2022 International Conference on Power, Energy and Innovations (ICPEI 2022)
October 19-21, 2022, Pattaya, THAILAND

Investigation of microstructure and mechanical properties of laser welded complex phase steel lap joints

Mikko Hietala
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
mikko.hietala@oulu.fi

Atef Hamada
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
atef.hamadasaleh@oulu.fi

Markku Keskitalo
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
markku.keskitalo@oulu.fi

***Abstract*—In this study the microstructure and mechanical properties of laser welded complex phase steel lap joints were evaluated. Three different welding parameters were used in the experiments. The weld geometry and microstructure of the weld were studied. The joints were evaluated by hardness measurements, shear strength and fatigue strength tests. The geometry of the lap joints was affected by the welding parameters, and the width of the joint increased the lower the welding speed was. The weld metal (WM) microstructure with highest welding speed exhibits a fine columnar grain structure. As welding speed increased, the dendritic grain structure was coarser. With lowest welding speed, the microstructure changed to an equiaxed grain structure due to slower cooling. The WM with highest welding speed had the highest hardness with an average value 413 HV. The shear strengths of the joints were markedly influenced by the welding speed. With the lowest welding speed, the shear strength of the single weld was 222% higher than that of the highest welding speed. A joint with multiple welds achieved shear strength corresponding to the strength of the base material (1000 MPa). Fatigue limit of the lap joint with lowest welding speed was low < 20 MPa.**

***Keywords*—laser welding, complex phase steel, microstructure, lap joint, fatigue**

I. INTRODUCTION

Reducing emissions place greater demands on reducing the weight of vehicle structures. In particular, the reduction of the weight of structures of vehicles is directly related to emissions. Weight reduction is very important when considering the total cost of the structure as the cost of raw material decreases, especially during periods of high inflation. Utilizing high strength steels is one of the ways to reduce weight of the structures because of the good mechanical properties of structures made of high strength steels [1].

One of the high strength steel grades for various structures are complex phase (CP) steels which combine high strength with high ductility. CP steels also have good formability and weldability. The typical microstructure of CP steels has fine grain size, and it contains martensite, bainite, retained austenite and pearlite [2].

When joining CP steels, laser welding is excellent as a welding method since heat-affected-zone (HAZ) is very narrow [3,4]. However, it is important to understand how the parameters of laser welding affect quality, mechanical properties and microstructure of the weld [5,6].

Laser welding is a versatile welding method because it can easily be used to welding lap joints, which other welding methods are very difficult to use [7,8]. In lightweight structures, laser welding also has the advantage of extremely low heat input, due to which the deformation of the structure is small [9].

Several papers have been made on laser welding of CP steels, but research on these papers has focused on the study of butt joints. Huang et al. [10] investigated laser welded CP steel butt joints. Their observation was that microstructure of the HAZ, and weld metal mainly consists of lath martensite. They also observed that the strength of CP steel butt joints were as high as the strength of the base material. Rozanski et al. [11] studied laser welding of CP steel. Their study showed that the strength of the welded joint was at least equal compared to the yield strength of CP steel base material.

In this paper the microstructure and mechanical properties of laser welded complex phase steel lap joints are evaluated. Effects of the welding parameters to joint geometry, microstructure, hardness, shear strength and fatigue strength are investigated.

II. EXPERIMENTAL METHODS

A. Test material

Test material used in the experiments was 3 mm thick HR 1000 CP complex phase steel. CP steel was hot rolled and had relatively high yield strength (YS) as can be seen from Table I.

TABLE I. MECHANICAL PROPERTIES OF THE CP STEEL

Material	Yield strength	Tensile strength	Elongation	Hardness
	[MPa]	*[MPa]*	*[%]*	*[HV0.2]*
CP steel	918	1030	4.1	3.41

B. Experimental setup

The setup consists of a laser source Trumpf HLD-4002 with maximum power of 4 kW. A Precitec YW-50 laser welding head with 300 mm focal length was attached to the Motoman UP-50 6-axis robot. The welding optic was connected to the laser using an optical fiber with diameter of 200 µm. The focus of beam was -1 mm and the beam diameter on the surface of the sheet 0.3 mm. Welding experiments were made with power of 4 kW and chancing welding speeds to produce different energy inputs (EI). Welding speeds were 4, 1.5, and 0.75 m/min. The welds were coded as W1, W2 and W3, corresponding to welding speeds of 4, 1.5 and 0.75 m/min, respectively.

Fig. 1. shows the dimensions of sample for shear and fatigue strength tests. Before welding the oxide layer on the surface of the sheet was grinded off. The samples were cleaned with ethanol before welding. The samples were overlapped in 50 mm distance when there were no more than 4 welds and when the number of welds was 5, the overlap was increased by 10 mm (Fig. 1). The welds were made in the middle of the overlapped area and the weld spacing was 10 mm. In addition, 3 mm thick 70 x 50 mm sheets were used on the sample for clamping to the testing machine as shown in Fig. 1.

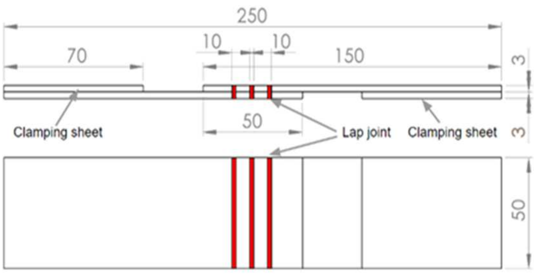

Fig. 1. The dimensions of the sample used in experiments.

C. Mechanical characterization

The shear strength tests we made with Instron 8802 testing machine. The speed used for test was 1.0 mm/min. The hardness measurements were made using Innovatest Falcon 500 Vickers hardness testing machine and 200 g load (HV0.2).

Load controlled fatigue tests were made with Instron 8802 testing machine. The used loading frequency was 5 Hz, and the stress ratio was 0 (R=0). Specimens for microstructure examinations and weld geometry analysis were polished and etched with 2% of nitric acid. Electron backscatter diffraction (EBSD) analysis was utilized to determine the microstructure.

III. Results and Discussion

A. Weld geometry

The profiles across a weldment of the CP steel joints are presented in Fig. 2a, b and c. The welding speed had markedly high effect to the width of weld and penetration. As seen from Fig. 2a with the W1, weld penetration was partial and approximately 3.55 mm. With W2 and W3 weld penetrated both sheets. The W1 also had the smallest weld width of approximately 0.36 mm at the interface of the sheets. The width of the welds W2 and W3 was significantly larger, as can be seen in Fig. 2b and c.

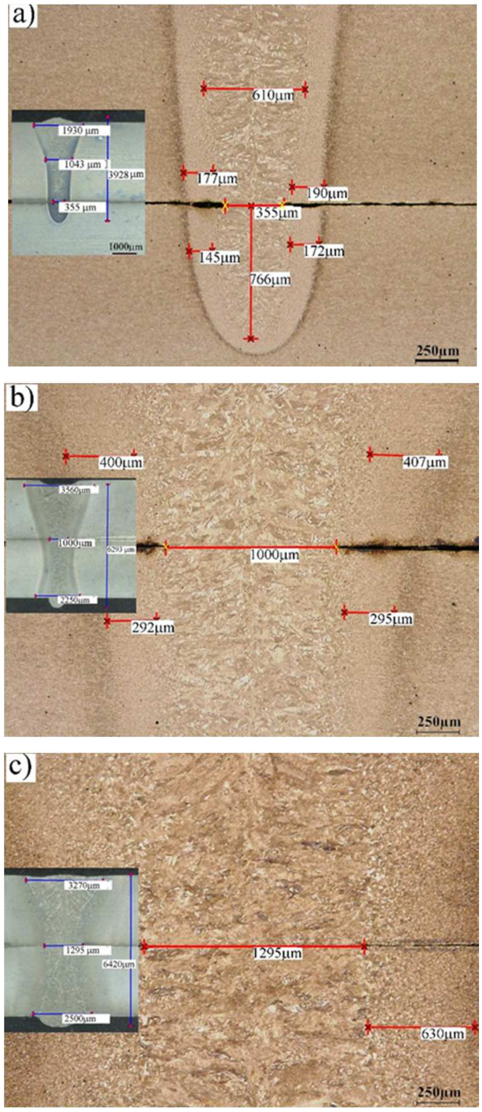

Fig. 2. Weld geometries for (a) W1, (b) W2, (c) W3.

B. Microstructure characteristics of the weld

It is well known that the microstructure of CP steel contains martensite, pearlite and retained austenite within bainite/ferrite matrix [12]. Fig. 3 shows the microstructure of CP steel BM, from which the microstructure is seen to contain fine-grained ferrite and bainite.

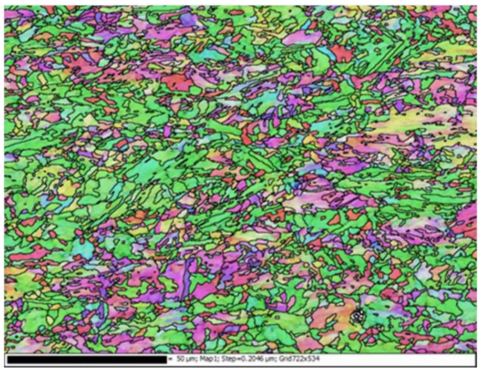

Fig. 3. EBSD map of the microstructure of the CP steel base metal.

The weld metal (WM) microstructure of lap joints with different welds is shown in Fig. 4 a, b and c. The microstructure of the W1 WM (Fig. 4a) exhibits columnar grain structure. In terms of phase fractions, the WM is mainly bainitic due to the high cooling rate, with some martensite. As welding speed decreased, the dendritic grain structure is clearly coarser compared to W1 weld. As shown in Fig. 4b, with W2 the solidification structure of the WM has a significantly more lath type structure, which is martensitic.

With W3 the microstructure changes more towards an equiaxed grain structure due to slower cooling of the weld. As the weld is in the recrystallization area for a longer time, the grains nucleate and grow equiaxially. According to the hardness data, the structure is still mainly bainitic-martensitic, with small portions of ferrite and retained austenite.

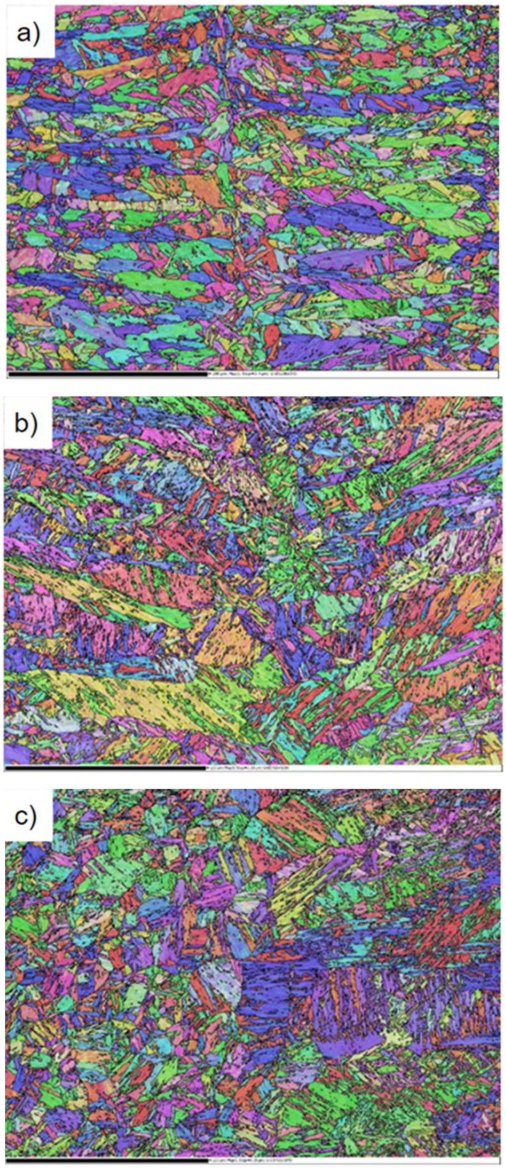

Fig. 4. EBSD maps of the microstructures of the weld metal (WM) (a) W1, (b) W2, (c) W3.

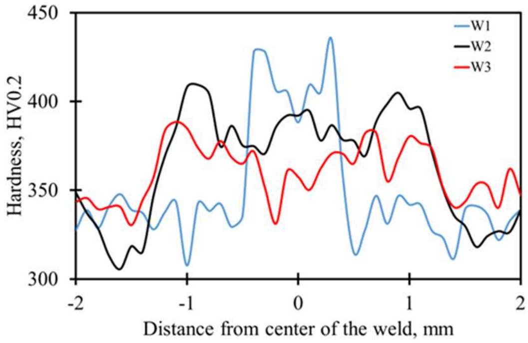

Fig. 5. Hardness measurement profiles of the weldments at different welding speeds.

Vickers hardness profiles across the weldments were evaluated (Fig. 5). It can be observed that the HAZ contains a softened region with W1 and W2. The minimum hardnesses measured from the weld were 310 and 312 HV for W1 and W2, respectively. Widths of the WM were 0.9, 2.8 and 2.9 mm for the W1, W2 and W3, respectively. Clearly the welding speed, i.e., the welding parameters, had an effect on the width of the WM.

The hardness test results show strengthening in the WM. The WM of the W1 lap joint had the highest hardness with an average value 413 HV. The average hardness of the WM was 391 and 367 HV for W2 and W3, respectively.

C. Shear strength

The strength of the joint increased when the welding speed was decreased (Fig. 6). This is due to the effect of the welding energy input used for the joint. The maximum joint strength of a single lap weld was achieved with W3 resulting in a joint strength of 338 MPa, which was 222% higher than the joint strength of W1.

The summarized results of the shear strength tests of CP steel lap joints with different number of welds are shown in Fig. 6. Hietala et al. observed that the shear strength of the laser welded lap joints is related to the weld geometry [13]. Decreasing the welding speed and increasing number of welds, the shear strength increases. For instance, the shear strengths of the joints welded with three welds were 322, 721 and 1013 MPa for W1, W2 and W3, respectively. This is attributed to size of the weld bead with different welding speeds, see Fig. 2.

With W1, every joint was fractured across the WM. With W2 and five welds, the result was a joint whose strength was equal to the tensile strength of the BM. In this case, the fracture occurred from the BM. With W2 the joint fractured from the WM when the number of welds was four or less. With W3, the joint fractured from the WM with one and two welds. The joint fractured from the BM when the number of welds was three or greater.

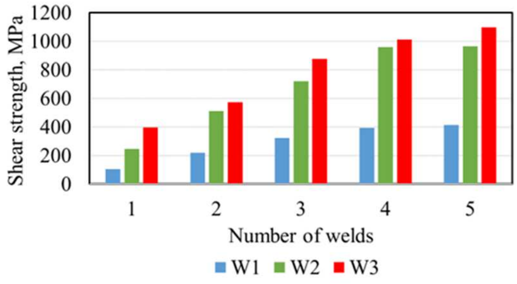

Fig. 6. Shear strength of the laser welded CP steel lap joints with different number of welds.

D. Fatigue strength

Fig. 7 shows the experimental fatigue data, S-N curve, measured for the CP steel lap joints with W3, which had the highest shear strength. The S-N curve follows the conventional trend, where the fatigue life gradually decreases with increasing the applied stress amplitude. It is observed that the fatigue limit of the lap joints was very low < 20 MPa. This in agreement with our previous work [14]. The fatigue damage and cracks initiate at the weld located at the interface between the two steel sheets. Moreover, the HAZ at the interface is a localized stress concentration region. Although the fatigue limit is relatively small, the joints can be used in structures, when the joint is designed in advance in a place that is not subject to high-cycle fatigue.

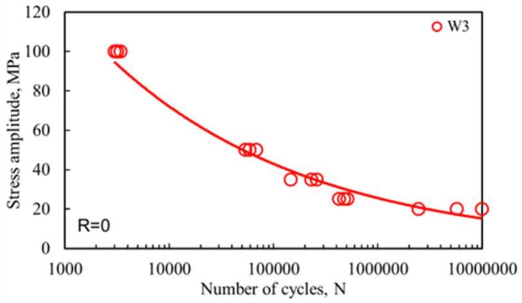

Fig. 7. Fatigue strength of the CP steel lap joint welded with welding speed of 0.75 m/min (W3).

IV. CONCLUSIONS

The microstructure, mechanical properties, and fatigue strength of complex phase steel lap joints were investigated in the study. The width of the joint and bead penetration was clearly related to the welding parameters used. The weld metal (WM) microstructure with the highest welding speed joint exhibits columnar grain structure. In terms of phase fractions, the WM was mainly bainitic due to the high cooling rate. As welding speed decreased, the dendritic grain structure was clearly coarser. With the lowest welding speed joint, the microstructure changed more towards an equiaxed grain structure due to slower cooling. The WM with highest welding speed joint had the highest hardness with an average value 413 HV. The highest joint strength of a single weld was achieved with the lowest welding speed joint resulting in a joint strength of 338 MPa. At the two lowest welding speed joints and with multiple welds a joint corresponding to the strength of the base material (1000 MPa) was achieved. Fatigue strength of the lowest welding speed joint was low.

ACKNOWLEDGMENT

The authors acknowledge the financial support from the EU, Nivala industrial park, City of Nivala and NIHAK. The companies SSAB Europe Oyj, Wärtsilä Finland Oyj and HT Laser Oy have supported this paper.

REFERENCES

[1] N. Shetye, M. Hagnell Karlsson, P. Wennhage and Z. Barsoum, "Life-cycle energy analysis of a high strength steel heavy vehicle component subjected to fatigue loading," Procedia Struct. Integr., vol. 38, pp. 538-545, 2022.

[2] H.B. Lee, H.H. Lee, Y.B. Song, J. Ham, Y.J. Kim, H.K. Kim and D.W. Suh, "Influence of chronological control of transformation on the microstructure and mechanical properties of complex phase steels," Scr. Mater., vol. 200, 113892, 2021.

[3] C. Köse, and C. Topal, "Texture, microstructure and mechanical properties of laser beam welded AISI 2507 super duplex stainless steel," Mater. Chem. Phys., vol. 289, 126490, 2022.

[4] W. Guo, Z. Wan, P. Peng, Q. Jia, G. Zou and Y. Peng, "Microstructure and mechanical properties of fiber laser welded QP980 steel," J. Mater. Process. Technol., vol 256, pp. 229-238, 2018.

[5] W. Xu, W. Tao, H. Luo, and S. Yang, "Effect of welding speed on microstructure and mechanical behavior of laser welded Al-Si coated 22MnB5 steel," Opt. Laser Technol., vol. 154, 108344, 2022.

[6] O. Berdnikova, V. Pozniakov, A. Bernatskyi, T. Alekseienko and V. Sydorets, "Effect of the structure on the mechanical properties and cracking resistance of welded joints of low-alloyed high-strength steels," Procedia Struct. Integr., vol. 16, pp. 89-96, 2019.

[7] T. Xu, S. Zhou, H. Wu, X. Ma, H. Liu and M. Li, "Dissimilar joining of low-carbon steel to aluminum alloy with TiC particles added in a zero-gap lap joint configuration by laser welding," Mater. Charact., vol. 182, 111574, 2021.

[8] H. Danielewski and A. Skrzypczyk, "Steel sheets laser lap joint welding—process analysis," Materials., vol. 13, 2258, 2020.

[9] D. Benasciutti, A. Lanzutti, G. Rupil and E. Fraenkel Haeberle, "Microstructural and mechanical characterisation of laser-welded lap joints with linear and circular beads in thin low carbon steel sheets," Mater. Des., vol. 62, pp. 205-216, 2014.

[10] J. Huang, Z. Li, H. Cui, C. Yao and Y. Wu, "Laser welding and laser cladding of high performance materials," Phys. Procedia, vol. 5, pp. 1-8, 2010.

[11] M. Rozanski, M. Morawiec, A. Grajcar and S. Stano, "Modified twin-spot laser welding of complex phase steel," Arch. Metall. Mater., vol. 61, pp. 1999-2008, 2016.

[12] R. Lima, F. Tolomelli, A. Clarke, K. Clarke, J. Spadotto and F. Assuncao, "Microstructural characterization of a 1100 MPa complex-phase steel," J. Mater. Res. Technol., vol. 17, pp. 184-191, 2022.

[13] M. Hietala, M. Ali, A. Khosravifard, M. Keskitalo, A. Järvenpää and A. Hamada, "Optimization of the tensile-shear strength of laser-welded lap joints of ultra-high strength abrasion resistance steel," J. Mater. Res. Technol., vol. 11, pp. 1434-1442, 2021.

[14] M. Hietala, A. Hamada, M. Keskitalo, M. Jaskari and A. Järvenpää, "Mechanical characterization of laser-welded double-lap joints in ultra-high and low strength steels for sandwich panel applications," Mater. Today, vol. 28, pp. 455-460, 2020.