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The Analysis of the Structure and the Hardness of TIG-welded Joints Made of Nickel Superalloy Inconel 600

Abstract: The tests discussed in the article aimed to analyse the structure and hardness of the heat affected zone and that of the weld in thin butt joints (1.0 mm) made of nickel superalloy Inconel 600 using the TIG method and variable welding linear energy restricted within the range of 45 J/mm to 80 J/mm. The test joints were subjected to visual tests, macro and microscopic metallographic tests, scanning electron microscopy-based structural observations and hardness measurements. The tests concerned with the effect of parameters applied during the TIG welding of butt joints made of 1.0 mm thick sheets (Inconel 600) in laboratory conditions revealed that the most favourable quality of the sheets was obtained when welding arc linear energy was restricted within the range of approximately 45 J/mm to 80 J/mm. An increase in linear energy within the above-presented range led to an increase in the width of the weld and that of the HAZ (observed in the joints subjected to macroscopic metallographic tests). In addition, an increase in linear energy restricted within the aforesaid range increased the grain size in matrix γ (in the HAZ) from approximately 120 μm to approximately 200 μm. The structure of the weld contained the zone of columnar grains oriented towards the fusion line as well as large groups of primary grains having the dendritic structure with clearly visible axes of primary dendrites of varied orientation. In addition, the weld structure also contained precipitates in the form of low-melting eutectics located in interdendritic spaces. The X-ray microanalysis concerning fragments having an area of 0.045mm^2, examined in the individual zones of the welded joints made of Inconel 600, revealed only slight differences in terms of mass and atomic concentrations of the primary chemical elements of the superalloy matrix such as nickel, chromium and iron or larger differences as regards carbide-forming elements such as niobium and titanium and the concentration of carbon itself.

Keywords: Inconel 600, TIG welding, grain size, X-ray microanalysis

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Introduction

Many industries important for the national economy, including the power, chemical, food, aviation and space industries as well as marine engineering, nuclear engineering and environmental protection require the development of new technologies enabling the production of metallic materials and products characterised by high mechanical properties as well as by resistance to highly aggressive corrosion environments (particularly gas corrosion at high operating temperature) [1-8]. Materials satisfying specific technological and operational requirements, particularly as regards heat resistance, high-temperature creep resistance (up to 1100°C) and resistance to aggressive environments, without simultaneously compromising the low coefficient of thermal expansion and relatively good weldability, include cobalt and titanium alloys as well as Inconel type superalloys [9–14]. Nickel-chromium type superalloys (Inconel) contain approximately 15-20% of chromium, up to approximately 18% of iron additions, up to approximately16% of molybdenum as well as up to approximately 5% of niobium and other chemical elements (Co, Cu, W). The above-named superalloys, characterised by high corrosion resistance and high strength at a temperature of up to approximately 1000°C, are used in the most thermally loaded parts of jet engines (constituting nearly 50% of their weight) [15–20].

Individual study

The tests discussed in the article aimed to analyse the structure and hardness of the base material, heat affected zone and that of the weld in thin butt joints (1.0 mm) made of nickel superalloy Inconel 600 using the TIG method. The chemical composition of the material used in the tests is presented in Table 1.

Test joints

The TIG welding of sheets made of Inconel 600 were performed in laboratory conditions, using a CastoTIG 2002 welding machine and the following constant parameters:

- welding rate: 3 mm/s,
- shielding gas: Ar – 12 l/min,
- root shielding: Ar – 3 l/min,
- tungsten (thoriated) electrode: WT20 (ø 2.4mm).

The variable parameter in the welding process was welding current, enabling the obtainment of welding linear energy restricted within the range of 45 J/mm to 80 J/mm. The current parameters are presented in Table 2, whereas exemplary joints are presented in Figure 1.

The test joints were subjected to the following tests:

- visual tests,
- macroscopic metallographic tests,
- structural observations performed using a light microscope,

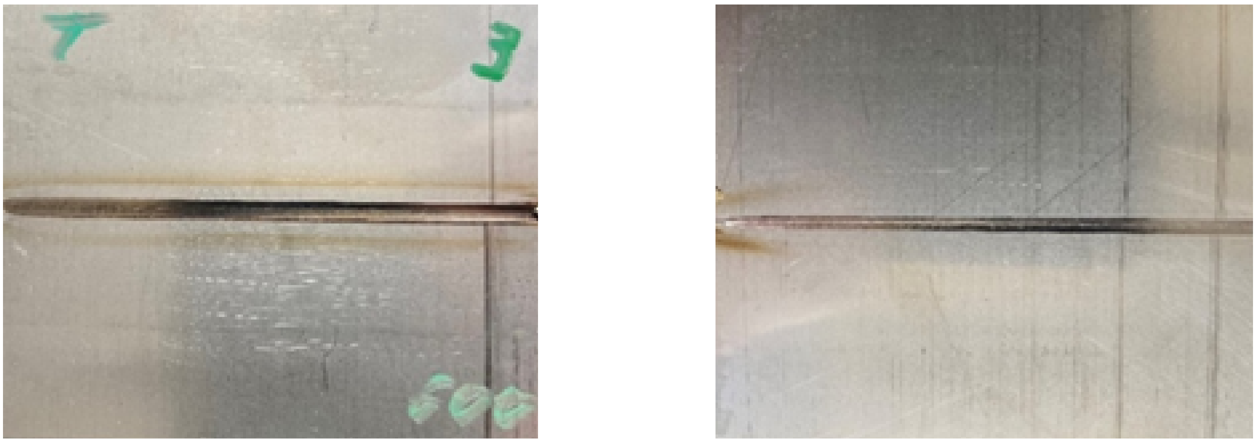
Table 1. Chemical composition of Inconel 600

Alloy type	Concentration of chemical elements, % by weight						
Inconel 600	Ni	Cr	Fe	Nb	Co	Mn	Cu
	74.43	15.76	8.60	0.08	0.05	0.25	0.09
	Al	Ti	Si	C	Mo	S	P
	0.18	0.27	0.12	0.01	-	0.002	0.005

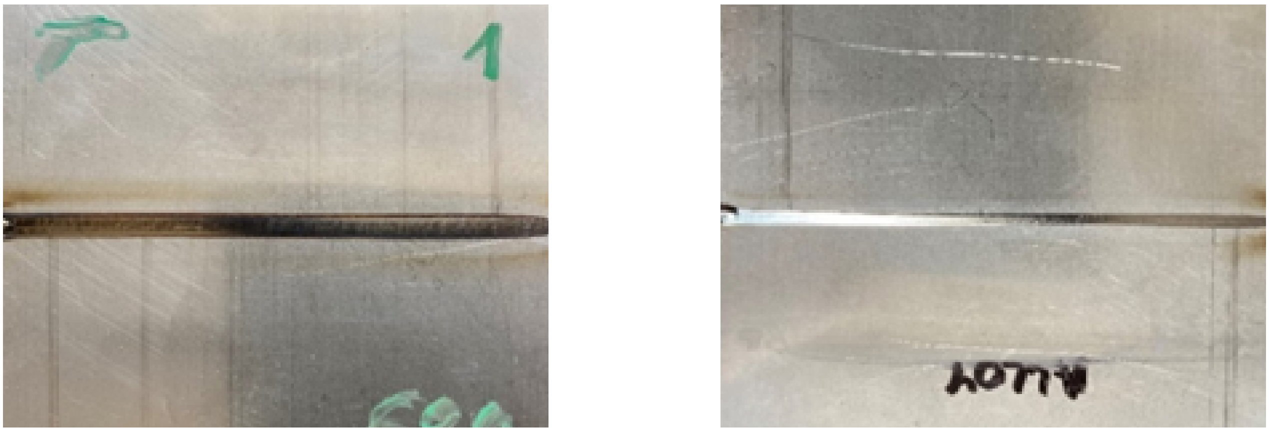
Table 2. Parameters used in the TIG welding of the test sheets

Joint designation	Welding current *I*, A	Arc voltage *U*, V	Welding linear energy *E*, J/mm
Z1	25	9.0	45
Z2	30	9.2	55
Z3	35	9.8	70
Z4	40	10.2	80

Weld face Weld root



Joint Z2



Joint Z3

Fig. 1. Welded joint made of superalloy Inconel 600 using various parameters

– structural observations performed using a scanning electron microscope,
– hardness measurements.

Analysis of test results

The visual tests of the welded joints revealed that most butt welds made of superalloy Inconel 600 were proper. However, some of the joints contained welding imperfections such as local burn-through in the weld, lack of partial penetration along the length of the beam and visible discolouration. The macroscopic metallographic tests of the welded joints made it possible to identify the shape of the welds as well as the width of the weld face, the weld root and of the HAZ in relation to the parameters applied in the welding process. The results of the macroscopic observations are presented in Table 3 and in Figure 2 (in macrophotographs). The geometry of the welds was trapezoidal with the weld face and the weld root being the upper and the lower bases of the trapezoid respectively. An increase in welding linear energy resulted in an increase in the width of the weld

Table 3. Dimensions of the weld and of the HAZ of the welded joints

Superalloy type	Joint designation	Average width, mm		
		Weld		Heat affected zone
		Face	Root	
Inconel 600	Z1	1.8	0.4	0.3
	Z2	2.3	1.2	0.4
	Z3	2.5	1.6	0.5
	Z4	3.4	1.7	0.6

face, weld root and of the HAZ (estimated metalographically).

The structure of superalloy Inconel 600 in the as-received state, being at the same time the structure of the base material, was nearly single-phase, i.e. austenitic. The structure contained banded austenitic grains of various sizes and numerous annealing twins. The austenite grain diameter was restricted within the range of approximately 5 µm to 50 µm (F. 3). The structure of the heat affected zone contained heterogeneous austenite grains. An increase in

a) Joint Z1 E_l = 45 J/mm

b) Joint Z2 E_l = 55 J/mm

c) Joint Z3 E_l = 70 J/mm

d) Joint Z4 E_l = 80 J/mm

Fig. 2. Macrostructure of the joints made of superalloy Inconel 600 using various values of arc linear energy

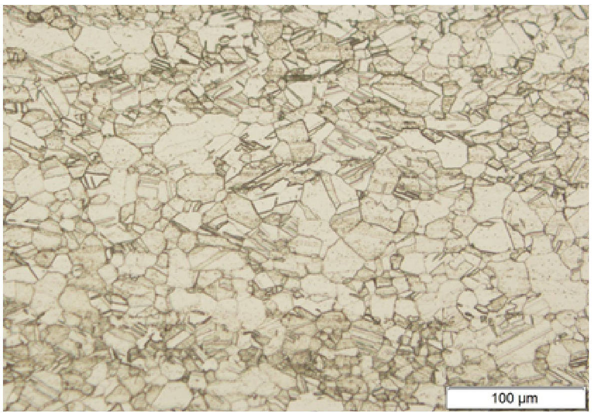


Fig. 3. Austenitic structure of the sheet made of superalloy Inconel 600 in the as-received state

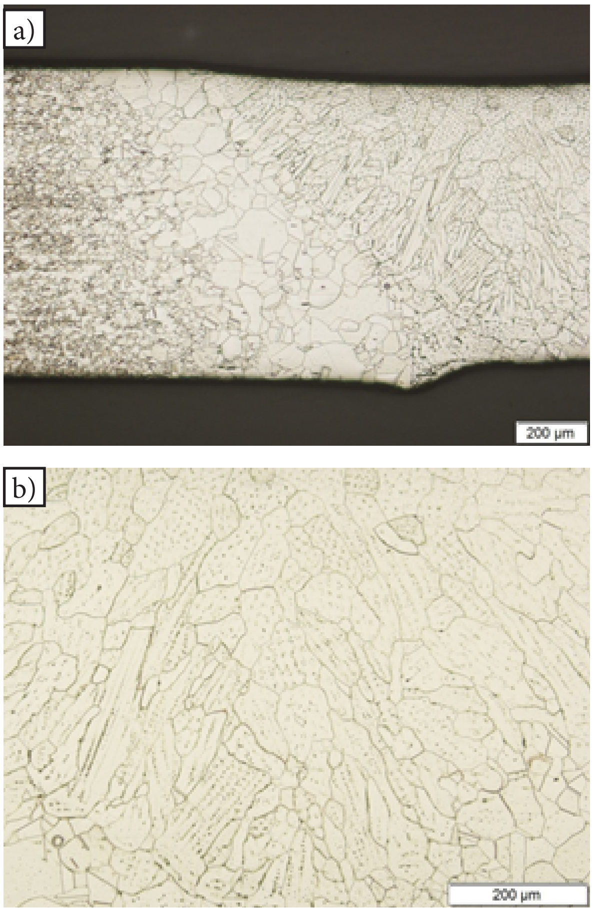


Fig. 4. Structure of the joint made of superalloy Inconel 600 (joint Z1); a) BM-HAZ-W, mag. 100x, b) – weld, mag. 200x

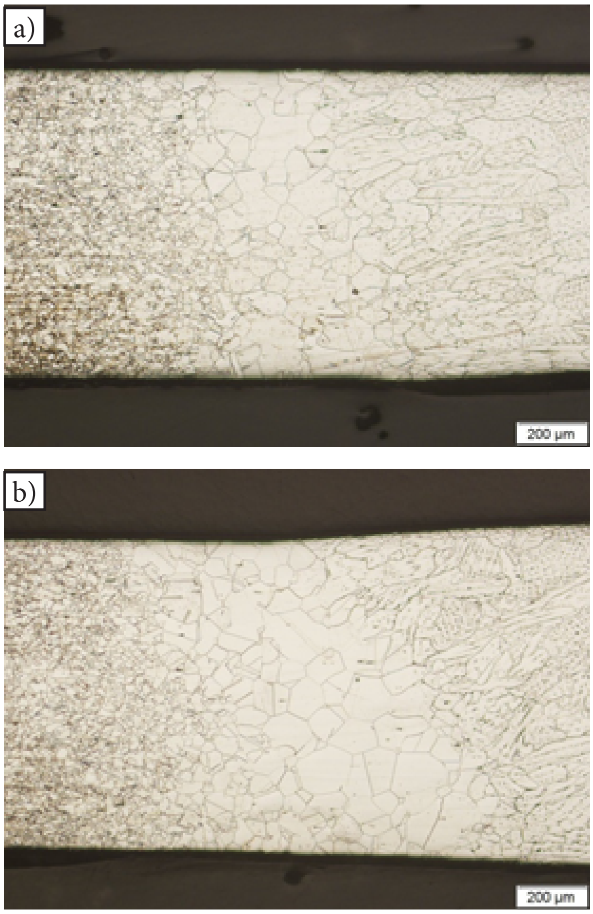
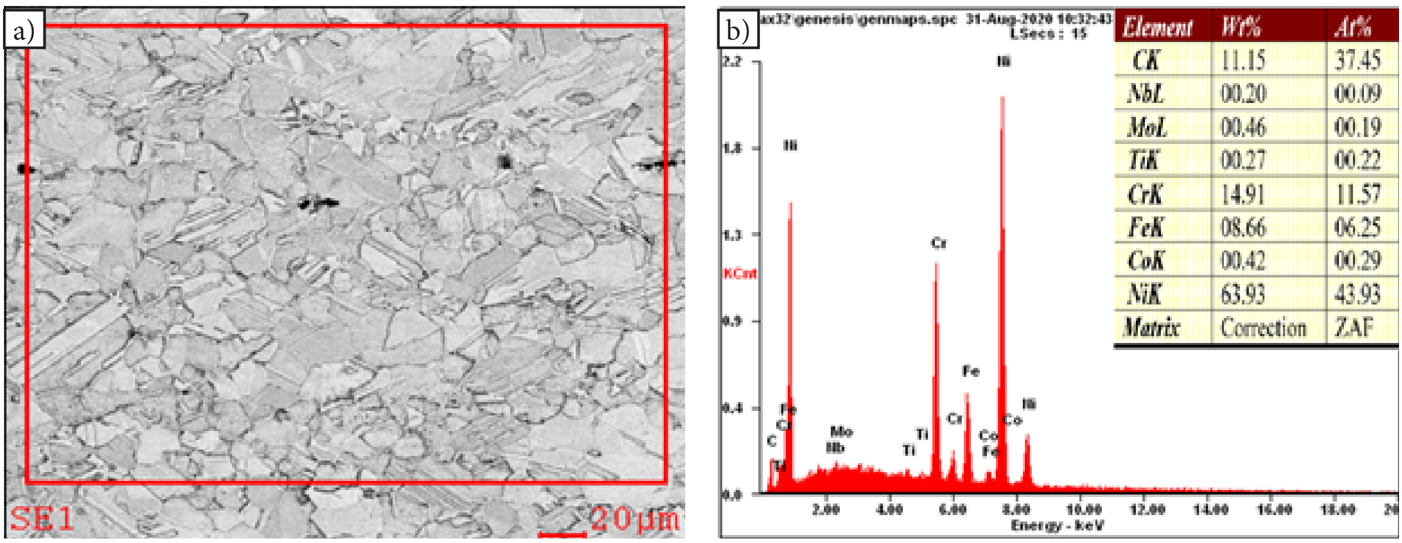


Fig. 5. Structure of the joint made of superalloy Inconel 600; a) joint Z2, mag. 100x, b) joint Z3, mag. 100x

welding arc linear energy from 45 J/mm to 80 J/mm resulted in an increase in the size of the aforesaid austenite grains from approximately120 µm to approximately 200 µm (Fig. 4, 5).

The SEM-based tests revealed important morphological details as regards the microstructure of the individual areas of the welded joints made using the highest welding arc linear energy. In addition, the use of the EDAX attachment enabled the identification of the chemical composition of the structural components of selected areas of the weld, the HAZ and of the base material. The aforesaid identification was performed using the surface method and X-ray local microanalysis. The results of the X-ray microanalysis of the areas being 0.045mm^2 in size and tested in the individual zones of the welded joints made of superalloy Inconel 600 revealed only slight differences in terms of mass and atomic concentrations of the primary chemical elements of the superalloy matrix such as nickel, chromium and iron or larger differences as regards carbide-forming elements such as niobium and titanium and the concentration of carbon itself (Fig. 6–10). The mass concentration (% by weight) of nickel in the BM and in the HAZ of joint Z4 made using a maximum arc linear energy of approximately 80 J/mm amounted to 63.93% and 65.43% in the BM respectively and was restricted within the range of approximately 66% to 68% in the HAZ. In all of the cases, the above-named values were slightly lower than those identified during the analysis of the chemical composition of the test sheets in the as-received state (77.43%) (Fig. 6 and 7). Similar observations were made in relation to the concentration of chromium and iron in the zones of the welded joint subjected to examination. The content of chromium was stable and restricted within the range of 14.9% to 15.2%. The content of iron was restricted within the range of 8.6% to approximately 9%; the contents of chromium and iron obtained in the basic analysis of the chemical composition of superalloy Inconel 600 amounted to 15.76% and 8.60%, respectively. The test results also revealed the lowest concentration of carbon in the weld and the highest carbon concentration in the base material. In terms of nickel concentration, the tendency was reverse. In the weld area, the concentration of carbon amounted to approximately 6.7%, whereas that of nickel amounted to approximately 67% (Fig. 8 and 9). The X-ray local microanalysis of the austenite grain boundary revealed the higher concentration of carbon (10.98%) and chromium (14.70%) and the lower concentration of nickel (approximately 64%), implying the formation of a local M_xC_y type carbide phase with chromium (e.g. $Cr_{23}C_6$) in the above-named area (Fig. 10).

The analysis concerning the effect of welding



Element	Wt%	At%
CK	11.15	37.45
NbL	00.20	00.09
MoL	00.46	00.19
TiK	00.27	00.22
CrK	14.91	11.57
FeK	08.66	06.25
CoK	00.42	00.29
NiK	63.93	43.93
Matrix	Correction	ZAF

Fig. 6. Results of the microanalysis of the joint made of superalloy Inconel 600; a) base material subjected to the tests and b) spectrogram with the quantitative analysis of chemical elements

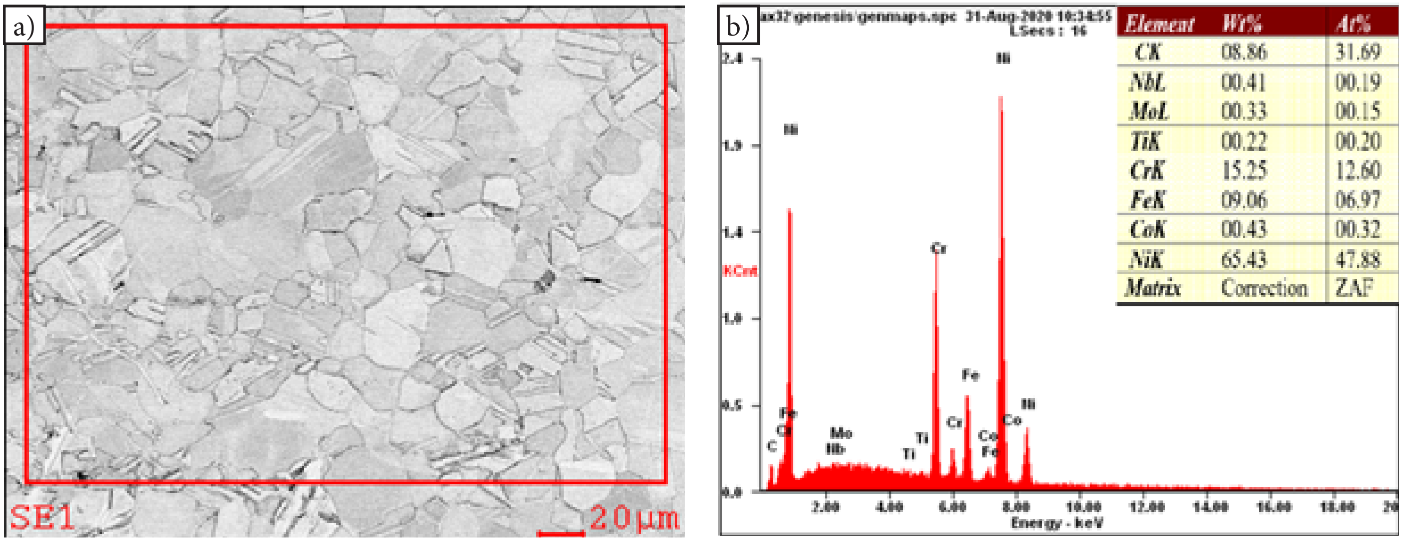


Fig. 7. Results of the microanalysis of the joint made of superalloy Inconel 600; a) heat affected zone subjected to the tests and b) spectrogram with the quantitative analysis of chemical elements

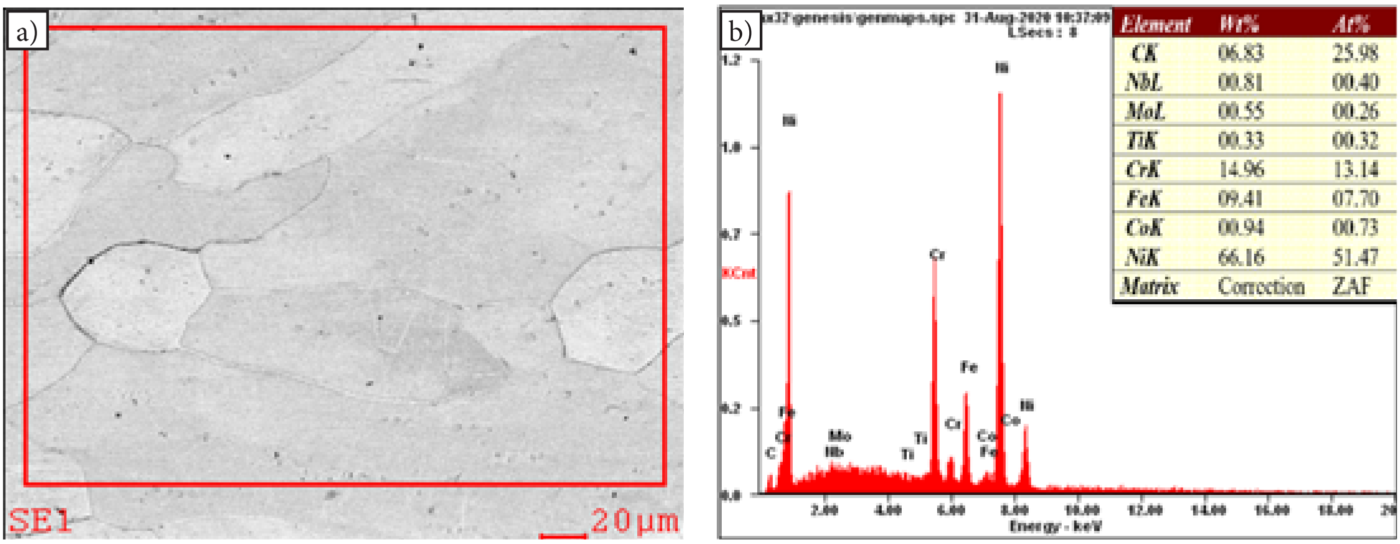


Fig. 8. Results of the microanalysis of the joint made of superalloy Inconel 600; a) weld subjected to the tests and b) spectrogram with the quantitative analysis of chemical elements

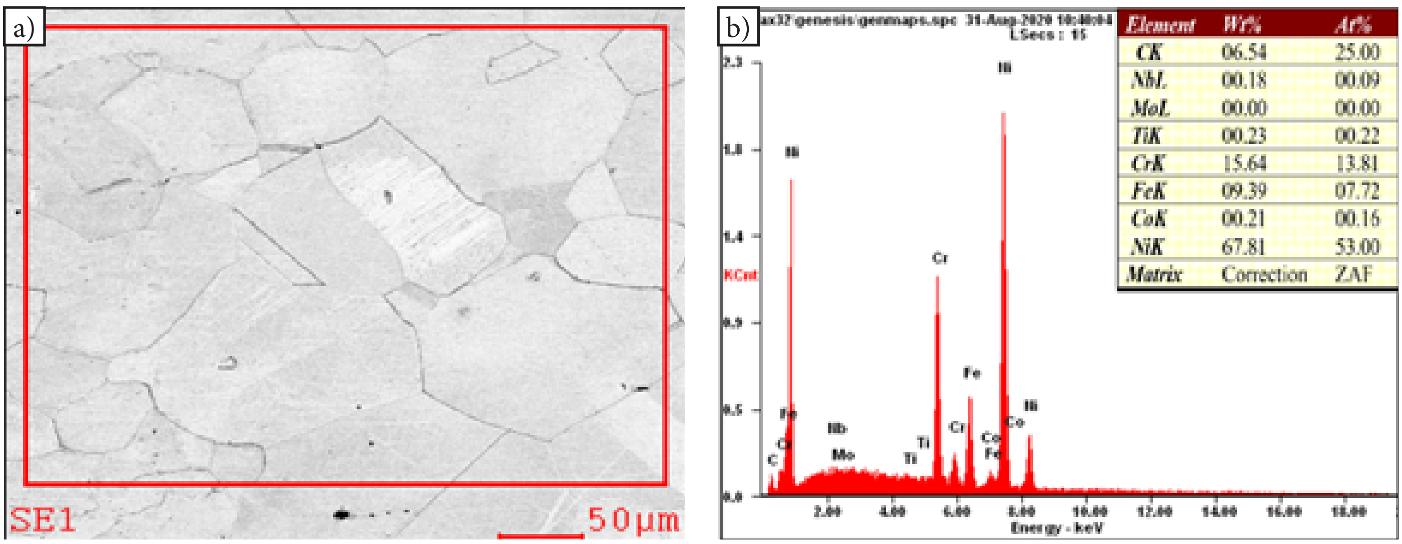


Fig. 9. Results of the microanalysis of the joint made of superalloy Inconel 600; a) weld subjected to the tests and b) spectrogram with the quantitative analysis of chemical elements

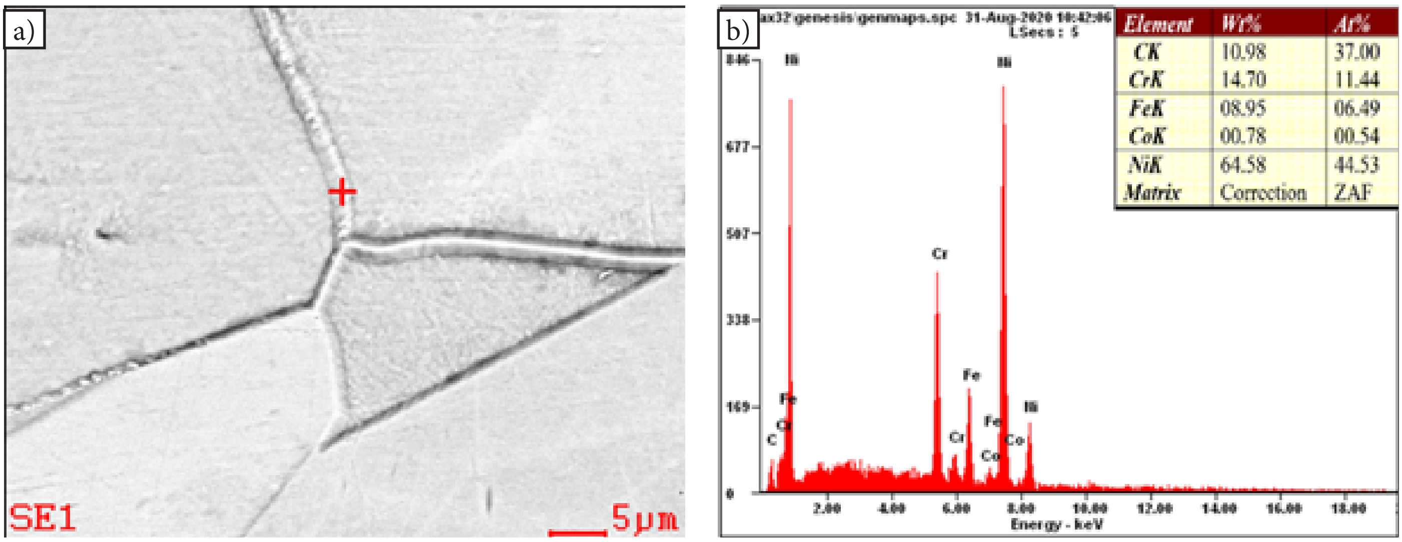


Fig. 10. Results of the microanalysis of the joint made of superalloy Inconel 600; a) weld area subjected to local microanalysis and b) spectrogram with the quantitative analysis of chemical elements

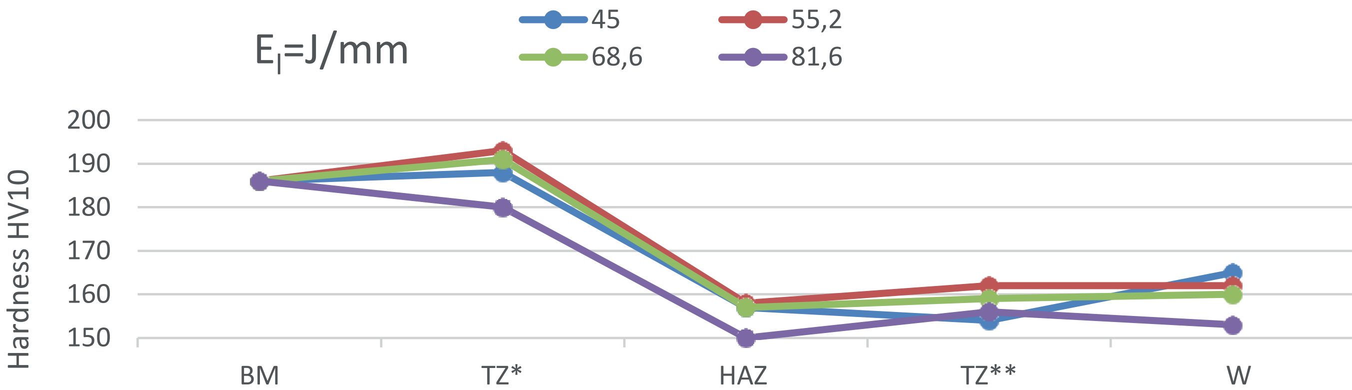


Fig. 11 Effect of welding linear energy on the hardness of the joint made of superalloy Inconel 600: BM- base material, TZ* - BM→HAZ transition zone (interface), HAZ – heat affected zone, TZ** - HAZ → W transition zone (interface), W – weld

parameters on the hardness of the joints made of superalloy Inconel 600 revealed that the minimum and, at the same comparable hardness of the HAZ and of the weld (approximately 150 HV), was identified after welding performed using the maximum arc linear energy (approximately 80 J/mm). Slightly higher hardness values in the above-named areas (by between 10 HV and 15 HV) were determined after welding performed using lower arc linear energy (restricted within the range of 45 J/mm to 55 J/mm) (Fig. 11).

Concluding remarks

The above-presented results of the tests concerning the effect of the TIG method-based butt welding of 1.0 mm thick sheets made of superalloy Inconel 600 revealed the following:

– quality of the thin joints made of superalloy Inconel 600 in laboratory conditions was the highest in relation to welding arc linear energy restricted within the range of approximately 45 J/mm to 80) J/mm,
– increase in welding linear energy within the adopted range led to an increase in the width of the weld and that of the HAZ (in the joints subjected to macroscopic observations),
– increase in welding arc linear energy (within the adopted range) affecting the HAZ increased the size of the grains in matrix γ from approximately 120μm to approximately 200μm,
– structure of the weld contained the zone of columnar grains oriented towards the fusion line as well as large groups of primary dendritic grains with clearly revealed primary axes of variedly oriented dendrites and precipitates

in the form of low-melting eutectics in the interdendritic spaces,
- SEM-based microstructural observations of the joint made of superalloy Inconel 600 and the performance of X-ray microanalysis made it possible to reveal important morphological details of the structural components and identify their chemical composition, indispensable for phase verification.

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