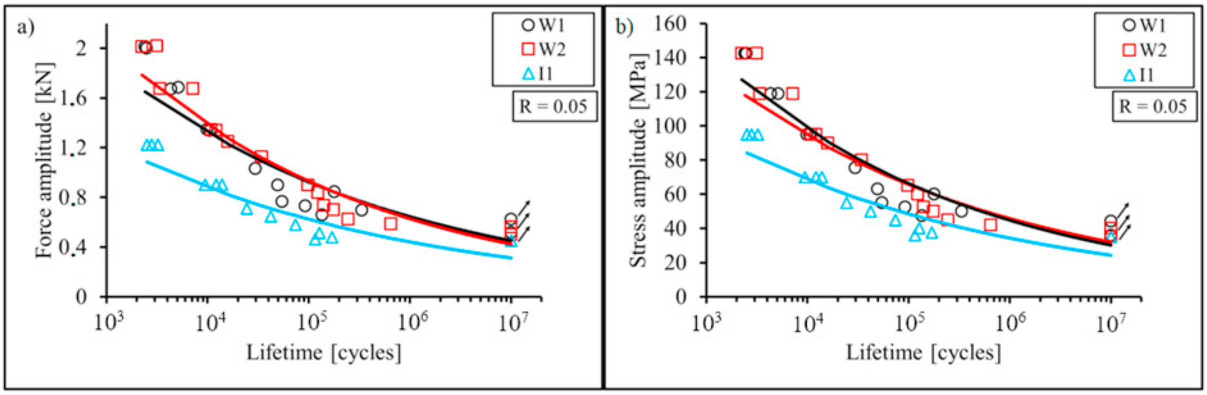

Fig. 5. Fatigue strength of W1, W2 and I1. (a) Force amplitude and (b) stress amplitude vs. number of cycles to failure.

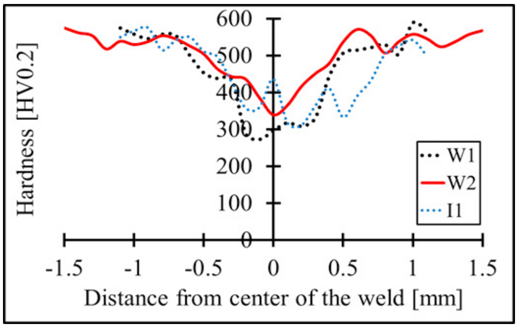

Fig. 6. Hardness profiles of W1, W2 and I1 after fatigue test.

4. Conclusions and outlook

The properties of the lap joints of severely temper-rolled austenitic AISI 301 stainless steel were studied using two welding parameters W1 (low energy) and W2 (high energy). The following conclusions can be made:

- The weld metal was soft (about 250 HV) in comparison to the temper-rolled base material (about 500 HV)
- A decrease in welding energy input reduced the width of the softened area and its strain hardening under dynamic loading
- The results showed that shear stress of lower energy input weld W1 was 7% higher than that of higher energy input weld W2.
- Shear stresses of the continuous welds were slightly lower compared to the yield strength of the base material. In comparison to tension yield strength of the base material, the shear stress of W1 was 22% lower.

- The lap joints W1 and W2 had very similar fatigue strength. The lower energy input weld W1 was slightly weaker than the W2.
- The area of the investigated lap joints was high in comparison to area of the cross-section of the welded sheet. The area of the investigated lap joints was approximately 57% larger compared to area of cross-section of the welded sheet.
- Intermittent lap joint laser weld is usable in welding thin sheets. Its static properties are proportional to the length/area of the weld. Intermittent lap joint can be used when limited welding energy input is necessary to prevent distortions in structures, but it may expose the weld for fatigue failures due to stress localization.

The study showed that 0.3 mm thick ultra-high strength stainless steel is usable in laser-welded simple panel structures. However more information of the lap joints is needed. The microstructure of laser welds must be investigated more closely. Also, it would be interesting to investigate the use of nitrogen as a shielding gas.

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