Influence of 904L steel shot peening on residual stress distribution and fatigue life of welded joints

PhD Barbara Nasiłowska, PhD Zdzisław Bogdanowicz, PhD Joanna Zdunek

Abstract— The paper presents an influence of shot peening of joints made of 904L austenitic steel, welded with a laser beam CO_2 and with GTAW method, on residual stress distribution in subsurface layers. Structural changes due to shot peening caused an increase in fatigue life. The fracture strength initiation, revealed during the microfractographic tests of the shot peened specimens, occurred in the subsurface layers dependently on resultant stress of a working cycle and residual stress.

Index Terms— shot peening, residual stress, fatigue life, welded joints, austenitic steel , 904L steel, laser beam, GTAW.

◆

1 INTRODUCTION

An essential aim of shot peening is generating a favourable distribution of residual, mainly compressive, stress in the processed material, due to a phenomenon of an elastic-plastic stroke in the grinding material – the processed object point of contact [1]. According to work [2], a jet shot peening process is a dynamic strengthening processing consisting in transmitting a part of kinetic energy of burnishing balls, speeded up under the working pressure, to a processed material, which causes generating of a field of stress. As a result of acting of dynamic loads on the material, the arrangement of atoms in the crystal structures extends beyond the minimum level of kinetic energy, which disturbs construction of a primary crystallographic mesh and leads to a state of disorder, causing stress in the material around the striations which are a factor of plastic deformations. Only a part of atoms takes their initial locations, whereas the rest takes new locations, which is a main reason of generating the residual stress inside the material.

The results of numerical analysis of stress distribution [3] correlated with experimental tests of residual stress of 316 steel presented in work [4] after laser peening (LP) and shot penning (SP). Roentgen analysis of a diffraction line profile of LP and SP specimens ran in a similar way; however, dislocation thickness of an SP specimen was considerably greater than in the case of an LP specimen [4]. Dependently on values of forces constraining deformation, time of their operation and elastic-plastic properties, under an influence of austenitic steel shot peening, there occurs plastic deformation of part of a surface layer which can be textured to the depth of ca 100 μm [3, 5, 6].

Under an influence of shot peening of 1.4907 austenitic steel, according to [3, 5] and 304 [7, 8], there occurred in the surface layer a considerably greater thickness of grains dislocation, their smaller size, improvement of microhardness and occurrence of compressive stress.

Takakuwa and Soyama [9] as well as Hatamleh [10] pointed to reduction of an increase of fatigue fracture in 1.4404 austenitic steel after shot peening. Experimental tests described in works [11, 12, 13, 14] also proved that a process of steel processing in the form of, among others, shot peened, nitriding and hammering, increases fatigue life up to ca 30% by shifting initiation of fracture into the material (Fig.1).

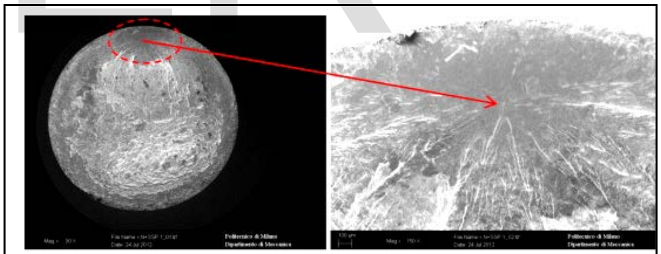

Fig. 1. Fatigue fracture in low-carbon shot peened steel with the initiation of fracture under the surface [11]

A factor influencing fatigue life of the structure is accumulation of stress occurring in the places of a change of a geometric form called a notch [14]. Reduction of resistance to initiation of the fracture is caused by concentration of residual stress [15] and microstructural changes generated as a result of a long-lasting operating life [16]. Fatigue fractures are caused by occurrence of regions of plastic deformations dependent on a load size and a kind of flaws, in which there occurs energy dissipation transformed into heat dissipated to the outside of the material; however, the remaining part of energy causes gradual damage of material coherence.

The studies presented in work [17] proved that joints welded with GTAW method are characterized by frequent imperfection of the joint in the form of non-metallic inclusions, sigma phases, Laves phases [18], too big top of the face and root of weld, as well as lack of penetration, which, as a conse-

---

[1] Military University of Technology, Institute of Optoelectronics, st. Gen. Sylwestra Kaliskiego 2, 00-908, Warsaw 49, Poland, E-mail: barbara.nasilowska@wat.edu.pl,

[2] Military University of Technology, Faculty of Mechanical Engineering, st. Gen. Sylwestra Kaliskiego 2, 00-908, Warsaw 49, Poland, E-mail: zdzislaw.bogdanowicz@wat.edu.pl,

[3] Warsaw University of Technology, Faculty of Materials Science and Engineering, st. Wołoska 141, 02-507, Warsaw, Poland, E-mail: jzdunek@inmat.pw.edu.pl

quence, leads to a failure of constructions of chemical installations mainly. Application of a laser beam for materials welding is presently a more and more frequent technological solution regarding products satisfying the high requirements of quality, precision, performance and automation.

Despite a wide application of 904L austenitic steel to production of chemical installations, the available literature lacks analysis of an influence of shot peening of welded joints with GTAW method and with a laser beam on fatigue life.

1. Experimental research

There were tested flat specimens of 500x60x5 mm dimensions, cut out with Waterjet technique from the metal sheet of 904L steel and welded with GTAW method using a non-consumable tungsten electrode φ 2,5mm MTC MT-904L and G/W 20 25 5 CuL (20% Cr, 25% Ni, 4.5% Mo, 1.5% Cu) weld in Plant Construction Chemical Equipment - Group Azoty in Tarnow according to a production technology applied virtually to produce, among others, chemical equipment.

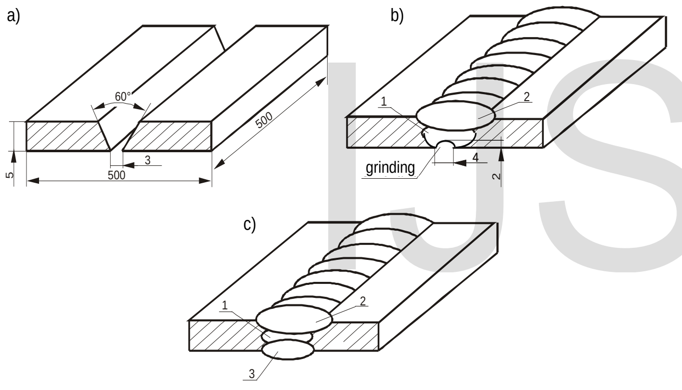

Fig. 2 Geometry of preparation of metal sheet elements before welding 904L steel with GTAW method (a) and a scheme of root of weld undercut execution (b) and pre-welding (c) according to technology used in Plant Construction Chemical Equipment - Group Azoty in

The weld was made using GTAW method with three stitches (fig. 2 c). After chamfering the edges (V) (Fig. 2 a), there was conducted welding with two passages from the face side (fig. 2 c – 1 and 2), next the root of weld was undercut (fig. 2 b – grinding) and then welded from the root of weld side (fig. 2 c – 3).

The joints made with a laser beam of dimensions 500x60x5 mm, as in the case of GTAW method, were carried out in Laser Processing Research Centre, Kielce University of Technology with the use of CO_2 TRIUMF 1005 laser according to Table 1.

Table 1.Parameters of welding 904 L austenitic steel with a laser beam

No	Welding parameters	Measurement unit	Data
1	distance of lens focal length	mm	260
2	spot on the specimen surface	mm	φ 0.4
3	power	kW	P = 4.5
4	welding speed	m/min	v = 1.4
5	protective gas	–	hel helium

Shot peening of the surface layer of joints made of 904L steel welded with a laser beam and GTAW method was conducted in the Institute of Precision Mechanics in Warsaw with a shot stream of spring steel (ca 640 HV) with a diameter of ϕ 0.8 mm, under pressure of 5 atm. The exposure time was 6 minutes, whereas the specimen coverage was 100%. Intensity of shot peening determined with the use of Almen Strips's plate (type A, grade II) was f_C=0.25 mm. Such parameters were applied for a great number of welded structures.

Diffraction recordings for determining the residual stress were carried out with D8 Discover roentgen diffractometer, from Bruker company, operating on a spot beam with a diameter of 1.5 mm with a PSD VANTEC positionally sensitive detector, from Bruker company, located in the Faculty of Materials Engineering, Warsaw University of Technology. Recording conditions were as follows: tension – 40 kV, current – 40mA, step - Δ2Θ0.03, computation time – 200 s. Diffraction recordings were also carried out , for comparison, only on the surface ,in the Institute of Non-Ferrous Metals in Skawina. Stress was calculated based on $\sin^2\Theta$ method consisted in plotting the changes of interplanar distances in the function of a specimen inclination angle at angle Θ (Fig. 3).

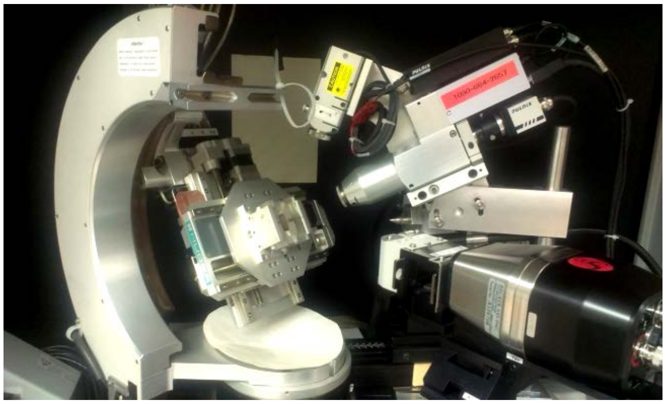

Fig. 3. Portable roentgen diffractometer D8 DISCOVER, Series 2, from Bruker AXS company, Faculty of Materials Engineering, Warsaw University of Technology (b)

The measurements were taken at the heat affected zone

- HAZ and in the weld - W (in accordance with to the scheme – Fig. 4). In order to remove the successive surface layers and to reveal subsurface residual stress, a series of specimens (from the same supply) was electrochemically etched for 2, 4, 15, 30 and 60 minutes.

Measurements of residual stress (of the second type σ^S - balancing within the limits of crystallites) were conducted on the surface of the specimens in the above mentioned regions of the welded joints before and after shot peening the joints made with GTAW method and with a laser beam (Fig. 4). The distribution of transversal σ_x and longitudinal σ_y residual stress was tested.

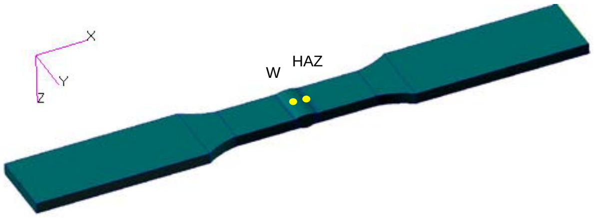

Fig. 4. Spots of transversal σ_x and longitudinal σ_y residual stress measurements

The tests of fatigue life of the welded joints were conducted on a hydraulic pulsator INSTRON 8802 at the amplitude level of nominal stress σ_{an} = 490, 438 and 375 MPa for ultimate tensile strength of 0.6, 0.7 and 0.8 determined experimentally [19]. An asymmetry coefficient was R 0.1, whereas the frequency was f = 4 Hz.

Analysis of microfractography of fatigue fractures was carried out with the use of the scanning electron microscope Quanta 3D FEG.

2. Research object

The research object was 904L austenitic steel (with the percentage content, according to the supply certificate: Ni 24-26, Cr 19-21, Mo 4-5, Cu 1.2-2.0, Mn ≤2.0, N ≤0.15, Si ≤0.7, P ≤0.030, S ≤0.010, C ≤0.02) supplied from Zakładach Budowy Aparatury Chemicznej - Grupa Azoty in Tarnów, produced by Outokumpu Stainless AB Stockholm Sweden (Fig. 5).

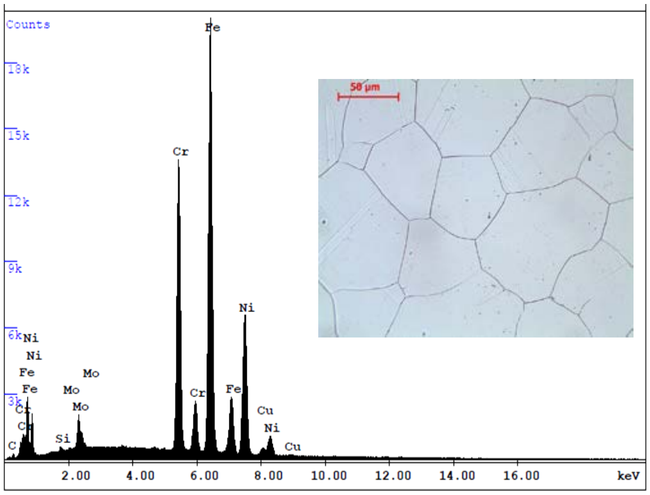

Fig. 5. Exemplary record of chemical composition of 904L steel

3. Structure of welded joints

Tests of the structure of the base material (Fig. 6 a, b), the region of the joint welded with a laser beam (Fig. 6 c, d) and GTAW method (Fig. 6 e, f) of 904L steel proved deformation of austenite grains caused by deformation of the surface layer to the depths of 200 μm (BM base material), 300 μm (laser joint) and 250 μm (GTAW joint), respectively. These depths were obtained through measurements of microhardness of the surface layer [20].

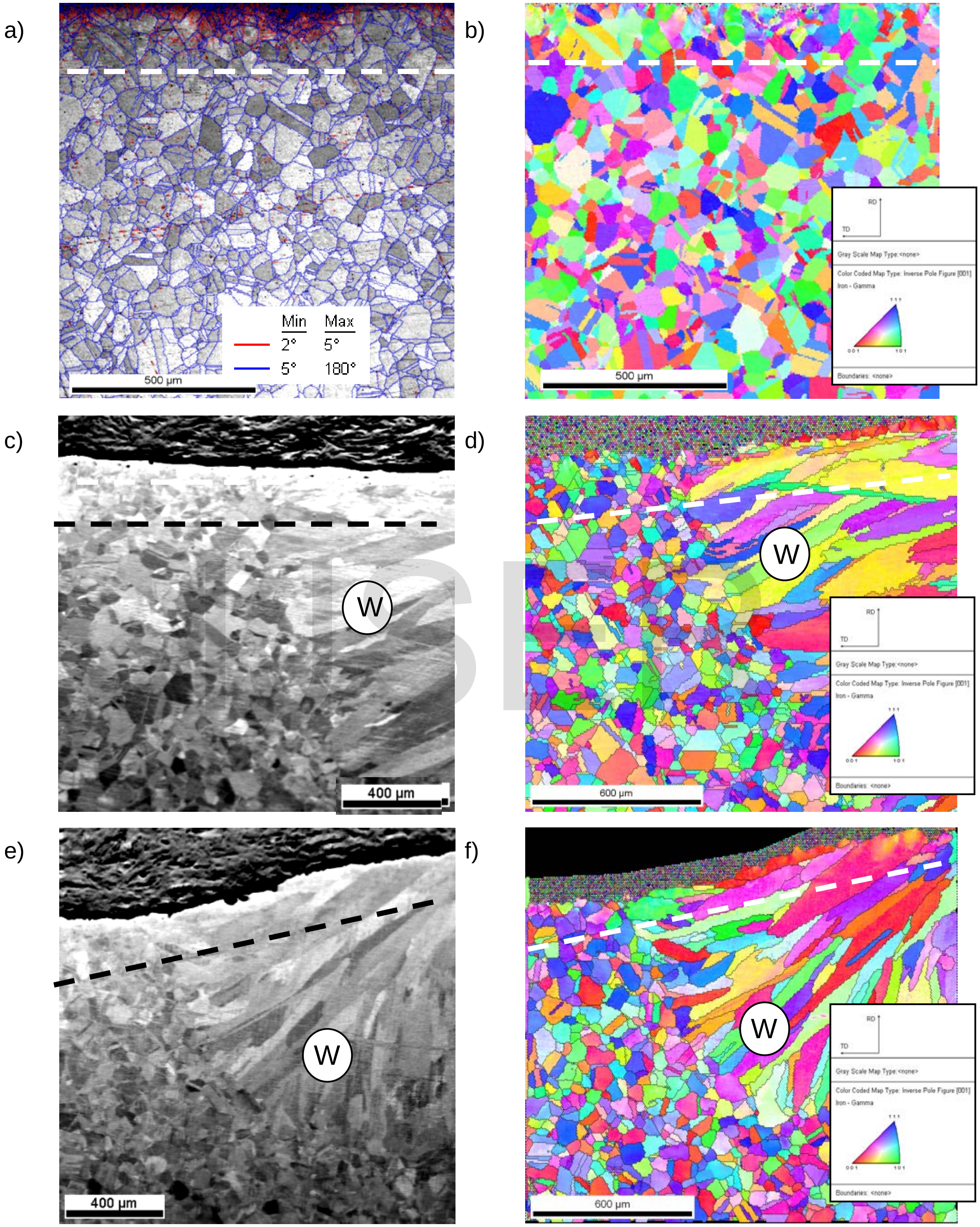

Fig. 7. Microstructure of the surface layer after mechanical shot peening of the base material (a, b), region of joints welded with a laser beam (c), (d), and with GTAW method (e), (f) carried out with the use of the scanning electron microscope Quanta 3D FEG, from FEI company, using FSD detector (a, c, e) and EBSD (b, d, f) [20].

A dashed line in the photo of the microstructure demonstrates the depth of the strengthened surface layer of the elements after shot peening, whereas symbol S shows the microstructure of the weld. The tests of the microstructure of the joint region of 904L austenitic steel demonstrated the prevailing vectors of translation into three crystallographic directions [100], [010], [001]. All the grains in the same colour correspond to an identical orientation of the crystal.

4. Residual stress in the surface layer

Distribution of residual stress determined with the use of the roentgen diffractometer in the shot peened weld made with GTAW method and with a laser beam is presented in Fig. 8. There were observed two regions of peak compression stress: one at the surface (1), and the other one under the surface, presumably at the place of the greatest strain of the material after shot peened (2).

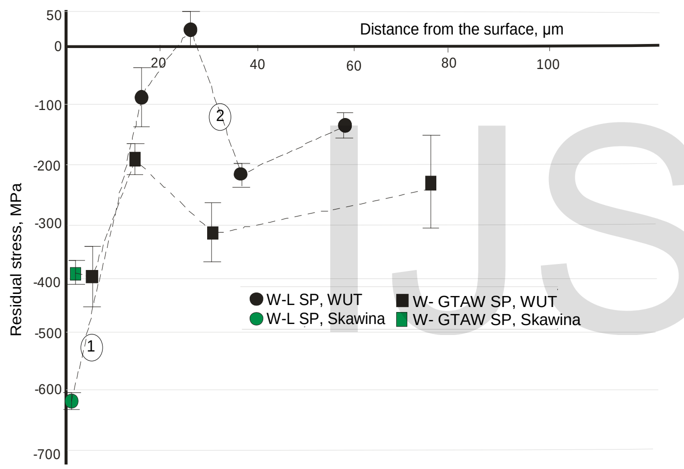

Fig. 8. Residual stress of the second type σ^S after shot peened in the subsurface layer in the weld made with GTAW method and with a laser (W - weld, L – laser, SP – shot peened specimen, black colour – research conducted in Warsaw University of Technology (WUT), green colour – research conducted in Skawina)

The results of the research indicate occurrence of this characteristic spot for joints made with GTAW method and with a laser at the depth of ca 35÷40 μm under the surface. There should be still taken into account a character of the research with a roentgen diffractomer which reads out the measurement signal from the depth of ca 10÷12 μm averaging the residual stress of the second type σ^S between the neighbouring grains. This method, a so called sin²Θ method, is based on the shift effect of diffraction lines occurring in the stress conditions of the materials with a crystal structure. Under the influence of shot peening, deformation of the grains occurs. Therefore, it should be assumed that the measurement signal can be read out from the lower depth.

Figures 8 and 9 also present the results of residual stress tests, marked with green colour, carried out on the surface with the use of a roentgen diffractomer in the Institute of Non-Ferrous Metals in Skawina (W – L SP and W – GTAW SP, Skawina).

Distribution of residual (subsurface) stress of the second type σ^S was also carried out in the heat affected zone from the face side. The test was conducted in the bottom of the geometric notch on the embedding line between the base material and the weld. There were observed (Fig. 9) the changes of residual stress distributions in the subsurface layers in which two regions of the greatest change of compressive stress can be distinguished. It should be noted that passages between region "1" and region "2" are not so clear as in the case of distribution of subsurface residual stress in the weld axis. In the joint made with a laser, the greatest subsurface compressive stress occurred at the depth of ca 55 μm and was equal to -560MPa.

In the case of distribution of residual stress of the second type σ^S occurring in the heat affected zone (HAZ) of the joint welded with GTAW method, the greatest compressive stress equal to -510 MPa occurred ca 20 μm under the surface (Fig. 9).

Fig. 9. Residual stress of the second type σ^S after shot peened in the subsurface layer in the heat affected zone, made with GTAW method and with a laser (HAZ- heat affected zone, L – laser, SP – shot peened specimen, black colour – research conducted in Warsaw University of Technology, green colour – research conducted in Skawina)

5. Fatigue life of welded joints made with GTAW method

The tests presented in paper [19] showed that the greatest tensile residual stress in the joints made with GTAW method (not shot peened) occurred in the heat affected zone. After shot peening, however, the residual stress decreases to the level of compressive stress (Fig. 8, 9).

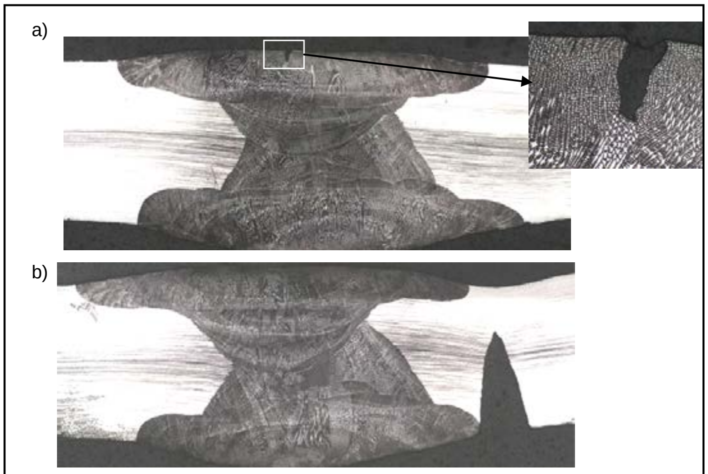

Fig. 10 Transverse microsections of the specimens with a developing primary fracture within the weld made with TIG method (not shot peened – a; shot peened – b)

The least favourable stress occurred in the weld (at the depth of 40μm in W -300 MPa, whereas HAZ -510 MPa) where initiation of fatigue fractures in few specimens was observed (Fig. 10 a). However, prevailing fracture in the specimens welded with GTAW method occurred mainly in the heat affected zone (Fig. 10 b), which was caused by both a geometric and a structural notch generated during the welding process.

Microfractography of a fatigue fracture of the joint made with GTAW method and shot peened joints revealed development of subsurface fractures. There was observed separation of the surface layer and origin of deep secondary fractures parallel to the specimen surface (Fig. 11 a).

Under the influence of the surface layer strengthening in the form of shot peening the surface, there occurred an average increase of 55% in fatigue life of the specimens made with GTAW method compared to not shot peened specimens (Fig. 12).

However, fatigue life of the base material was 8, 7 and 6 times longer (490, 438, 375 MPa) than in the case of elements with the weld made with GTAW method (not shot peened).

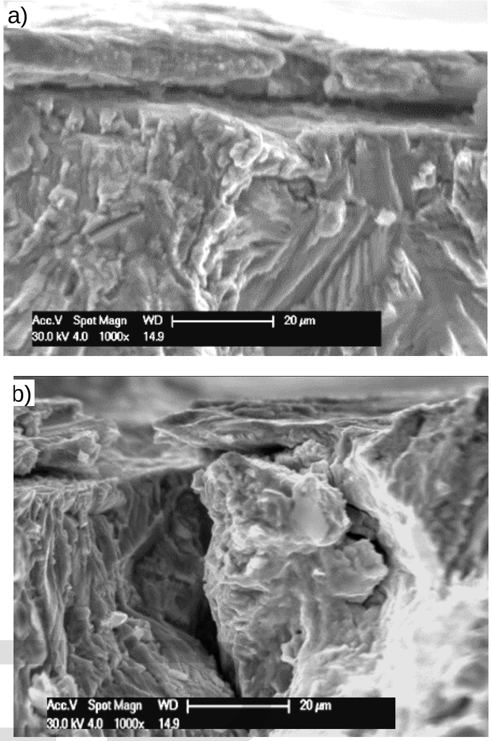

Fig. 11. Fatigue fracture of specimen welded with TIG method tested at σ_{an} = 375 MPa illustrating the centre of the fatigue fracture in the subsurface layer (a) and on the element surface (b)

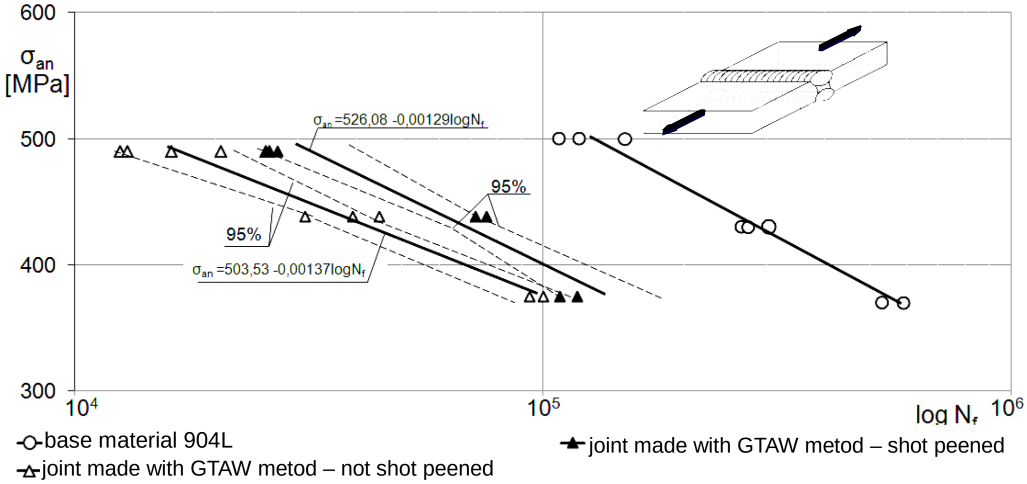

Fig. 12. Fatigue life of base material and joints welded with GTAW method before and after shot peening

6. Fatigue life of welded joints made with laser beam

In the joints welded with a laser beam (not shot peened), the greatest tensile stress occurred in the weld axis (296 MPa in HAZ, 117 MPa in W) [19], where a fatigue fracture initiated (Fig. 13 a, b, c). The fatigue fracture in these joints occurred in the weld passing into the embedding line and the heat affected zone (Fig.13 a). Under the influence of shot peening, there occurred a transformation of residual stress into compressive stress equal to 730 MPa in HAZ and -713 MPa in the weld.

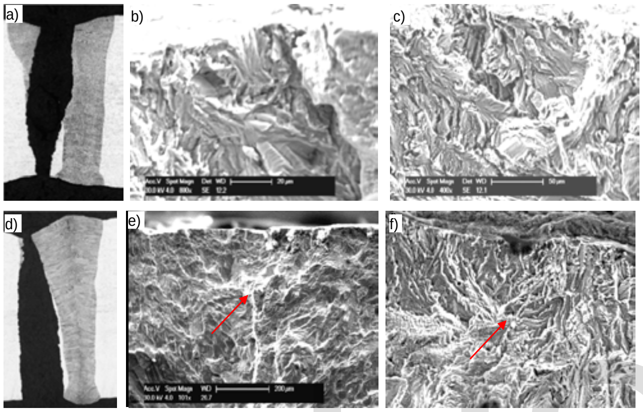

Fig. 13. Development of fatigue fractures in joints of elements welded with a laser beam before (a, b, c) and after shot peening (d, e, f). Arrows indicate the places of fractures in the shot peened elements.

Analysis of fatigue fractures metallographic images showed that, in shot peened joints, fatigue fracture took place in the heat affected zone next to the embedding line in the place where the lowest compressive stress occurs (Fig. 13 d, e, f).

As a result of shot peening the surface, there occurred a number of beneficial factors, i.e., strengthening of the surface layer of the welded elements, an increase in compressive stress and microhardness, which influenced fracture development under the surface layer and a growth in fatigue life by 24% (Fig. 14).

Microfractographic analysis revealed that fatigue fracture of the joints welded with a laser beam and shot peened was initiated to 200 μm (Fig. 13 e, f) in the depth of the surface layer. The place where the fracture initiation occurs depends on nominal stress of the working cycle applied in the tests and on the arrangement of residual stress after shot peening.

Additionally, on the fatigue life graph (Fig. 14), there were marked the results of the base material tests. The fatigue life of the base material in respect of the joints welded with a laser beam was 4 , 2.75 and 2.70 (490, 438, 375 MPa) times longer than in the case of elements with the weld made with a laser beam (not shot peened).

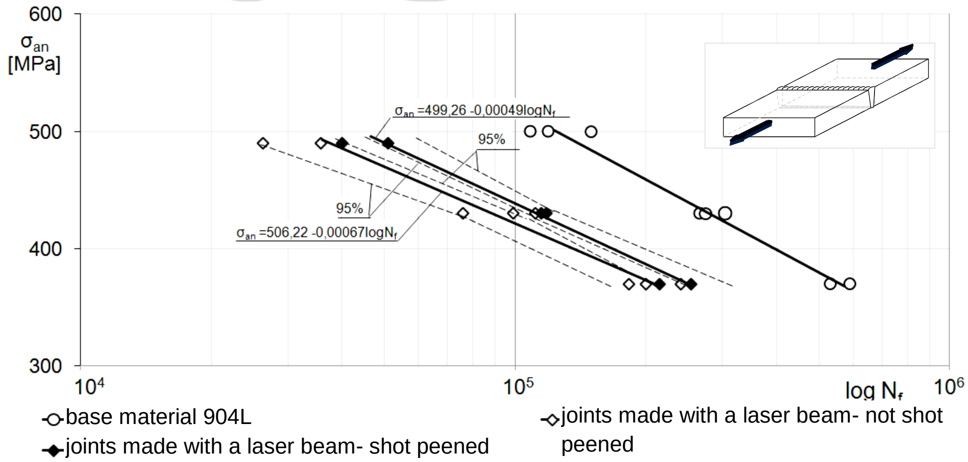

Fig. 14. Fatigue life of base material and joints welded with a laser beam before and after shot peening

SUMMARY

The experimental research proved that the greatest fatigue life occurred in the case of the base material obtaining a number of cycles to damage N_f = 556 550, 281 537 and 125 766 at the tested level the amplitudes of nominal stress σ_{an} = 370, 430 and 500 MPa.

A number of the total cycles to damage the specimen made of the base material was respectively greater by ca 800, 700 and 600% (at level σ_{an} =490, 438 and 375 MPa) than in the case of joints made with GTAW method and by 400, 275 and 270 % than in the case of joints made with a laser beam. The not shot peened welded joints made with a laser beam were characterized by fatigue life twice as much greater than in the case of joints made with GTAW method.

The joints made with a laser beam (not shot peened) were characterized by fatigue life greater by 100 ÷ 114% compared to the joints made with GTAW (not shot peened), e.g., when σ_{an}=375 MPa than for a joint made with GTAW method N_f = 89 034, whereas for the joints made with a laser beam N_f = 197 429 cycles.

Shot peening of the surface resulted in an increase in fatigue life of the joints made with a laser beam and GTAW method compared to not shot peened specimens by ca 24 and 55%, respectively.

The centres of fatigue fracture of the specimens with a joint/weld made with GTAW (not shot peened) occurred from the face side in the heat affected zone and the weld axis developing simultaneously and not joining together. However, a prevailing increase in fatigue fracture along with a residual zone was taking place in the heat affected zone, which was also determined by a level of residual stress.

In the joints welded with a laser beam, the fracture initiated in the weld axis passing into the heat affected zone.

REFERENCE

[1]. P. Sharma, H.Roy, “Engineering Failure Analysis”, *Pitting corrosion failure of an AISI stainless steel pointer rod*, vol. 44, pp. 400–407, 2014. (Unplublished manuscript)

[2]. R.Piekarski, *Zastosowanie metod prądów wirowych do pomiaru naprężeń własnych wywołanych wybranymi obróbkami powierzchniowymi*, Praca doktorska, WIP PW, Warszawa, 2001. (Book style)

[3]. K.Zhan, C.H.Jiang, V. Ji, “Materials and Design”,*Effect of prestress state on surface layer characteristic of S30432 austenitic stainless steel in shot peening process*, 42, pp. 89–93, 2012. (Plublished manuscript)

[4]. Kumagai M., Akita K., Itano Y., Imafuku M., Ohya S., “Journal of Nuclear Materials”, *X-ray diffraction study on microstructures of shot/laser-peened AISI316 stainless steel*, 443 (1–3), pp. 107–111, 2013. (Plublished manuscript)

[5]. K. Zhan, C.H. Jianga, V. Ji, “Applied Surface Science”, *Surface mechanical properties of S30432 austenitic steel after shot peening*, 258, pp. 9559– 9563, 2012. (Plublished manuscript)

[6]. K.Murugaratnam, S.Utili, N.Petrinic, *A combined DEM–FEM numerical method for Shot Peening parameter optimization*, “Advances in Engineering Software”, vol. 79, pp. 13–26, 2015. (Plublished manuscript)

[7]. K. Zhan, C.H. Jiang, V. Ji, “Materials Letters”,*Uniformity of residual stress distribution on the surface of S30432 austenitic stainless steel by different shot peening processes*, 99, pp. 61–64, 2013. (Plublished manuscript)

[8]. L.Shen, L.Wang, Y.Wang, Ch.Wang, “Surface & Coatings Technology”, *Plasma nitriding of AISI 304 austenitic stainless steel with pre-shot peening*, , 204, pp. 3222–3227, 2010. (Plublished manuscript)

[9]. O. Takakuwa, H. Soyama, “Journal of Hydrogen Energy”, *Suppression of hydrogen-assisted fatigue crack growth in austenitic stainless steel by cavitation peening international*, , 37, pp. 5268-5276, 2012. (Plublished manuscript)

[10]. O., *Hatamleh* , “International Journal of Fatigue”, *A comprehensive investigation on the effects of laser and shot peening on fatigue crack growth in friction stir welded AA 2195 joints*, 31(5), pp. 974–988, 2009. (Plublished manuscript)

[11]. S. M. Hassani-Gangaraj, A. Moridi, M. Guagliano, A. Ghidini, M.Boniardi, “International Journal of Fatigue, 62, 9th Fatigue Damage of Structural Materials Conference”, *The effect of nitriding, severe shot peening and their combination on the fatigue behavior and micro-structure of a low-alloy steel*, pp. 67–76, 2014. (Plublished manuscript)

[12]. Y. K. Gao, “Journal of Materials Engineering and Performance”*Influence of deep-nitriding and shot peening on rolling contact fatigue performance of 32Cr3MoVA steel*, vol. 17 pp. 455–459, 2008. (Plublished manuscript)

[13]. M. A. Terres, N. Laalai, H. Sidhom, “Mater Desing”, *Effect of nitriding and shot-peening on the fatigue behavior of 42CrMo4 steel: experimental analysis and predictive approach*, , vol. 35, pp. 741–748, 2012. (Plublished manuscript)

[14]. S. Faszynka, D. Rozumek, J. Lewandowski, „XXV Sympozjum Zmęczenie i Mechanika Pękania, Bydgoszcz – Fojutowo”*Rozwój ścieżki pękania przy cyklicznym zginaniu ze skręcaniem w próbkach o przekroju prostokątnym* , 2014 (Conference proceedings).

[15]. Cz. Goss, B. Nasiłowska, L. Śnieżek, „Biuletyn WAT 4”, *Niskocyklowa trwałość zmęczeniowa połączeń spawanych ze stali X5CrNi18-8*, pp. 249-263, 2012.

[16]. B. Zorc, A. Nagode, K. Borut, L. Kosec, “Engineering Failure Analysis”, *Analysis of weld cracking in shotblasting chambers made of Hadfield steel*, vol. 33, pp. 48–54, 2013. (Plublished manuscript)

[17]. Z. Bogdanowicz, P. Jóźwik, B. Nasiłowska, “Metallurgy and Foundry Engineering”, *Microstructure and mechanical behavior of a CO2 laser and TIG welded 904L steel*, Vol. 40, No. 2, pp. 69–81, 2014. (Plublished manuscript)

[18]. F. Sun, J. Zhang, Sh. Maob, X. Han, *Structural,electronic and elastic propertiesof the C14NbCr2*, “Laves phase under hydrostatic pressure, 2011”.

[19]. B. Nasiłowska, Z. Bogdanowicz, G. Mońka, M. Brzezieński, M. Wojucki, W. Szymański, *Wpływ shot peened na właściwości materiału rodzimego oraz połączeń spawanych stali austenitycznej 904L wykonanych metodą TIG i wiązką laserową*, „Inżynieria Powierzchni”, 1/2015. (Plublished manuscript)

[20]. B. Nasiłowska, Z. Bogdanowicz, M. Wojucki, “Journal of Constructional Steel Research”, *Effect of shot peening on corrosion resistance of 904L austenitic stainless steel welds made by GTAW and laser method*, Vol. 115, pp. 276-282, 2015. (Plublished manuscript)