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Fatigue behavior of laser and hybrid laser-TIG welds of high-strength low-alloy steels

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Abstract

The hybrid laser-tungsten inert gas welding technology was applied to butt weld 3-mm-thick high-strength low-alloy (HSLA) steel sheets. Although the carbon equivalent number of HSLA steel is relatively low, rapid cooling rates accompanying laser welding promote the formation of quenching microstructures in the fusion and heat affected zone of such alloy. The intent of low-current arc addition was to preheat the material to reduce the cooling rate and thus to modify the weld structure. High-cycle fatigue tests were performed to evaluate the effect of heat input on fatigue behavior of S460MC and S700MC laser and hybrid welds. Laser welding led to the dramatic drop in fatigue properties of the samples, especially for S700MC. Preliminary fatigue tests at the 350-MPa level of stress amplitude revealed that the preheating has rather a negative effect on fatigue lifetime of S460MC while increasing arc current increased the fatigue lifetime of S700MC hybrid welds. During detailed high-cycle fatigue tests allowing to construct the S-N curves, a positive effect on fatigue lifetime of S700MC has not been proved. The presence of surface notches probably influences the fatigue behavior of welded samples much stronger than local microstructural changes.

Keywords: Laser welding; Hybrid laser-TIG welding; High-strength low-alloy steel; Fatigue

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1. Introduction

Mechanical properties of structural materials are determined primarily by their chemical composition and by the process of their production, affecting the material microstructure. Each fusion welding technology induces significant local changes in the material and this fact must be taken into account during the design of the welded construction to satisfy its safe operation during its required lifetime. The character and the range of these changes are determined not only by the applied welding technology but also by the individual combination of processing parameters used within the one technology. Residual stresses present after the welding, phase transformations, fused metal and heat affected zone width, possible internal defects and surface roughness modifications can significantly influence the lifetime of welded construction, especially under cyclic loading. Thus, the prediction of mechanical properties of welded structures is quite complicated and partial experimental tests must always be done.

Modern fine-grained thermo-mechanically rolled high-strength low-alloy (HSLA) steels combine high both yield and tensile strength with relatively high ductility. Conventional welding methods can lead to the unacceptable grain growth and subsequent softening in the heat affected zone (HAZ) as was demonstrated by Bayley and Mantei, 2009. Low-heat-input joining technologies, like laser welding, are recommended to reduce heat-induced distortions and to reach a narrower weld so that the fine-grained structure of the HSLA steel, responsible for its high strength properties, is not destroyed in a wide range. Steen, 1998 says that cooling rates in orders of 10^2 - 10^3 °C.s^{-1} are characteristic for continual laser welding. He at al., 2003 computed cooling rates in orders of 10^4 °C.s^{-1} for spot laser welding while only 40 °C.s^{-1} for gas tungsten arc welding. Thus, although the carbon equivalent number of HSLA steels is very low, these steels tend to form quenching microstructures resulting in undesirable hardness changes in both fused metal and HAZ during laser welding as was demonstrated by Xu et al., 2013.

To reduce hard brittle microstructures increasing weld susceptibility to cold cracking, the cooling rate must be decreased which is possible by the preheating. The application of conventional preheating methods is quite problematic especially because of high laser welding speed. In our present research, we investigate the possibility of use of low-current arc discharge of tungsten inert gas (TIG) source for the local preheating of the workpiece immediately before the laser beam impact to improve the weld properties while maintaining acceptable HAZ. This technology is referred as hybrid laser-TIG (LasTIG) welding. It is easy-to-implement and does not require too high investments. The cooling rate can be modified by means of heat input changes set via the arc current changes in a wide range. This leads to both geometrical and microstructural variations implying also mechanical properties changes.

Fatigue properties of HSLA laser welds for different materials mostly in lap joint or T-joint configurations have been investigated by some authors both experimentally and numerically (Asim et al., 2014, Onoro and Ranninger, 1997, Goyal et al., 2018). Nevertheless, to our knowledge, no research has been published about the effect of local preheating on fatigue properties of laser nor hybrid welds, especially in butt weld configuration. In this paper, we focus on high-cycle fatigue behavior of samples with fiber laser and LasTIG butt welds of 3-mm-thick S460MC and S700MC HSLA steel sheets performed under the different heat input.

2. Material

Fatigue properties of the welds of HSLA steel S460MC (1.0982) and S700MC (1.8974) produced by the Austrian company Voestalpine were analyzed. The chemical composition of each of these steels detected by glow-discharge optical emission spectroscopy is shown in Table 1. Low levels of carbon and manganese with the precise addition of niobium, vanadium and titanium result in a fine-grained structure responsible for the high strength characteristics.

Table 1. Chemical composition of steels to-be-welded

	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Al (%)	Nb (%)	V (%)	Ti (%)	Cr (%)	Ni (%)	Sn (%)	Sb (%)	Cu (%)	B (%)
S460MC	0.07	0.01	1.01	0.007	0.003	0.046	0.05	0.05	0.00	0.01	0.02	0.01	0.01	0.02	0.0005
S700MC	0.06	0.02	1.86	0.007	0.001	0.038	0.06	0.01	0.14	0.01	0.02	0.01	0.01	0.02	0.0006

3. Experiment

The IPG YLS 2000 ytterbium fiber laser with maximum output power of 2 kW was used for the butt welding experiments. The laser beam was delivered by a 200-µm optical fiber to the Precitec YW30 processing head mounted on the arm of the ABB IRB 2400 robot. The beam was focused by 200-mm lens 1 mm under the metal sheet surface to reach 0.4-mm spot size, sufficient to bridge any potential gap between pieces.

The Fronius MagicWave 1700 Job TIG source was employed. A tungsten torch with 2.4-mm diameter was fixed with a special holder to the laser welding head to be 1.5 mm above the workpiece. It was tilted off 35 degrees and distanced 2.5 mm toward the beam axis. The experimental setup of the TIG leading configuration is depicted in Fig. 1. Pieces to be welded were ground to remove the dross, degreased, mounted and tacked together prior to the LasTIG procedure to avoid gap opening during the welding itself.

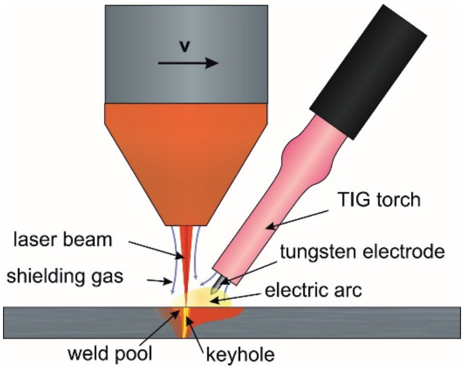


Fig. 1. Experimental setup

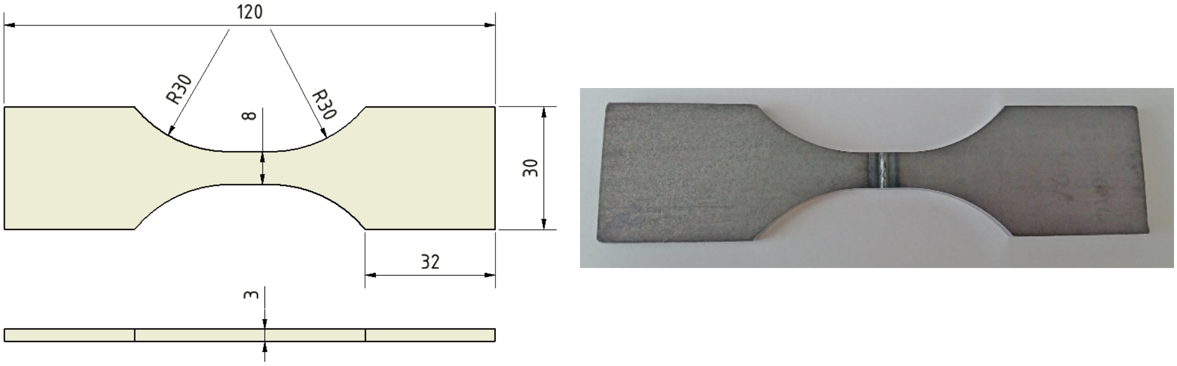
The 3-mm-thick S460MC and S700MC steel samples were butt welded using laser and hybrid LasTIG technology. All experiments were performed with laser power of 1.5 kW and welding speed 20 mm.s^{-1}. Argon with the flow of 18 l.min^{-1} was applied as a shielding gas coaxially to both the laser beam and tungsten torch. The only variable was TIG welding current, namely 0 A, 20 A, 40 A and 60 A, respectively. Current 0 A represents laser welding, and higher values correspond to the hybrid welding with the arc preheating the material, however not significantly melting its surface.

All the welds were fully penetrated, free of significant defects. Linear misalignment and negligible pores were detected within the few welds. We discussed both base metals and weld macro- and microstructures in detail in (Šebestová, 2018) together with tensile and Vickers microhardness test results.

4. High-cycle fatigue tests

High-cycle fatigue tests were performed with the resonant system Schenck PVQ at room temperature in a normal atmosphere under the sinusoidal load with frequency 40-44 Hz and stress ratio R = -1. The tests were stopped when the sample broke or 10^7 cycles were reached. The fatigue strength was determined by the method of two unbroken samples at the one level of the stress amplitude.

First, fatigue characteristics of both alloys were investigated. The base metal samples with dimensions presented in Fig. 2a were tested. Both base materials reached the fatigue strength about 300 MPa.



(a) (b)

Fig. 2. Fatigue tests samples dimensions (a) and a sample with the weld (b)

The alternating stress amplitude of 350 MPa was chosen for the comparison of fatigue properties of the base metal samples and samples with the weld. The position of the weld was in the middle of measured length of the test sample (Fig. 2b). Three samples of each welding conditions were evaluated. Fig. 3 presents the average and median results of laser and LasTIG weld fatigue tests.

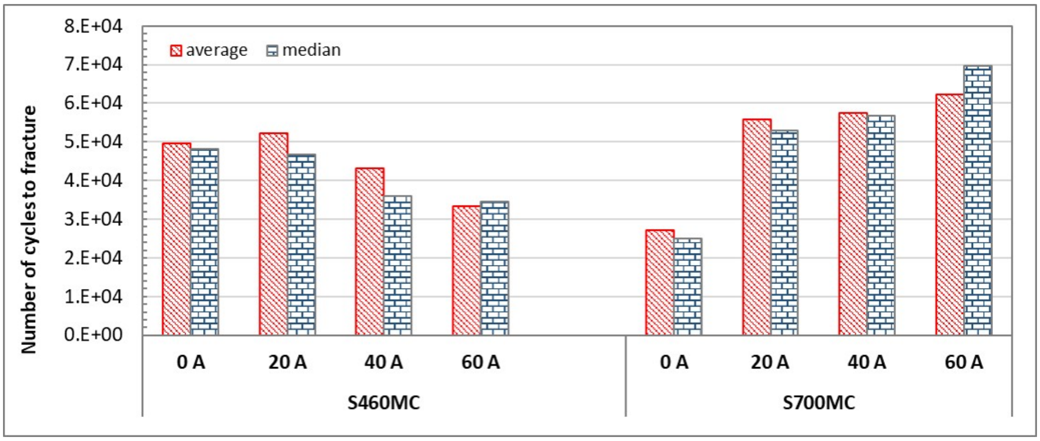
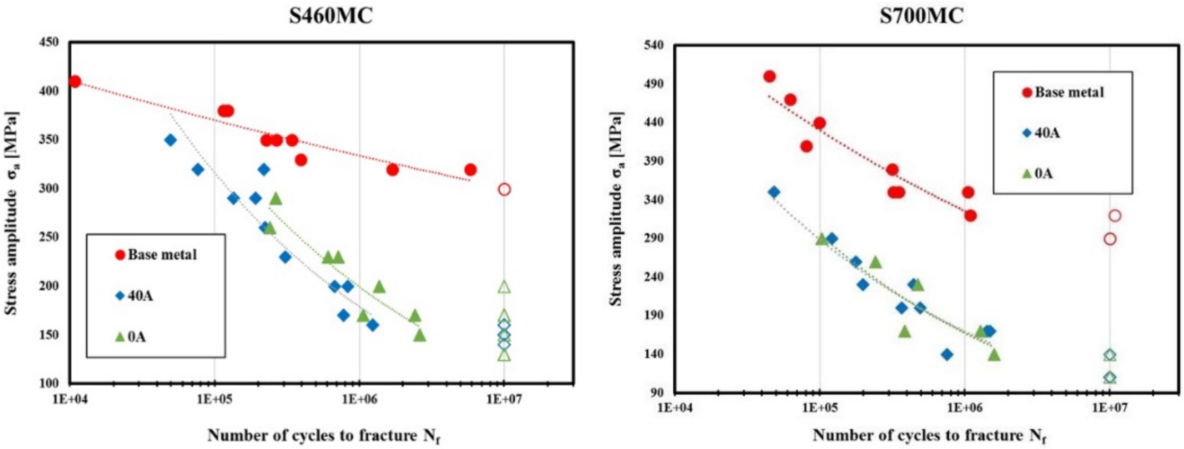


Fig. 3. The effect of arc current on fatigue lifetime of S460MC and S700MC welds under the cyclic stress with the amplitude of 350 MPa

Both base metals sustained about 3.10^5 cycles at this level of the stress amplitude. It is evident that any weld significantly reduces the fatigue lifetime of both materials. Increasing arc current and thus increasing heat input worsens the fatigue properties of S460MC LasTIG welds while significant improvement is discovered at S700MC and increases with increasing arc current. The applied preheating prolongs weld fatigue lifetime more than twice.

Further high-cycle fatigue tests at different levels of the stress amplitude were conducted to verify this assumption. Because the testing procedure is very time-consuming, only the samples with laser weld and LasTIG weld at 40 A were evaluated. The results together with both base metals S-N curves are concluded in Fig. 4.



(a)

(b)

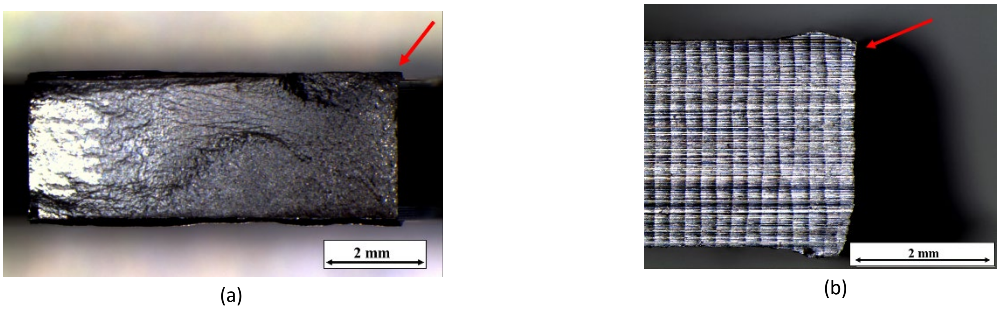
Fig. 4. The S-N curves of (a) S460MC and (b) S700MC base metal and samples with laser (0 A) and LasTIG (40 A) welds

The S-N curve of S460MC LasTIG (40 A) weld is lower compared to those of laser weld (Fig 4a). Thus, it seems that the negative effect of the preheating has been proved. Nevertheless, a linear misalignment was detected within some LasTIG samples. Although this geometrical defect was less than 5 % of the material thickness, its presence led to the formation of multiaxial stress state in critical regions under the cyclic loading that could influence the final fatigue lifetime data.

On the other hand, the results of high-cycle fatigue tests of S700MC for lower stress amplitudes (Fig 4b) did not show any positive effect of the preheating. Again, there was a little linear misalignment of some LasTIG welds that could shade the expected trend. It is very problematic to piece together such thin sheets absolutely precisely and even a mutual shift of the sheets less than one-percent can affect the fatigue behavior. However, according to the differences between the lifetime of identical samples tested at one level of the stress amplitude, detected variations between laser and LasTIG samples would probably be within the standard deviation at higher number of tested samples at each stress amplitude.

Laser and LasTIG welds had also a different geometry. Laser welds both fusion zone and HAZ were narrower compared to LasTIG welds for both metals (see Šebestová, 2018). Laser welds had low-diameter reinforcements at both face and root sides reaching about 0.2 mm. Such reinforcement naturally concentrates the stress in the fusion zone and thus accelerates fatigue crack initiation and reduces fatigue lifetime. LasTIG welds reinforcement was lower, which should be more favorable to fatigue lifetime. However, the problem is more complex. The effect of surface defects will be the subject of our further research.

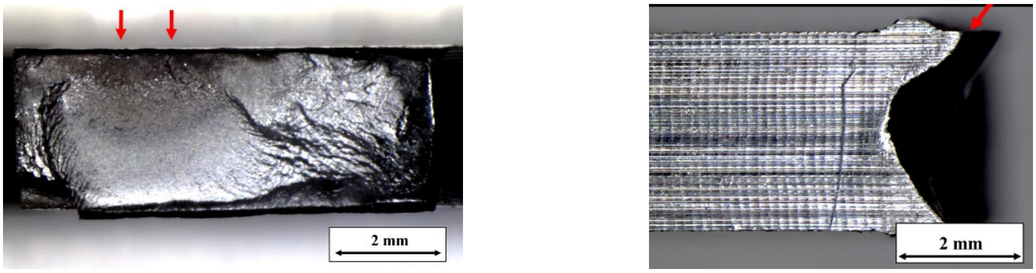
In S460MC, irrespective of welding technology, the fatigue cracks initiated the most often on the material surface facing the laser beam at the fusion line, i.e. fused metal and HAZ border, where geometrical notches concentrating the stress were always present. The cracks then propagated along the fusion line or through the fused metal. Rare pores with 100-250-μm diameter were detected on the fracture surface of LasTIG samples. However, the fatigue crack has never initiated from these internal defects. Fig 5 presents an example of fracture surface and profile of S460MC.



(a) (b)

Fig. 5. Fracture (a) surface and (b) profile of S460MC LasTIG sample (red arrow indicates fatigue crack initiation site)

In S700MC, the fatigue crack initiated at similar locations (Fig 6). Multiple initiations were often detected, especially at higher levels of the stress amplitude. The cracks propagated mainly along the fusion line. No internal welding defects were detected. However, S700MC welds had higher surface roughness and more rugged topography compared to S460MC.



(a) (b)

Fig. 6. (a) fracture surface of LasTIG weld and (b) fracture profile of laser weld, both S700MC (red arrow indicates fatigue crack initiation site)

5. Conclusions

The effect of local preheating of laser welds with LasTIG technology on high-cycle fatigue properties has been analyzed in this research. Although the preliminary tests at 350 MPa showed the positive effect of the preheating on fatigue properties of S700MC, detailed testing on lower levels of stress amplitudes haven’t proved it. Conducted experiments and tests clearly showed the necessity to test various levels of stress amplitude to evaluate high-cycle fatigue properties of samples.

The fatigue limit of both steels welded samples dropped close to 100 MPa irrespective of welding technology. This drop can be caused by the microstructural changes and mainly by the presence of surface notches that naturally act as stress concentrators significantly shortening the time to crack initiation. Weld macro and microstructural variances induced by different heat input are negligible compared to the surface profile changes or other possible geometrical defects presence. The effect of surface notches will be further examined.

Acknowledgements

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