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The normal and shear strength properties of laser lap weld

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Abstract

The study was aimed to clarify the shear strength and the normal strength properties of the lap joint. The welds were characterized with respect to hardness, tensile and fatigue properties. The test materials of this study were low strength carbon steel (LSS) and ultra high strength wear resistant steel (UHSS). The shear strength, perpendicular strength and fatigue resistance of the lap joint laser weld was determined by tensile and fatigue tests. The shear strength of the LSS weld was higher than the strength of the base material. The shear strength of UHSS weld was higher than the LSS weld. However, compared to strength of the base material of the UHSS the weld was weaker even though the weld was harder than the base material. The normal strength of the UHSS and LSS welds was over two times higher than the shear strength of the same welds.

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Keywords: Laser weld; Shear strength; Normal strength

1. Introduction

The high strength steels are being used to improve the performance and reduce the weight of structures [1]. Laser welding is commonly used, and the characteristics of lap joint have been investigated in the literature. However, the normal direction strength properties of the laser weld have not been investigated. The laser weld lap joint is commonly used in the sandwich panels and the other lightweight structures. Laser welding has many advantages compared to the conventional welding methods. Advantages of laser welding are relatively low distortion of the weld, low heat input per unit volume, narrow heat affected zone, high welding speed and high penetration of the weld [2][3][4].

The welding of the thin steel structures can be challenging due to the distortions of the high heat input. Therefore, the laser welding is the recommended due to low heat input. The direction of the stress of the lap joint weld is variable from shear stress to normal stress [5].

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The tensile test specimen of the UHSS butt weld fractures usually in the softened area of the heat affected zone (HAZ) where the martensite is tempered [6][3]. The tensile test specimen of LSS butt weld fracture initiated always in the base material due to harder weld area. In the laser welded lap weld the highest stress concentration is in the fusion zone of the weld which is usually stronger than the base material due the higher hardness and changed microstructure. There are also residual stresses in the lap weld which affects to the local stress states of the weld area [7]

According to Kocak et. al. the ultimate strength of the C-Mn-steel base material was 550 MPa, in the weld HAZ was 750-850 MPa and in the weld metal was 1150 MPa-1250 MPa [8]. According to Ha et. al. the shear strength of SPRC 340 lap weld was approximately same as the normal strength, but the welding energy was significantly higher than in this study and the weld joint was one sided weld so that the stress of the weld was not pure shear stress [5].

Laser welded structures are often subjected to cyclic loading conditions. The geometry of the lap joint is problematic because natural crack or notch tips are present at the edges of the weld bead. Fatigue cracks are usually initiated from the natural crack or notch tips of lap joints. The mechanical properties mismatch between the weld and base material can significantly reduce the fatigue life. The problem occurs especially when using high strength steels (UHSS) [9][10].

2. Experimental methods

2.1. Test Materials

The first test material was formable low carbon structural steel (LSS) and the second test material was ultra high strength abrasion resistant steel (UHSS). Steel sheets with a thickness of 2.0 mm were used in this investigation. The mechanical properties of the steels are given in table 1. The compositions of the test steels are given in table 2.

Table 1. The measured mechanical properties of the test materials.

	Thickness (mm)	Yield strength (MPa)	Ultimate strength (MPa)	A50 (%)	Hardness (HV ^{0,2kg})
LSS	2.00	161	296	41	120
UHSS	2.00	1212	1347	6	430

Table 2. The weight % composition of the test materials.

	C	Si	Mn	P	S	Cr	Ni	Mo	B	CEV
LSS	0.12		0.60	0.045	0.045					0.22
UHSS	0.23	0.80	1.70	0.025	0.015	1.50	1.00	0.50	0.01	0.46

2.2. Welding parameters

The laser welds were made by using 4 kW diode pumped disk laser. The properties of the laser equipment and welding parameters are given in Table 3. The welds were welded without shielding gas. The laser welding parameter was selected with very low energy input on purpose to minimize area of the heat affected zone. In addition, the weld depth was limited to 3 mm in order to produce the symmetric tension bar (Fig. 1).

Table 3. Laser welding parameters

Power (kW)	Speed (m/min)	Focal point level (mm)	Focal length (mm)	Focal point diameter (mm)	Beam quality (mm×mrad)	Energy input (J/mm)
3.0	4.5	-1.0	300	0.3	8	40

2.3. Test parameters

The hardness profiles of the welds were tested by using 0.2 kg Vickers test method. The hardness of the welds was measured by using 0.1 mm interval over the weld zone from 0.5 mm the surface of the joint.

The width of the lap joint welds was measured from the grinded, polished and etched perpendicular cross sections of the welds by using microscope measurement. The width of the weld was measured according to mean value of the 15 measurement. The test stresses of the welds were calculated by using the width of the weld and measured length of the weld. For the LSS and the UHSS the width of the welds were 0.44 mm and 0.48 mm respectively.

The tensile test specimen of the shear direction of the weld was made by welding two lap welds both side of the plate according to Fig. 1. The penetration depth of each weld is approximately 3 mm.

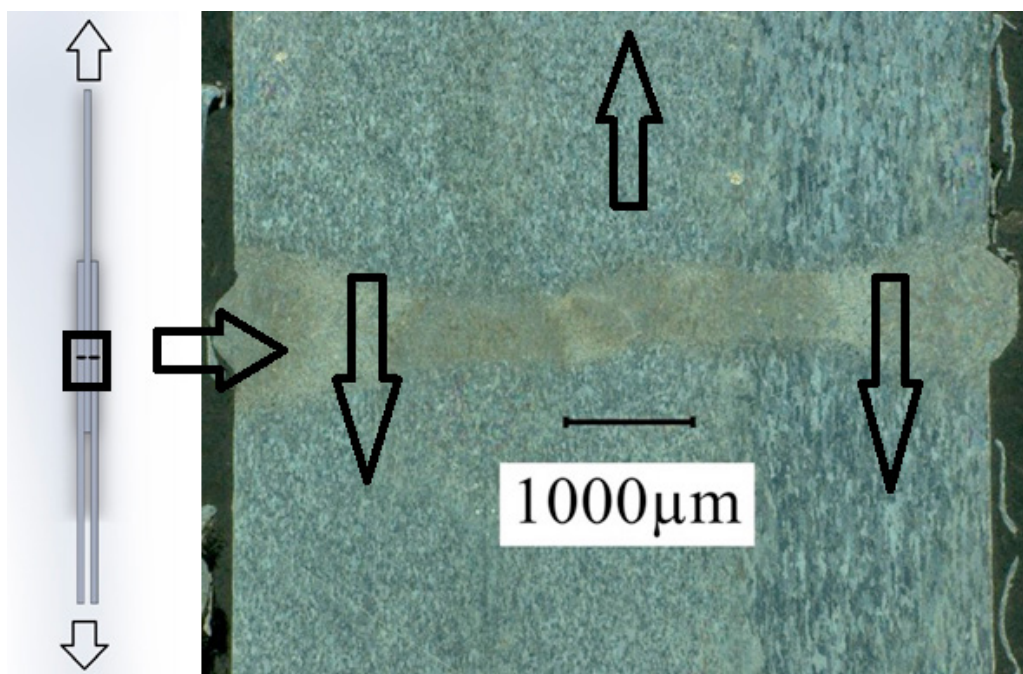


Fig. 1. The shear tension test bar

The normal tensile test specimen was made in following order: First the 2,0 mm thick test sheet was welded to the test frame. Then the second test sheet was welded to another test frame (Fig. 2a). The test sheets were joined by welding the test weld through a hole of the test base as shown in Fig. 2b. Finally, the clamping plates were welded on the test frame using Manual Metal Arc Welding (MMAW) (Fig. 2c). The perpendicular tensile test bar was drawn by using test procedure (Fig. 2d).

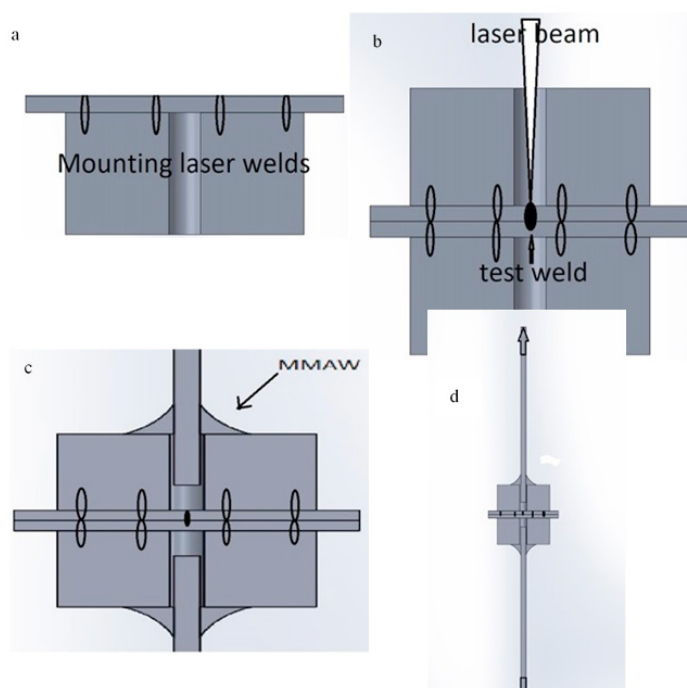


Fig. 2. The test procedure of the normal tensile test a) Mounted test plate b) Test weld c) MMAW welds between test frame and clamping plates d) Complete test bar

The tensile tests were made by using Instron 8802 servo-hydraulic test equipment with Blue hill test program. The 1 mm/min test speed was used in all tests.

The fatigue tests were made by using Force-controlled fatigue tests (LCF Standard ASTM E606-04) were carried out with an Instron 8802 servo-hydraulic test equipment with Wave matrix test program. The test loading frequency was 5 Hz at higher load amplitudes and 10 Hz at lower load amplitudes. The stress ratio (R) was 0 in all tests.

3. Results

3.1. Hardness profiles

The hardness profiles were measured over the weld area using 0.1 mm interval. The hardness profiles of the LHS and UHSS are seen in the Fig. 3.

The 0.48 mm wide area of the UHSS weld on the middle of the hardness profile is the fusion zone. The hardest area of the weld, where the highest hardness is 488 HV, is in the HAZ nearby the fusion zone. There the temperature has risen over the austenite boundary (870 °C) and decreased immediately under 500 °C causing the hard martensitic microstructure formation. The 0.4 mm wide softest area of the weld is between above mentioned area and base material where the martensitic base material has tempered causing decreasing of the hardness down to 320 HV.

The 0.44 mm wide fusion zone of the LHS weld is the hardest area of the weld due to quenching of the material. Nearby the fusion zone the grain refinement of the HAZ causes the hardness increasing of the coarse-grained base material. The hardness decreases uniformly from the fusion zone to the base material.

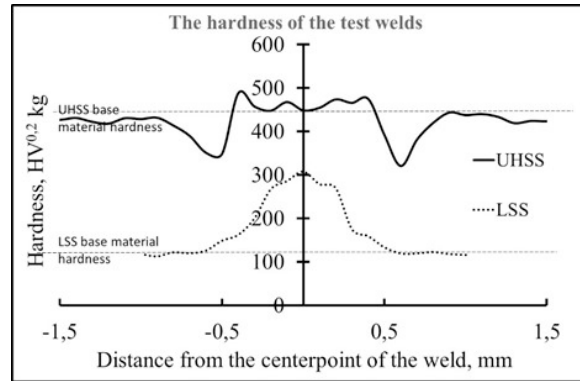


Fig. 3. Hardness profiles of the LSS and UHSS welds

3.2. Shear strength

The Shear strength of the LSS and UHSS lap weld is shown in Fig. 4a and b. In the Fig. 4a the yield strength of the weld is not in the 400 MPa instead it depends on base material forming.

The Shear strength results of the LSS and UHSS lap weld is shown in Fig. 4a and b. The LSS yield strength is 161 MPa and the test specimen yielded before the weld fractured. The stress of the weld is 400 MPa when the test specimen yields Fig. 4a. The UHSS weld shear stress was 830 MPa and the tension stress was 390 MPa.

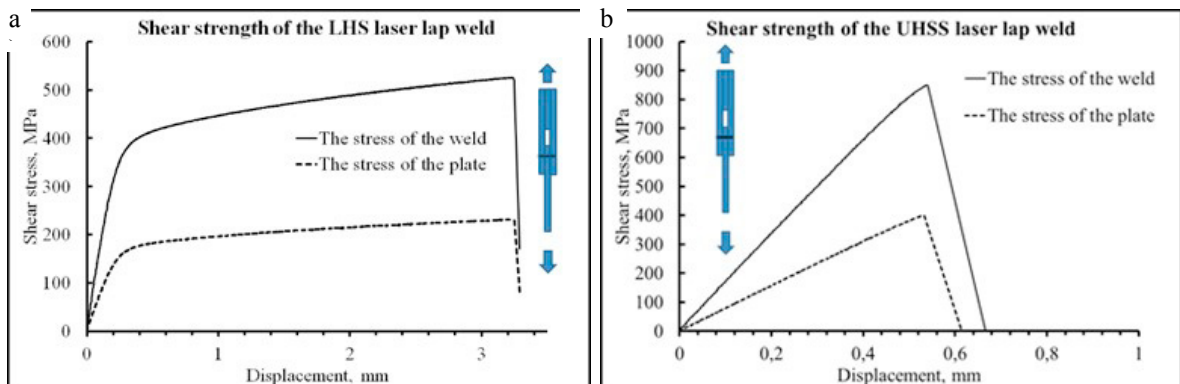


Fig. 4. a) Shear strength of the LSS weld b) Shear strength of the UHSS weld

3.3. Normal strength

The average normal strength of the LSS and UHSS lap weld is shown in Fig. 5. The LSS test specimen yielded at 700 MPa before the weld was fractured. Finally, the LSS weld fractured at 1260 MPa. The UHSS weld normal strength was 1893 MPa.

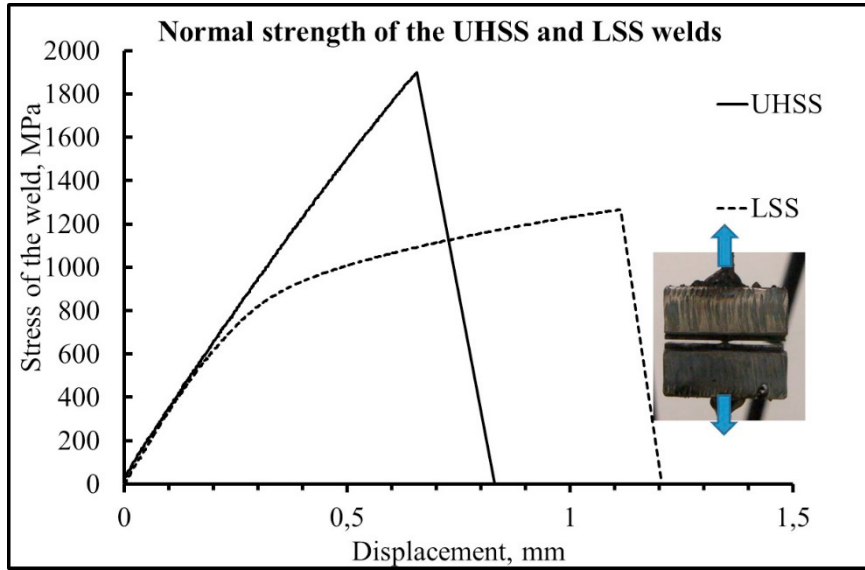


Fig. 5. Normal strength of the LSS and UHSS welds

3.4. Fatigue strength

The shear fatigue strength and normal fatigue strength of the LSS and UHSS weld is shown in Fig. 6. The LSS weld normal fatigue strength was better than the UHSS weld when the stress amplitude was higher than 200 MPa. The shear fatigue strength of the UHSS weld was significantly better than the LSS. However, with small stress amplitudes the difference between the test materials reduced.

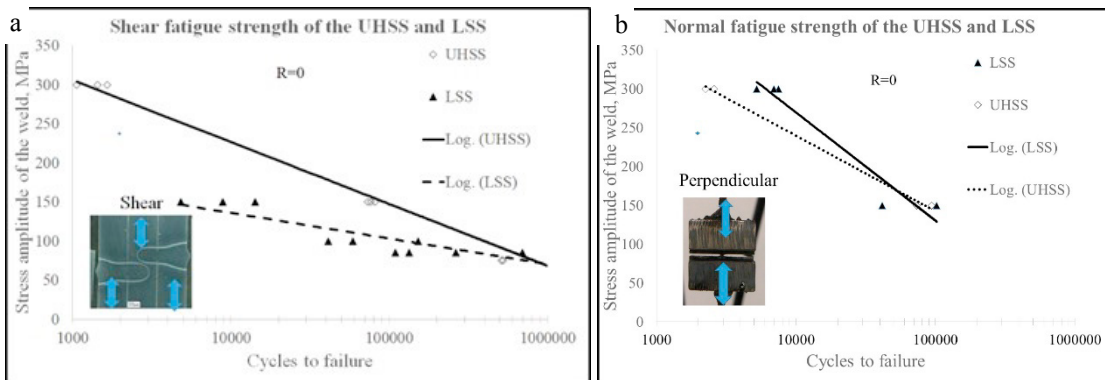


Fig. 6. a) Shear Fatigue strength of the LSS and UHSS b) normal fatigue strength of LSS and UHSS

3.5. Cross-sections of the welds

The grinded, polished and etched cross sections of broken normal tension test samples are shown in Figs. 7 and 8.

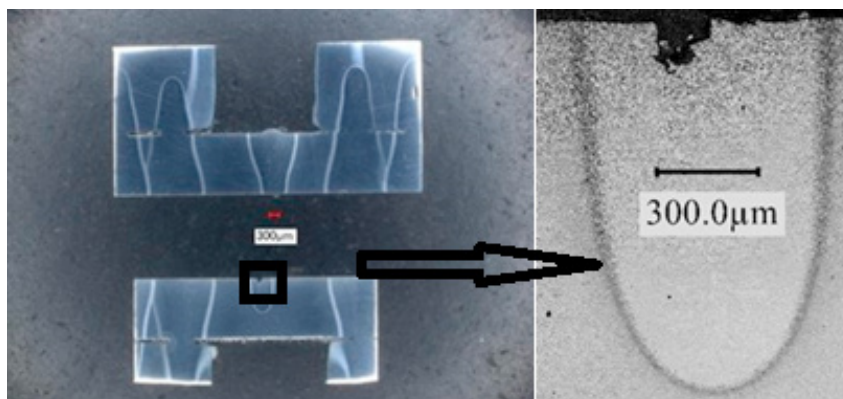


Fig. 7. The cross section of the UHSS test sample in normal direction

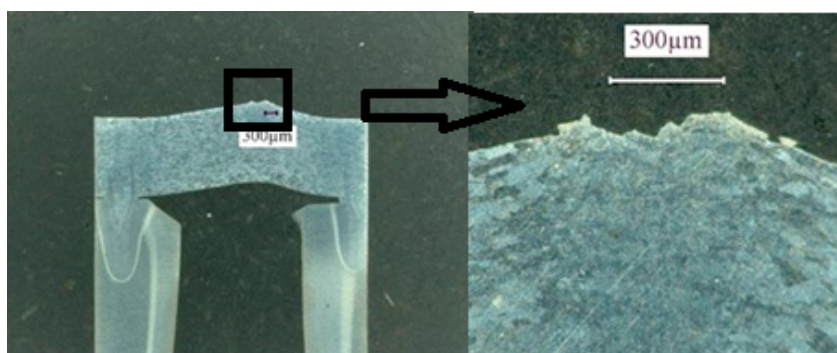


Fig. 8. The cross section of the LSS test sample in normal direction

4. Discussion

The hardness profiles of the LSS and UHSS welds were different due to different state and composition of the steels. The UHSS is quenched and has a high carbon (CEV 0.46) martensitic microstructure. The LSS is annealed and has a low carbon (CEV 0.22) coarse grained structure as seen in Fig. 8. The LSS weld was harder than the base material due to quenching of the material in the rapid temperature drop of the low energy welding and also more fine-grained weld metal structure (Fig. 7). The hardness profile of the UHSS had 0.3 mm wide soft areas from 0.5 mm distance of the center of the weld due to tempering of the martensitic structure of the base material. The softer areas of the weld are shown in Fig. 7 as a darker area in the HAZ. The hardest area of the HAZ near the fusion zone of the UHSS weld was re-quenched lath martensite which seems like the base material (Fig. 7.) [11]. The microstructure of fusion zone is slightly softer solidified and quenched martensite.

According to Fig. 4a the shear strength of the LSS weld was 550 MPa. The shear strength of the LSS weld was significantly increased compared to strength of the base material. Testing of the LSS laser weld was difficult because the base material yielded before the weld fractured/sheared (Fig 4 a). The shear strength of the UHSS weld was 850 MPa which is higher than the LSS weld but lower compared to strength of the base material. According to Ha et. al. the shear strength of SPRC 340 lap weld was approximately same as the normal strength even though the welding energy was significantly higher than in this study [5].

According to Fig. 5. the normal strength of the LSS and UHSS welds was over two times higher than the shear strength. In the normal strength curve the yield strength of the LSS seems to be 700 MPa but it comes from the

influence of the bending of the low strength base material between the test welds and the fixing welds as shown in Fig. 8. According to Fig. 7 and 8, there were not lamellar tearing in the welded plates due to quite deep penetration of the plug type weld and low Sulphur and phosphorus content of the base material. In the case of this study the bottom material of the lap weld was very fine-grained sheet metal. It should be taken into account that the result can be different when using thicker and coarser grained UHSS steels as bottom plate.

The normal fatigue strength of the UHSS was two times better at 300 MPa of the weld stress amplitude than the shear fatigue strength. The normal fatigue strength of the LSS was almost as high at 300 MPa of the weld stress amplitude than the shear stress at 150 MPa weld stress amplitude. The normal fatigue strength of the LSS was better than the UHSS fatigue strength.

According to Fig. 8 the grain size of the LSS laser weld is significantly finer than the base material. The grain size of the UHSS laser weld is coarser than the base material. The finer grain structure of the LSS weld area hardens the weld joint which is seen in the hardness results (Fig. 3) and also in the static and dynamic strength results.

The test speed was relatively slow in the tensile tests. Therefore, impact strength of the welds should be tested especially in the UHSS welds.

5. Conclusions

The shear and normal strength of the LSS laser weld was higher than the base material. The shear strength of the UHSS weld was slightly lower than the base material. The normal strength of the weld was over twice as high as the shear strength. The fatigue strength of both test materials was higher in normal direction than in shear direction at low cycle and high stress amplitude area. The normal fatigue strength of the LSS was significantly better than the UHSS fatigue strength at 300 MPa stress amplitude.

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