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LASER WELDING OF LEAN DUPLEX STAINLESS STEELS AND THEIR DISSIMILAR JOINTS

Abstract

The recently developed lean duplex stainless steels (LDSS) have similar corrosion resistance and significantly higher strength than these of most common austenitic grades. This advantageous combination of properties ensures their extensive spreading in the industrial applications as substituting materials of AISI 304, 316 and 321 type austenitic grades. However, the presence of more and more new LDSS grades involves a few new problems. One of these is concerning special welding methods, for example laser welding, and another comes from the needs for welding dissimilar grades.

The paper presents welding experiments carried out by laser, TIG and MIG welding on LDX 2101 and 2205 type stainless steel grades, using cold wire or metallic powder as a welding consumable. High power Nd:YAG laser was used for welding of butt welded joints. The effect of nitrogen content in shielding gas was also evaluated. The investigation focuses on the ferrite content of dissimilar joints, both in weld metal and heat affected zone. The ferrite content was measured by using magnetic and metallographic methods. Residual stress of a 5 mm thick welded plate was measured by a new method that uses a holographic gage-camera for determining the 3D surface deformation field in the bore-hole process.

Keywords

lean duplex stainless steel, laser welding, dissimilar joints, ferrite content, residual stress, holographic measurement

1. Introduction

Usage of stainless steels in some parts of the industry is widely spread. The raw materials used in the oil-and chemical industry are considered strongly reducing and corrosive media for the conventional structural steels.

To meet the growing industrial needs, duplex steels were constructed and marketed at first in the late 1920s.These steels have got a characteristic microstructure: it contains nearly 50-50 % delta-ferrite and austenite. Duplex stainless steels are an important class of the stainless steels. Their main alloying elements are chromium (Cr), nickel (Ni), molybdenum (Mo) and nitrogen (N), which ensure a corrosion resistance for the duplex steels even better than that of austenitic steels. [1,2]

Welding and finishing of early duplex steels had many difficulties. Due to the low toughness of welding joints, duplex steels could use only in a few fields of the industry.

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Thanks to development of the steel manufacturing technology and continuous improvements nitrogen had been added to the duplex steels during the manufacturing process in the 1970-s which improved the weldability of these steels. In the late 1980-s the so-called third generation of duplex steels appeared, and the chemical composition of these duplexes was regulated very precisely during the production. [1] Thanks to the low carbon content and increased nitrogen content, the weldability of duplex steels has improved, which promoted their wider spreading greatly.

Nowadays, duplex steels are used in more and more fields, so the continuous development requires even more accurate knowledge of their properties. In addition to traditional material machining processes laser material processing gets more and more emphasis so new questions are arising regarding the applicability of laser material processes for duplex steels. Laser welding process causes a very concentrated heat input, which can significantly modify the phase ratio of the heat-affected zone compared to the phase ratio of the base material. The modified ferrite-austenite ratio affects the mechanical properties of the steel and its resistance against corrosion negatively, so selection of the proper welding technology, shielding gas and filler material is highly important.

2. Welding experiments

Samples with 100 × 40 mm size were cut out from 1.5 mm thick plates of LDX 2101 and 2205 type duplex steels (Table 1) by water jet cutting. Although only little burr forms during water jet cutting, the edges of the sample plates were milled parallel, in order that the samples fit together without gaps. To create butt joints the samples were fitted along their machined edges, and were tack welded to each other with tungsten inert gas (TIG) welding at the two ends. Part of the TIG-welded samples were fit together according to the recommendations which propose welding with welding rods, and 2.0 mm gap to be left between the welding edges [3].

During the implementation of manual TIG welding argon shielding gas was mixed with nitrogen gas and the nitrogen content of the gas mixture was varied as experimental factor, finally, three type of test specimens were prepared. The laser beam welding was performed with Rofin DY 027 type Nd:YAG laser in the Bay Zoltán Ltd. for Applied Research.

Table 1. Chemical composition of the duplex steels used for the welding experiments

Type of steel	Chemical composition, (weight %)									
	C	Si	Mn	P	S	Cr	Ni	Mo	N	Cu
LDX 2101	0,023	0,66	4,97	0,022	0,001	21,49	1,51	0,29	0,228	0,25
2205	0,019	0,37	1,42	0,022	0,001	22,4	5,8	3,16	0,177	–

Table 2. Chemical composition of the welding powder and TIG welding rod

Filler materials	Chemical composition (weight %)							
	Fe	Cr	Ni	Mo	Si	C	N	Mn
Metco 41C welding powder	Main component	17	12	2,5	2,3	0,03	–	–
Avesta LDX 2101	Main component	23	7	<0,5	0,4	0,02	0,14	0,5

The plates were placed in a levelled device, prepared for this purpose. We prepared laser welded joints with and without welding powder, during the welding with a given protective gas composition the technological factors were constant. Then we changed the composition of the shielding gas, and with the same technological parameters we produced joints again, with and without welding powder. As a consumable, we used Metco 41C type welding powder. The composition of the welding powder is shown in Table 2. According to the literature, in case of welding duplex stainless steels, such powder should be used which has a nickel content 2-4 % higher than the nickel content of the base material [1]. We varied the nitrogen content of the protective gas and the welding speed during the laser welding experiments. Finally, we prepared 14 well-evaluable welded joints for further examinations.

3. Ferrite content measurement

After the welding procedure we measured the ferrite content of the seams with Fischer Feritscope FMP 30 type device in a way that both the face and the back side were measured in 3-3 points. In each measurement point we took three measurements and the average of the three measurements was considered the ferrite content of that point. Based on the average values we can state that the ferrite content of the laser welded joints made with powder is lower, than of the joints which were made with the same welding factors, but without powder for each sample. The ferrite content of the TIG-welded joints is lower, than the ferrite content of the laser welded joints.

In several cases the standard deviation of the measured values is more than 5 %, which implies that the measurement with Fischer Feritscope is not accurate enough in this case; by our explanation the weld geometry – basically, the width of the seams which may be less, than the width of the zone excited by the probe of the ferritscope – significantly affects the measured value, resulting in a measurement error.

4. Metallographic examination

To study the microstructure cross section micrographs were made. To distinguish the ferrite and austenite phases, we used colour etching (Beraha-etchant). Fig. 1 and Fig. 2 show the macroscopic and the cross-sectional view of a TIG-welded and a laser welded joint (etchant: 5 g $CuCl_2$, 100 ml HCl, 100ml H_2O).

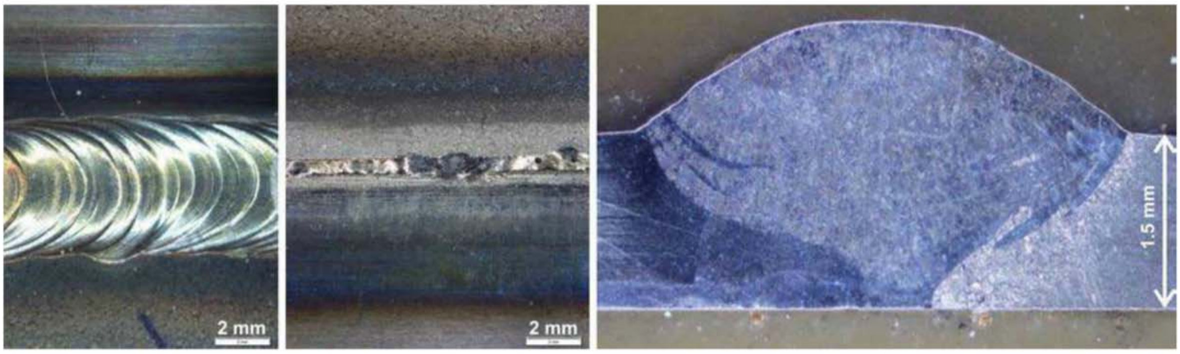
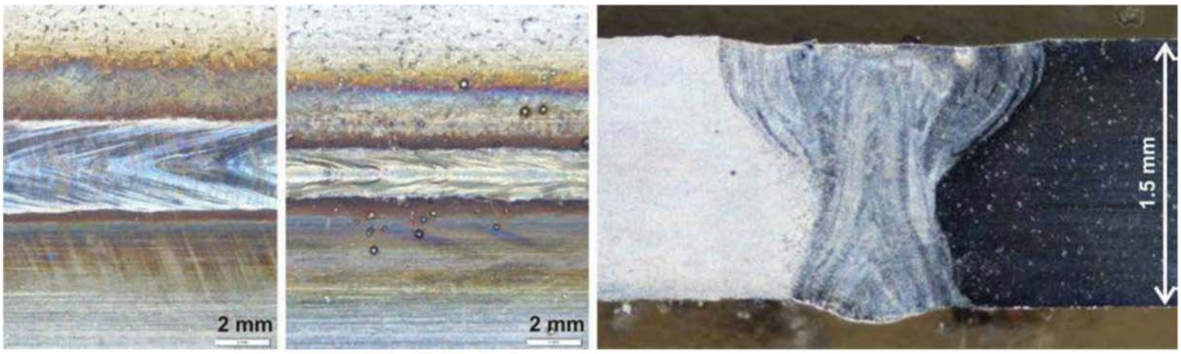


Fig. 1. Face side, back side and cross-sectional view of a TIG-welded joint made without gap



1. Figure: The face side (a) back side (b) and cross-sectional view (c) of a laser welded joint

Fig. 3a-3d clearly show, that the microstructure of the heat affected zones of the dissimilar joints made with TIG-welding are different. Austenite was formed in the heat affected zone of LDX 2101 type duplex steel at the boundaries of the ferrite grains and within the ferrite grains too. In case of 2205 type duplex steel less austenite was formed inside and at the boundaries of the ferrite grains and coarsening of the ferrite grains can be observed in the heat affected zone, because at high temperatures the austenite is formed at the grain boundaries from the solid delta-ferrite phase, at lower temperatures the austenite formation starts within the ferrite grains too [4] [5]. In the fusion zone the austenite grains show Widmanstätten-type pattern. In this case the austenite formation started at the grain boundaries and during their growing the coadjacent austenite grains penetrated into the ferrite. Fig. 3e-3h show the light-colored, Widmanstätten-type austenite needles in the fusion zone and in the heat affected zone at high magnification.

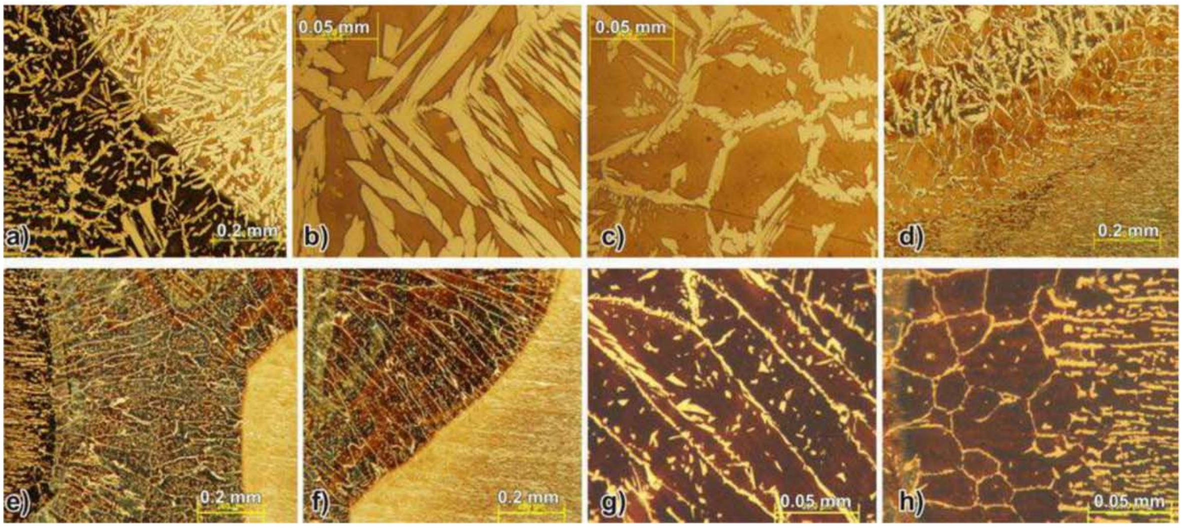


Fig. 3. a)-d) Microstructure of the TIG-welded joint. The HAZ of LDX 2101 (a) and 2205 (d), the weld metal (b) and the HAZ of the 2205 (c).
e)-h) Microstructure of the laser welded joint: fusion zone (e) and the HAZ-s (e and f). Elongated ferrite grains of the fusion zone (g) and the HAZ of the 2205 (h)

The microstructures of the laser welded fusion zones are significantly different from the TIG-welded fusion zones. In the former case the direction of the longitudinally elongated ferrite grains follow the temperature gradient which formed during the welding process (Fig. 3e-3h). A thin austenite network was evolved at the boundaries of ferrite grains, which breaks at some points (Fig. 3h). Within the ferrite grains, small austenite needles were precipitated. Within the ferrite grains in the heat affected zone very low amount of austenite was formed. This microstructure is similar to the microstructure of the electron beam welded seams which is presented in the literature [4].

The speed of the austenite formation is determined by the speed of the nitrogen diffusion. More nitrogen dissolves in the ferrite at high temperatures than at lower temperatures, which means that the nitrogen content of the ferrite phase decreases during the cooling. The released nitrogen diffuses to the grain boundaries, where austenite formation starts. Firstly, the austenite formation starts at the grain boundaries, then it is followed by the formation of the Widmanstätten structure, and finally austenite is formed within the ferrite grain. These depend on the size of the ferrite grains and the cooling rate. [1, 2, 6, 7] During the precipitation of austenite, the grain size is smaller, than that of the initial ferrite, and significantly less, than that of those structures, which are crystallized in an austenitic way [8, 9].

The dissimilar microstructure of the seams made with different welding processes refers to different cooling rate [1, 6]. In the case of laser welding, the cooling rate was higher and due to the higher cooling rate less austenite is formed than in case of the TIG welded seams. This is confirmed by the ferrite measurement results as well.

The ferrite-austenite ratio was determined by the pictures about the microstructure of the seams, with image analyser software, for which colorful, contrasting, high-quality photos were needed. We prepared 500-fold magnification pictures of the heat-affected zones and the fusion zones, and we identified the ferrite-austenite phase ratio with JMicroVision image analysis software, using the background separation method. Based on these results, we can state that the ferrite content of the TIG-welded joints was always lower than the ferrite content of the laser welded joints.

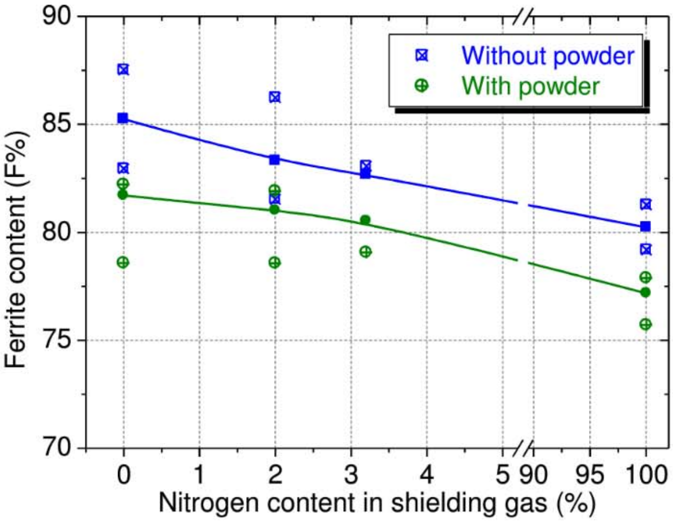


Fig. 4. The ferrite content of the fusion zone as a function of nitrogen content of the shielding gas in case of laser welded joints

The data were plotted as a function of the nitrogen content of the shielding gas (Fig. 4) and were compared with the values measured with ferritscope. Significant increase in the nitrogen content of the shielding gas has a measurable impact on the austenite content of the seams. To detect the effect of 0.5-2.0 % nitrogen content – according to the literature recommendation – more samples and / or more accurate measurement method would be required [1]. Similarly to the results measured with ferritscope, the ferrite content of the metal powder addition laser welded weldments is lower than of those which were made without welding powder.

To compare the ferrite content results measured by the two measurement methods, we calculated the average of the values measured at 3 points on the face side of each sample, and these values were compared with the ferrite content specified with the image analysis software (Fig. 5).

The graph shows that there is quite big difference between the two measurement methods therefore it is not possible to compare the values. Consequently the probe of the ferritscope is not suitable for measuring such narrow seams, because it generates volume not only in the weld, but also in its close environment, which may cause measurement error.

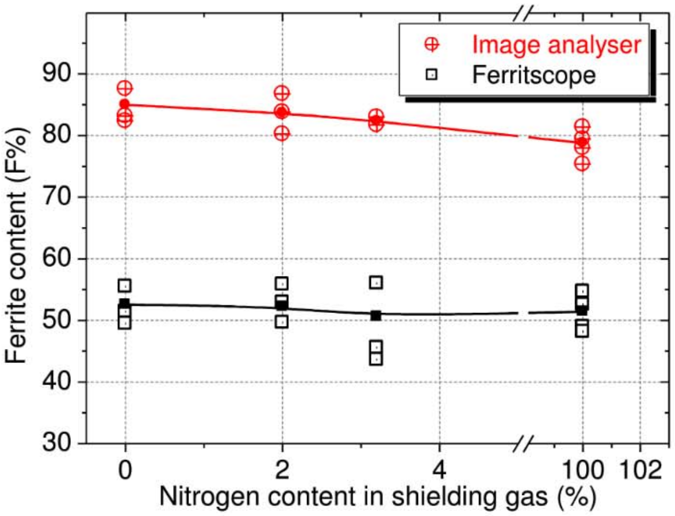


Fig. 5. Ferrite content determined with ferritscope and with the image analysis software

5. Corrosion test

The corrosion test was performed in accordance with ASTM G 48 standard, which require strict conditions for the examination of pitting corrosion of the steels and their weldments. During the sample preparation firstly we removed the burrs from the cutting edges, and then we cleaned the samples in an ultrasonic cleaner with acetone. In order to detect the subsequent weight loss, the weight of the samples was measured on an analytical balance and then we immersed them in 6% iron(III)-chloride solution for 48 hours. After 48 hours the samples were taken out from the test solution, cleaned with acetone again and their weight was measured again. It was easy to measure the weight loss in each case. The relative weight loss of the laser welded samples made with welding powder was less than in case of those which were made without welding powder.

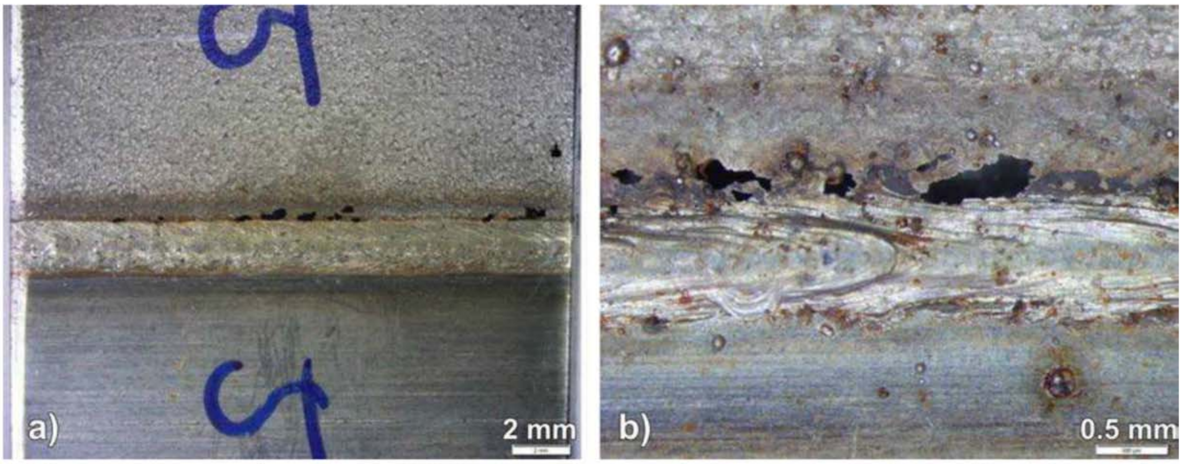


Fig. 6. Pitting corrosion of the laser welded joint on the side of lean duplex steel on the face side (a) and on the back side (b)

The corrosion of the laser welds (Fig. 6) is different than the corrosion of the TIG welded joints. In the former case there are small gaps in the heat affected zone of LDX 2101 on the face and back side as well. While in the case of laser welded LDX 2101 type duplex steel huge gaps can be seen in the heat affected zone both on the face and back side, and in many points the plate was perforated. Based on the stereomicroscopic examination the so-called gap density is higher on the back side than on the face side. This can be explained with the inadequate root protection. While in case of the 2205 type steel very few gaps can be found in the fusion zone as well as in the heat affected zone on both sides of the seam. From test results it can be concluded that the two welding technologies have different effect on the corrosion resistance of duplex steels. The heat affected zone of the LDX 2101 type duplex steel is sensitive to pitting corrosion.

6. Holographic measurement of residual stresses

Two LDX 2101 type 5 mm thick steel plate of 300×150 mm were joined by using MIG welding; the filler metal was Avesta MIG LDX2101. As the plates were fixed in an appliance that prevented the displacement, the welded specimen do not distorted but obviously enclosed high residual stresses [10]. These residual stresses were measured by using the "Laser-FALCONEYE /V-H" holographic gage-camera. This system can measure with a very high sensitivity the surface deformations, when they happen in consequence of bore-hole. Fig. 7 shows the welded plate before and after the bore-hole.

Holes with 3 mm in diameter were placed systematically along the centreline of the seam both on the face side and the back side of the joint, and at the middle of the plate perpendicularly to the seam. The holographic gage-camera detected the submicron scale surface displacement field, and on the base of the rules of linear elasticity the system software computed the stresses that cause the measured displacements / deformations / shape changes. In Fig. 8 is seen the surface distribution of residual stress in two directions, both on the face and back side of the plate, moreover along the welding seam and perpendicularly to that. Fig. 9 shows the in-depth distribution of residual stress in three different points: in the centreline of the seam, in the HAZ and finally quite far away from the fusion boundary.

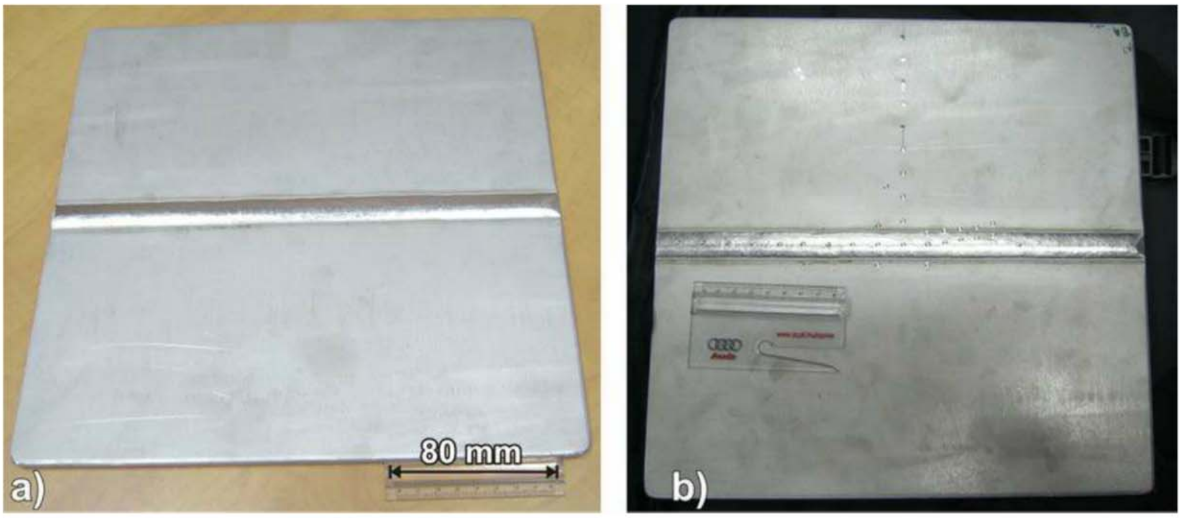


Fig. 7. MIG-welded 5 mm thick welded plate
before (a) and after (b) the holographic residual stress measurement

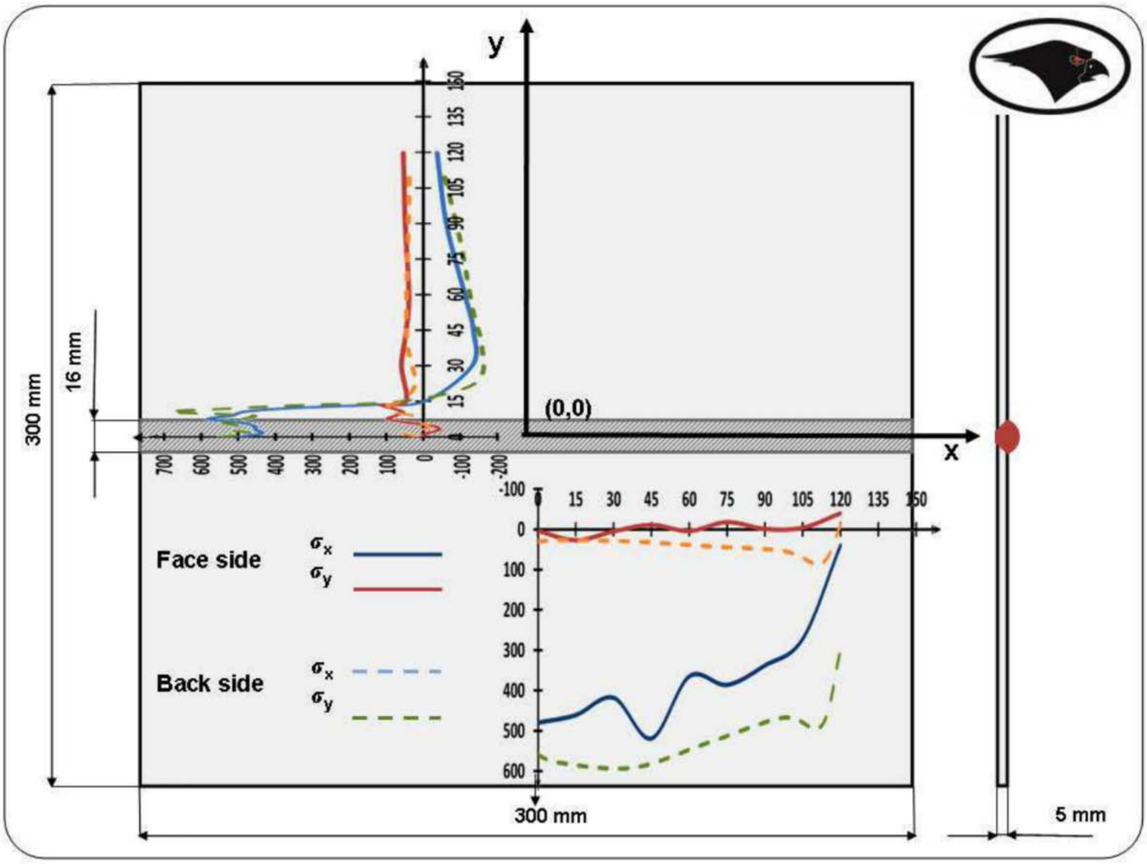


Fig. 8. Surface distribution of residual stress in two directions (on the face and the back side of the welded plate): along the welding seam and perpendicularly to it

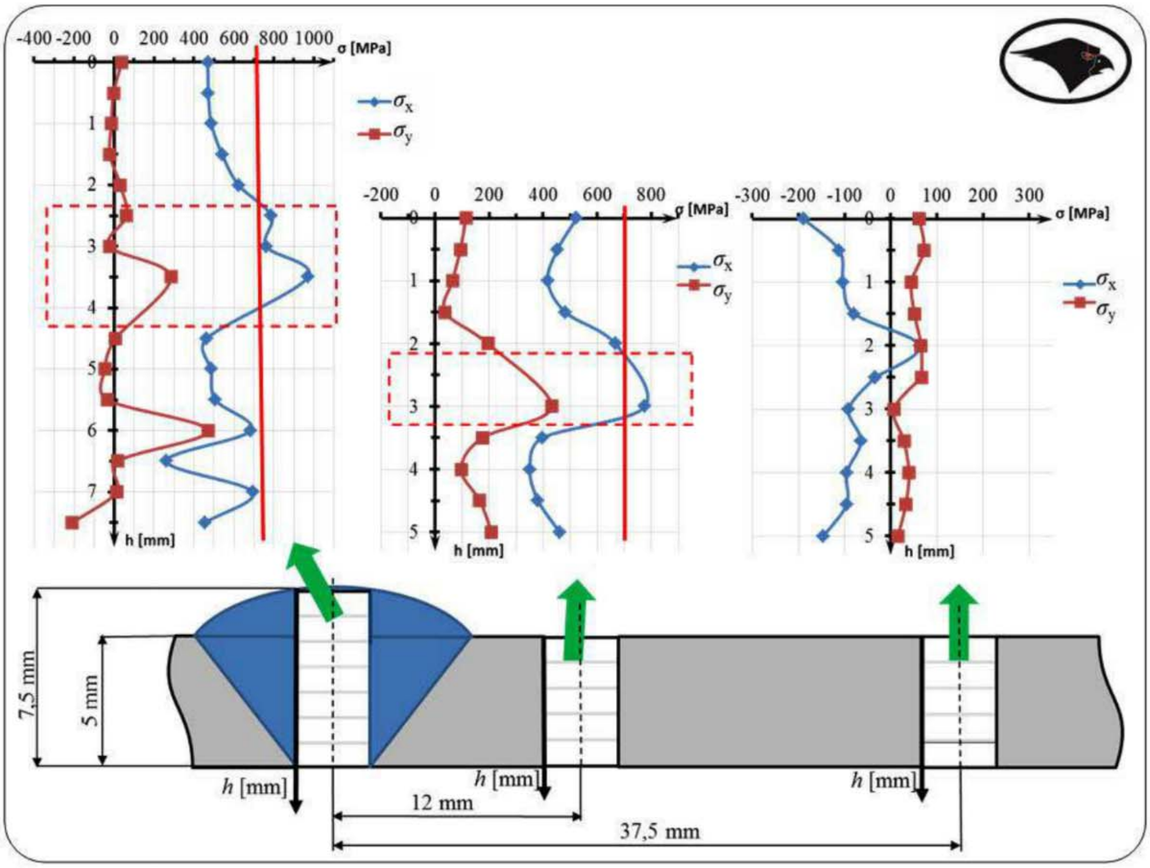


Fig. 9. The in-depth distribution of residual stress in three different points: in the weld seam, in the heat affected zone and finally quite far away from these

5. Summary

We determined the ferrite content of the laser welded and TIG-welded butt joints with metallographic examination and image analysis software and also with ferritscope. The results of the two measurement methods significantly differ from each other, so they cannot be compared with each other.

However, the results show that the ferrite content of the laser welded joints is higher than the ferrite content of the TIG welded joints, not only in the heat affected zone, but also in the weld metal. The filler material (rod, powder) and nitrogen in the shielding gas, increases the amount of austenite in the weld metal. The ferrite-austenite ratio of the TIG welds is close to the phase ratio of the base material. According to the corrosion test results, heat affected zone of the 2205 type steel corroded only slightly, which leads to the conclusion, that not only the ferrite content level affects the corrosion properties, but also the distribution of the alloying elements within the phases. Based on these, it is likely that the weld metal and heat affected zone of two 2205 duplex stainless steels could have adequate resistance against pitting corrosion.

A very sensitive method, the holographic „photography” pointed out that the residual stress distribution of the weld seam is very inhomogeneous both along the length and the depth.

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