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THE EFFECT OF LASER WELDING PARAMETERS OF DUPLEX STEEL ON FATIGUE LIFE OF JOINTS WITHOUT GEOMETRIC NOTCH IN THE FORM OF FACE AND ROOT

Key words

Laser welding, fatigue life, duplex steel, stainless steel, welding parameters.

Abstract

A geometrical and a structural notch effect have the main influence on the local stress and strain concentration in the welded joints. These factors have a significant influence on the fatigue life of welded joints. This paper presents the results of the fatigue life tests of laser-welded joints of DUPLEX 2205 steel, taking into account the structural notch. The geometric notch in the form of face and root was removed. The Nd-YAG disk laser was used to weld butt joints. The welding process was conducted using two different parameters of welding without using additional material. The parameters were chosen based on previous studies (according to PN-EN ISO 15614-11:2005).

In the study of the fatigue life of laser-welded joints, the geometric notch was ground out. Based on this research, the effect of welding parameters on the fatigue life was not observed. The fatigue cracks initiation and propagation occurred in the base materials in all cases. In addition, the results of the fatigue life of welded joints were related to the fatigue life of the samples taken from the parent material.

Introduction

The progress in materials engineering and welding engineering leads to the creation of new materials and joining techniques [1, 2, 3]. A growing number of new material joining technologies used in practice results in the fatigue life/strength of welds being similar to that of the parent material. The difference in the fatigue life/strength arises from various heterogeneities in the material relating to the geometric and structural notches (caused by, e.g., other temperature processes occurring during the welding), which frequently lead to the local variation of deformations and hence fatigue cracks [4].

One of the relatively new joining methods being more and more frequently used in the industry is laser welding. When compared to the conventional welding methods, the laser welding shows high efficiency and precision. Laser welding allows deep fusion penetration with relatively small dimensions of the weld area (W) and, in particular, the heat-affected zone (HAZ), low heat input, short cycle time, and good cosmetic welds [5, 6]. In addition, a proper selection of welding parameters results in a close-grained structure. Both the narrow HAZ and the close-grained structure have a positive impact on the strength of the weld, particularly in case of time-varying loads [4].

The advantages of the laser welding influence its use in joining various types of structural materials such as corrosion-resistant DUPLEX (DSS) steel. DSS is a dual phase steel of austenitic-ferritic structure. It combines relatively high strength and hardness with good corrosion resistance, being higher than that of the most of the standard austenitic steel grades [7].

DUPLEX steel grades are considered to be readily weldable, e.g. using conventional welding techniques [8, 9] and friction stir welding (FSW) [10]. According to the literature [7, 11], the maintenance of an optimum relation between the corrosion resistance and the strength of welds may be achieved when maintaining the approximate 50/50 ratio between the ferrite and the austenite phases. However, no results have been found for fatigue tests of laser-welded joints in DUPLEX steel.

Based on the previous tests in the selection of DUPLEX 2205 steel welding parameters, sixteen welds were made using various laser-welding parameters. Based on the tests carried out in accordance with the standard [12], two of the best parameters were selected. Then the welded joints made within these parameters were subjected to fatigue tests. This research is a continuation of the studies included in [4]. The study was extended by fatigue tests of welded joints without a geometric notch in the form of face and root. The fatigue tests were related to the fatigue test results of samples taken from the parent material. The results were analysed and the conclusions were drawn.

1. Research object

DUPLEX 2205 steel (X2CrNiMoN22-5-3 according to PN-EN 10027-1:2007) was used for testing. The chemical composition of the material is presented in Table 1. The properties observed during the monotonic tensile test are presented in Table 2.

Table 1. Chemical composition [4]

C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Mo [%]	Ni [%]	Cu [%]	W [%]
0.0222	0.4831	1.5458	0.02096	<0.005	23.946	3.2478	5.3388	0.24302	0.02712

Table 2. Monotonic tensile test properties [4]

R_m [MPa]	$R_{p0.2}$ [MPa]	A_{20} [%]
797	611	35.65

The joints were made by laser welding with no filler, using Trumpf TrueLaser Robot 5020. The welding process and the steel sheet pressing method are presented in Figure 1. Both joints, (P_02 and P_11), were made using the beam of 2 kW. The welding speed used for P_02 joint was 0.1 [m/min] higher than that used for P_11 joint. The laser beam for P_02 joint was focused on the surface of the material being welded while that for P_11 joint was focused in the centre of the sheet. Argon was used as shielding gas, and it was supplied from the top surface of the sheet at the rate of 15 or 20 l/min. The laser welding parameters are listed in Table 3.

Fig. 1. Laser welding process on Trumpf TrueLaser Robot 5020 including sheet pressing system [4]

Table 3. Laser welding parameters [4]

	Power [kW]	Rate [m/min]	Focus distances of sheet metal surface [mm]	Shielding gas: argon [l/min]
P_02/G_02	2	0.5	0	15
P_11/G_11	2	0.4	-2	20

Despite minor differences in the welding parameters, the macrostructure pictures of the cross-sectional area of the P_02 and the P_11 joints show the differences in the weld shape (Fig. 2). There was observed a clear impact of the laser beam focal distance setting against the sheet surface on the weld shape. The weld width for the P_11 joint is practically constant between the top edge and the central part of the sheet. This is related to the laser beam focus setting in the central part of the sheet.

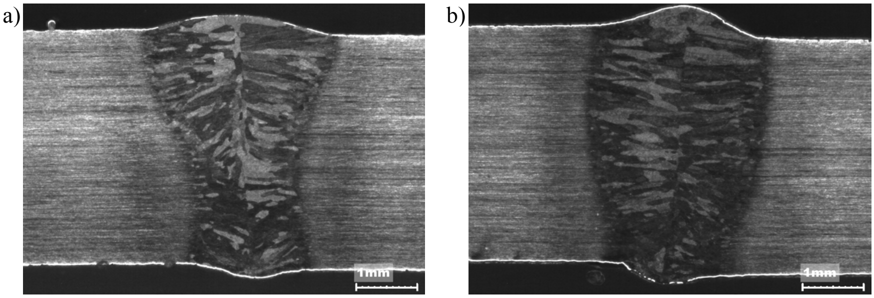

Fig. 2. Macrostructure pictures of joints: a) P_02 and b) P_11 [4]

2. Samples and research program

The tests were conducted at the accredited Institute Laboratory for Material and Structure Testing. The fatigue tests were carried out using an INSTRON 8501 hydraulic machine with controlled stress. Variable sine-wave loads were used with a constant stress amplitude, cycle asymmetry R = -1, and a frequency of from 1 to 10 Hz depending on the stress level. The tests were conducted on three stress levels for which the stress amplitude was 488.80, 403.26, and 336.05 MPa, respectively.

Three sample types were prepared for testing. Specimens of the first type were taken from a 4 mm thick sheet before welding (parent material – P_00). The next ones were taken from the welded joints with parameters listed in Table 3. A geometric notch in the form of face and root were ground out after welding. The samples after grinding were marked G_02 and G_11 for welding parameters P_02 and P_11, respectively. The test samples were made according to the dimensions presented in Fig. 3. The samples with the welds were made so that the load direction was perpendicular to the weld bead.

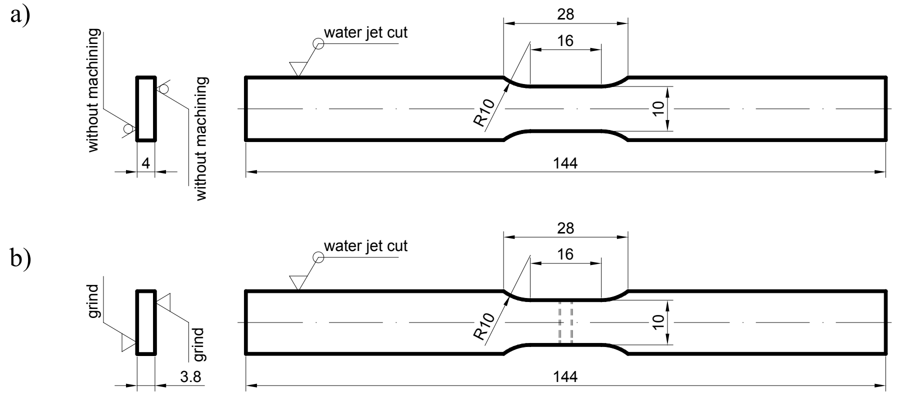

Fig. 3. Fatigue test sample taken from: a) parent material (P_00), b) welded plates after grinding the face and root of the weld (G_02 and G_11)

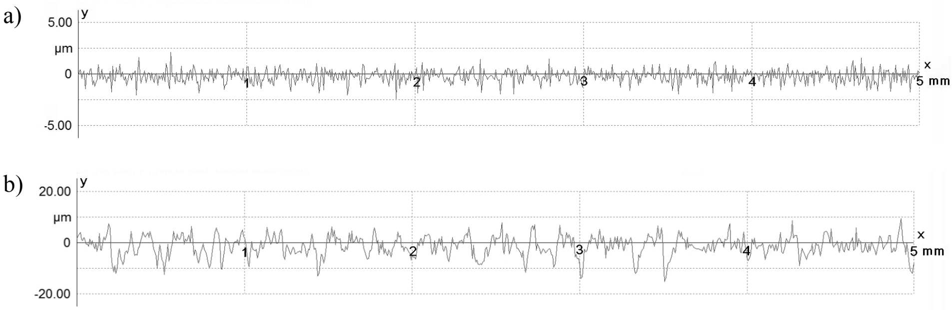

Fig 4. An exemplary distribution of profile deviation y [m] from average line x for ground (a) and water jet cut (b) surfaces

The roughness measurement was carried out after the grinding and water jet-cutting processes. Measurements have been performed on the MarSurf GD 120 equipment. Among other things, the arithmetic average of the absolute values (R_a) was determined. The R_a parameters were 0.49 µm for ground surface and 2.9 µm for the water jet cut surface. An exemplary distribution of profile deviation y [m] from average line x (for elemental section x = 5 mm) for ground and water jet cut surfaces are shown in Figures 4a and 4b, respectively.

3. Research results

The number of cycles to be destroyed was recorded during the tests. Complete failure of the test sample was adopted as a fatigue failure criterion. The results of the fatigue life for samples taken from the P_00 parent material and for the grinding samples (G_02 and G_11) taken from the P_02 and P_11 joints are specified in Fig. 5. The crack initiation and propagation occurred in the parent material in all tested samples.

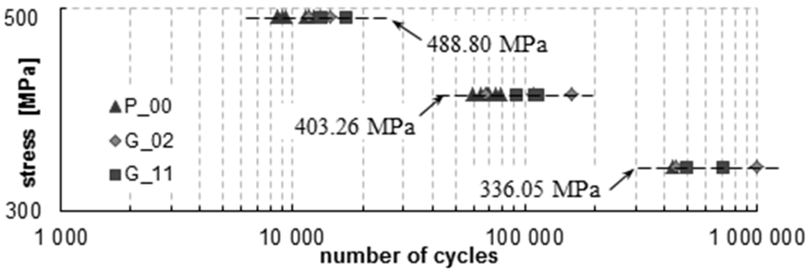

Fig. 5. Fatigue life results for the stress amplitude levels of 488.80, 403.26, and 336.05 MPa

Additionally, the strain and stress amplitudes were recorded during the testing, which made it possible to determine the hysteresis loop for the individual cycles at the respective stress level. Examples of the hysteresis loops for half of the fatigue life are presented in Figure 6. These hysteresis loops were taken from the 488.80 MPa stress amplitude level.

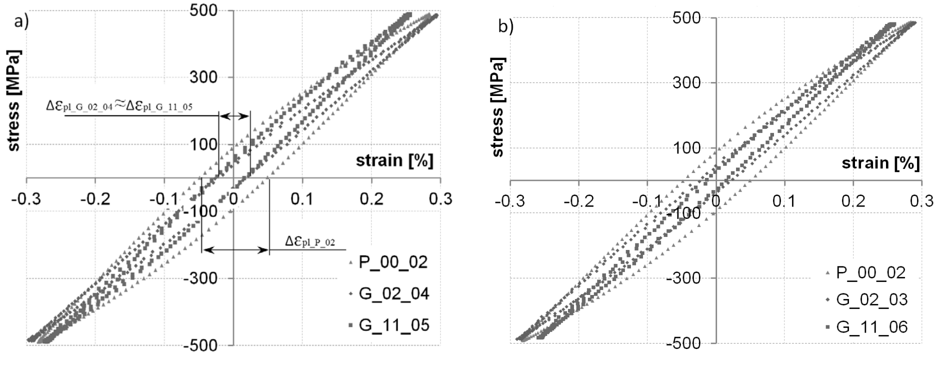

Fig. 6. Examples of hysteresis loops for half of the fatigue life for the stress amplitude level of 488.40 MPa for different samples a) P_00_02, G_02_04, G_11_05 and b) P_00_02, G_02_03, G_11_06

The strain was measured using an extensometer with gauge length of 12.5 mm. The weld zone, heat affected zone, and parent material were in the area of gauge length. The heterogeneity of the structure formed during the laser welding process caused differences in the shape of the analysed hysteresis loops (Fig. 6). The total strain range in comparison to the base material decreased in the case of the loop of G_11 and slightly increased in the case of the loop of

G_02. The plastic strain ranges (Fig. 6) were comparable for samples made with various welding parameters ($\Delta\varepsilon_{pl\_G\_02} \approx \Delta\varepsilon_{pl\_G\_11}$); however, they were significantly lower than the range of strain determined for samples of the parent material ($\Delta\varepsilon_{pl\_P\_00}$).

4. Research analysis

The statistical analysis was carried out based on the fatigue test results. To this end, the least squares method was applied and the fatigue life results were described in the log-log graphs in the form of a straight line. Considering the fact that the fatigue cracks of ground welded samples of G_02 and G_11 occurred in the base material, the results were described using one line. The effect was the square of the correlation coefficient $R^2 = 0.9872$ for the results obtained for the P_00 parent material and $R^2 = 0.9698$ for the results of the ground welded samples of G_02 and G_11 (Fig. 7).

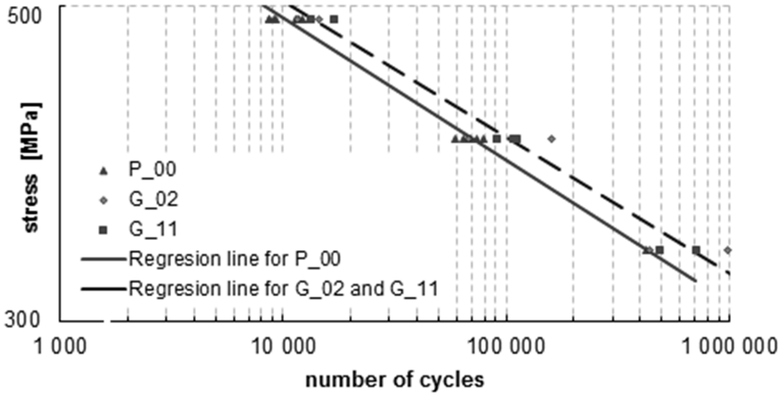

Fig. 7. Statistical results of the fatigue tests of parent material samples (P_00) and ground welded samples (G_02 and G_11)

For the parent material samples (P_00) and ground welded samples (G_02 and G_11), the fatigue category was determined based on the statistical results of fatigue tests (Fig. 7). According to Eurocode 3 [13], the fatigue category is expressed as the normative fatigue strength in [MPa] for $2 \cdot 10^6$ cycles. The results are listed in Table 4. The effect of the above is the percentage difference in the fatigue strength determined against the parent material samples (P_00), being about 5 [%] for the ground welded samples (G_02 and G_11).

The effect of the grinding operation on the fatigue strength/life can be observed after the analysis of the graph in Figure 7 and the results listed in Table 4. Grinding improves the fatigue strength/life, which agrees with the results of the studies included in the literature [14].

Table 4. Fatigue strength results

	Samples type	
	P_00	G_02 and G_11
Fatigue strength of specimens at $2 \cdot 10^6$ cycles [MPa]	288	303

Summary

Based on the previous tests of butt-welded joints in DUPLEX 2205 steel made using various laser-welding parameters, two joints were selected and subjected to fatigue testing. A comparative analysis was conducted for the results of the fatigue strength/life of laser-welded joints that had been ground against the fatigue strength/life of the parent material.

Based on the hysteresis loops, shape strengthening of the material was observed after the welding process compared to the base material. The strengthening may be caused by the increase in the hardness of the weld zone (about 290 HV0.1) and heat affected zone (about 275 HV0.1) compared to the base metal (about 265 HV0.1).

For the samples prepared in accordance with Fig. 3b made using two different welding parameters, which included ground face and root geometric notches, no changes were observed in the fatigue strength/life. The increase of the fatigue strength/life of ground and welded joints in relation to non-ground base material was observed. The grinding operation is better, especially for lower stress levels, and it increases the high cycle fatigue life. The grinding operation increased fatigue strength for $2 \cdot 10^6$ by about 5%.

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Wpływ parametrów spawania laserowego stali typu DUPLEX na trwałość zmęczeniową złączy z usuniętym karbem geometrycznym w postaci lica i grani

Słowa kluczowe

Spawanie laserowe, trwałość zmęczeniowa, stal duplex, stal nierdzewna, parametry spawania.

Streszczenie

W połączeniach spawanych występują lokalne spiętrzenia odkształceń spowodowane głównie geometrią złącza (karb geometryczny) jak również niejednorodnością strukturalną (karb strukturalny). Czynniki te mają znaczący wpływ na trwałość zmęczeniową złącza. W niniejszej pracy przedstawiono wyniki prób zmęczeniowych złączy spawanych laserowo ze stali typu DUPLEX 2205 z uwzględnieniem karbu strukturalnego. Karb geometryczny w postaci lica i grani spoiny usunięto. Złącza spawane czołowo wykonano przy użyciu lasera dyskowego typu Nd-YAG bez materiału dodatkowego dla dwóch różnych parametrów spawania. Parametry zostały dobrane na podstawie wcześniejszych badań (zgodnie z PN-EN ISO 15614-11: 2005) przeprowadzonych na złączach wykonanych kilkunastoma różnymi parametrami spawania. W badaniach trwałości zmęczeniowej połączeń spawanych laserowo pominięto karb geometryczny. Pozwoliło to na określenie optymalnych parametrów spawania laserowego stali typu DUPLEX 2205 ze względu na trwałość zmęczeniową powstałej podczas spawania struktury złącza. Dodatkowo otrzymane wyniki trwałości zmęczeniowych złączy spawanych odniesiono do trwałości zmęczeniowej próbek pobranych z materiału rodzimego.