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Original Research

Microstructure and Mechanical Properties of 15CDV6 Steel in TIG-Welded Aircraft Truss Structures

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Abstract

Despite the undisputed dominance of composite materials in the construction of lightweight aircraft, steel structures still find use - especially for engine mounts. Weight reduction of the structure is achieved through the use of tubular trusses, usually made of structural steel for tempering. An increasing number of requirements for this type of construction and the development of steel metallurgy provide the basis for the introduction of new steel grades. This paper presents the testing results of a welded truss made of advanced 15CDV6 steel as a potential replacement for 30HGSA steel. The microstructure and hardness of characteristic zones of TIG-welded joints are discussed, as well as the results of static tensile testing of the parent material and welded joints.

Keywords: airframe, welded tube structure, 15CDV6 steel, microstructure, mechanical properties

1. Introduction

Truss structures are commonly used in general aviation (GA). The design and construction of a frame or aircraft truss places requirements on the designer, primarily in terms of strength, operational reliability, functionality, and the development of such manufacturing technology that the listed requirements and criteria are met. The fundamental problem to be solved is to design and manufacture it in such a way that it can be reasonably executed. The developed structure of the truss, especially the engine mount (Fig. 1), must carry loads resulting from the external load spectrum of the aircraft, as well as loads resulting from internal thermal displacements.

Fig. 1. GA class aircraft engine mount frame.

Aerial truss structures are basically made of tubes with a circular cross-section, with outside diameters of up to 25 mm and wall thicknesses of 1 to 2 mm. Connections of pipes into a complete assembly are made by welding the interconnected tubes together to eliminate the gusset plates, thus reducing the weight of the structure. The use of such a concept requires the introduction of nodes connecting 2 to 9 elements (Fig. 2).

Fig. 2. Examples of aircraft truss nodes.

In the vast number of cases, the structure is statically non-determinable and effective determination of the forces in the individual bars is possible using the FEM method. This is due to their complex shape and the weld lines dictated by welding considerations, as well as the shaped ends of the bars.

Obtaining adequate load-bearing capacity of the structure requires the use of a material with high strength properties and good weldability. Past solutions have used 30HGSA structural steel, where the structure required heat treatment after welding. In many cases, this was very difficult due to the dimensions of the structure and its thermal deformation. In the design work carried out, 15CDV6 steel (1.7734 grade) was used, characterized by good weldability in the tempered state while providing high strength.

The 15CDV6 steel is considered as a high-strength low alloy and low carbon (Technical data of 15CDV6 steel, 2024) bainitic steel (Bandyopadhyay et al., 2012). Since the 1980s, it has increased in importance, especially in the aerospace, defence, and power generation industries (Sreekumar et al., 1982). The 15CDV6 steel in the hardened and tempered condition (austenitized at 980°C and quenched in oil, tempered at 650°C and quenched in oil) can reach a tensile strength of 1175 MPa, a yield strength ($R_{p0.2}$) of 980 MPa, and a hardness of 39 HRC. Its microstructure in quenched condition is composed of a mixture of lower bainite and martensite laths (Bandyopadhyay et al., 2012). According to Young and Bhadeshia (1994), the maximum strength of this steel is provided by the large volume fraction of tempered martensite (around 0.75). Increasing the fraction of martensite in a mixed martensite-bainite microstructure requires the addition of alloying elements to retard the bainite reaction (especially carbide forming elements, which greatly retard ferrite-pearlite transformation - chromium, in particular) therefore, research is being conducted on modifying the chemical composition of 15CDV6 steel, such as through the electroslag remelting process (ESR) (Bandyopadhyay et al., 2012; Srinivasan et al., 2017).

Improving the mechanical properties of the material should not result in a decrease in its technological properties. Chandra Sekhar et al. (2014) indicated that the use of ESR modification of 15CDV6 steel (causing an increase in its carbon content) does not preclude its welding. The 15CDV6 steel can be gas tungsten arc welded (GTAW) (Chandra Sekhar et al., 2014; Naveen Kumar et al., 2014; Srinivasan et al., 2017). Good quality joints were obtained using the TIG method, without the necessity for any post weld heat treatment (Srinivasan et al., 2017). The possibility of welding 15CDV6 steel with other steels has also been demonstrated (Naveen Kumar et al., 2014). Ramesh et al. (2015) successfully laser beam welded (LBW) this steel in the quenched and tempered condition.

Good plasticity of 15CDV6 steel makes it possible to cold shape tubes from it (e.g., by flow forming – Podder et al., 2011). This work includes the potential for" making aerospace tubular structures from 15CDV6 steel, instead of the commonly used 30HGSA steel. The results of studies of the microstructure and mechanical properties of welded joints are presented herein.

2. Materials and experimental methods

Welded tube nodes (Fig. 3) were made of 15CDV6 steel (Table 1) in tempered condition (1.7734.5 – acc. Technical data of 15CDV6 steel, 2024). Tubes of 22×2, 18×1, and 16×1 mm (diameter × thickness) and flat specimens (Fig. 4) were TIG welded without forced cooling. Welding parameters adopted:

- automatic feeding of cold wire,
- welding speed – 5 cm/min,
- welding arc voltage – 8.4 V,
- DC current – 50 A,
- wire feeding speed – 0.7 m/min,
- wire feeding delay of 1 s,
- shortening of wire feeding in final stage – 1 s,
- type and flow rate of shielding gas – Ar = 7 dm^3/min with 99.995% purity,
- diameter and material type of non-melting tungsten electrode – WL15 with 1.5% lanthanum content and d = 1.6 mm,
- diameter and type of secondary material (binder) – d = 1.2 mm, 15CDV6 steel wire,
- heat input – 36 J/mm.

The correctness of the adopted welding parameters was confirmed by visual, magnetic particle, and radiographic inspections. Welding and inspection processes were performed in the R&D Department at SZEL-TECH.

Table 1. Chemical composition of 15CDV6 steel.

Element	C	Si	Mn	S	P	Cr	Mo	V
Content, wt.%	0.12-0.18	≤0.20	0.80-1.10	≤0.015	≤0.020	1.25-1.50	0.80-1.00	0.20-0.30

a) b) c)

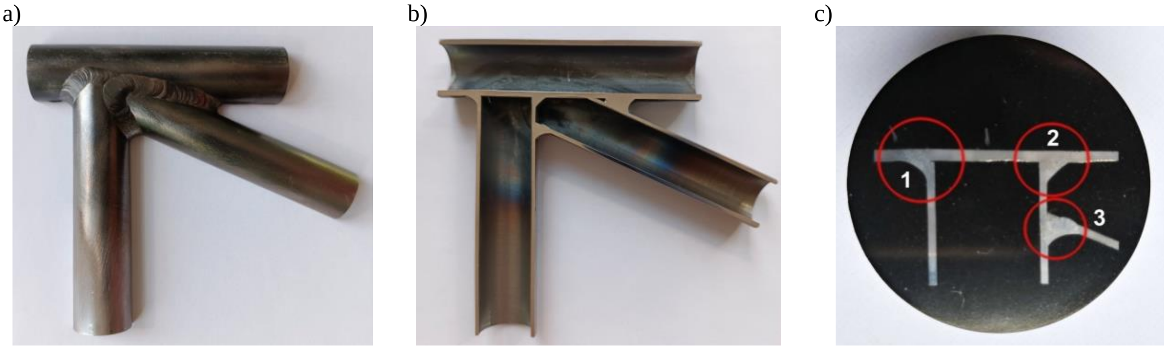

Fig. 3. Truss node made by welding from 15CDV6 steel: a) view of the node, b) cross-section with marked area subjected to microscopic examination, c) marking of welds.

The research was carried out in the Department of Materials Science at the Rzeszów University of Technology. Specimens for microscopic examination were cut with an Accutom-50 a precision cutter and encapsulated in Bakelite (PolyFast™) using a Struers CitoPress-5 device. They were ground and polished using standard methods. Metallographic deposits were etched with Nital reagent (2-5 ml HNO_3, 100 ml C_2H_5OH). Observations of the microstructure were carried out using a Leica DM3000 light microscope, equipped with a digital image recording system.

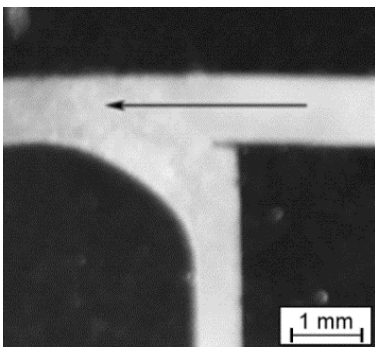

Fig. 4. Line of hardness measurements on weld cross-section 1 (as marked on Fig. 3c).

The hardness of the weld was measured using the micro-indentation method with an Innovatest Nexus 4303 micro-hardness tester. The Vickers method and a load of 0.5 kgf (4.9 N) were used. Measurements at a distance of approximately 0.3-0.5 mm were taken on the weld's cross-sectional area 1 (Fig. 3) - along a straight line, from the parent material, through the heat affected zone, to the weld metal (Fig. 4).

The mechanical properties of 15CDV6 steel and steel welded joints were determined by static tensile testing. Tensile tests at room temperature were conducted according to PN-EN ISO 6892-1:2020. Aircraft engine frame components may undergo local heating, which may affect their mechanical properties. Therefore, a tensile test at 200°C of parental material was also carried out, conducted according to PN-EN ISO 6892-2:2011, ISO 204:2023, ASTM E21-20, and ASTM E139-11. Flat specimens were used for mechanical properties testing (Fig. 5) – cut from 2.5 mm thick plate parallel to the rolling direction.

a)

b)

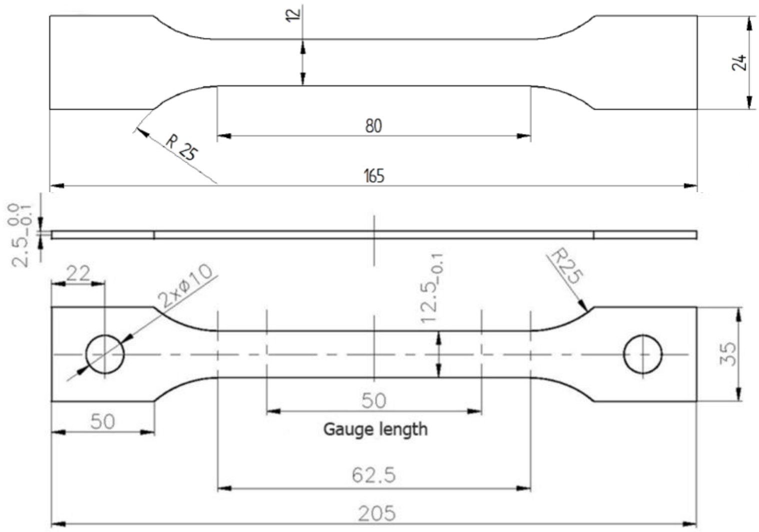

Fig. 5. Dimensions of tensile specimens at room temperature (a) and 200°C (b).

3. Results and discussion

3.1. Microstructure

3.1.1. Parent material

Light microscopy examinations indicate that the microstructure of the 15CDV6 steel is banded, resulting from the tube manufacturing process (most likely during the cold drawing process) (Fig. 6a). The microstructure of the steel, taking into account its condition - tempered - does not have features typical of high-tempered martensite. Considering the chemical composition of the steel under study (Table 1), as well as the results of other studies (Naveen Kumar et al., 2014; Ramesh et al., 2015), it cannot be ruled out that its microstructure is the result of both bainite and martensite tempering – the mixture of ferrite and cementite (Fig. 6b).

a) b)

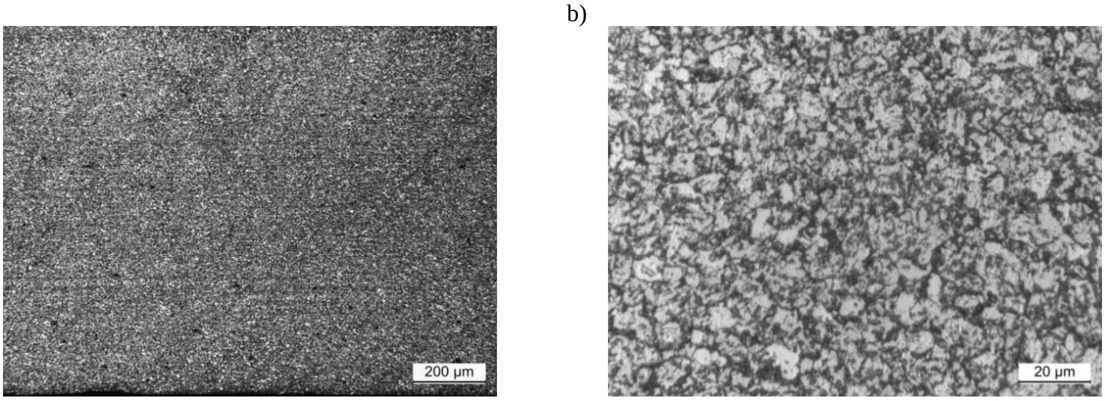

Fig. 6. Microstructure of 15CDV6 steel (longitudinal cross-section) – a) banding of phase constituents, b) the mixture of ferrite and cementite.

3.1.2. Weld

The microstructure of welded joints is characterized by a gradient resulting from the existence of a small (< 1 mm) heat-affected zone (HAZ) between the parent material and the weld metal zone (Fig. 7a, 8a, and 9a). In the HAZ zone, further tempering of the steel should occur, although once the A_{c1} temperature is exceeded (during welding) and after re-cooling, pearlitic transformation is possible. (Fig. 8b).

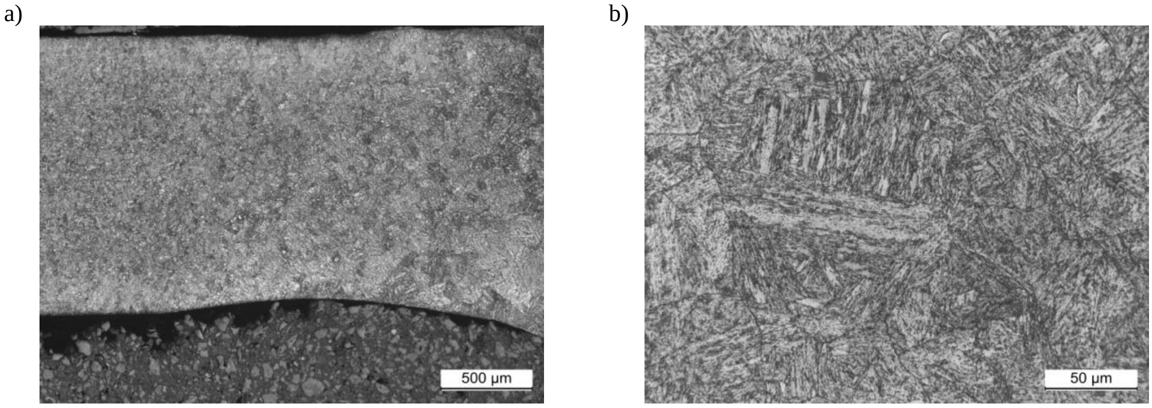

Fig. 7. Microstructure of weld 1: a) HAZ between parental material (left) and b) weld metal.

In the weld metal zone of all welds studied, a similar morphology of the phase components of the microstructure was identified (Figs. 7b, 8c, and 9b). As a result of the remelting of the 15CDV6 steel during welding and the fast crystallization during cooling, martensitic transformation is possible (Naveen Kumar et al., 2014; Srinivasan et al., 2017) – the needle-like character of the microstructure seems to confirm this. Unambiguous phase identification requires the use of other test methods, such as X-ray diffraction (XRD).

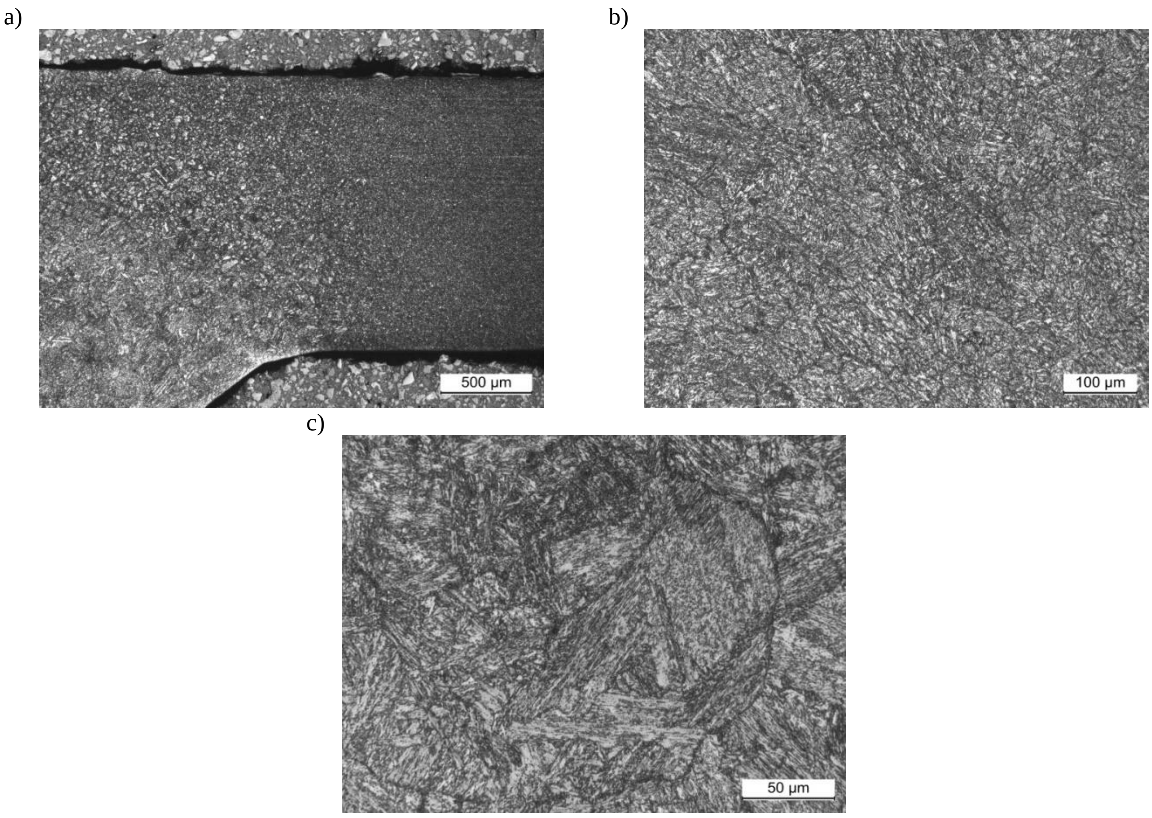

Fig. 8. Microstructure of weld 2: a), b) HAZ between parental material (right) and c) weld metal zone.

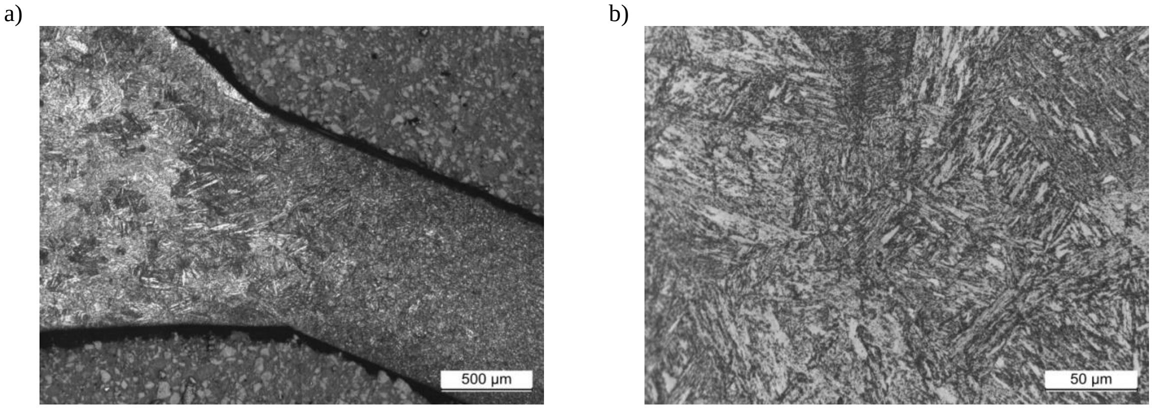

Fig. 9. Microstructure of weld 3: a) HAZ between parental material (right) and b) weld metal zone.

3.2. Hardness

Analysis of the results of hardness measurements of the selected welded joint of the tube junction (Figs. 3c and 4) indicates that the hardness of the parent material (points 1-4 – Table 2 and Fig. 10) is about 365 HV0.5 (37 HRC according to the hardness conversion table). It can be assumed that the hardness of the HAZ (point 5 – Table 2 and Fig. 10) is about 400 HV0.5, while the weld metal zone (points 6-12 – Table 2 and Fig. 10) is about 430 HV0.5 (44 HRC). The high variability of the results in the weld metal zone is due to the inhomogeneity of the microstructure, which significantly determines the results of hardness measurements obtained by the micro-indentation method. The hardness results obtained for the parent material and HAZ are similar to those presented by Ramesh et al. (2015) –however, they showed a higher hardness of the weld metal zone (about 480 HV/48 HRC) using a different welding method (LBW). The TIG method was used by Naveen Kumar et al. (2014) – they obtained a similar result (about 45 HRC), although they welded 15CDV6 steel in its softened state (<20 HRC). Moreover, the authors of this publication explain the hardness increase in this zone not only by the presence of martensite but also that of carbides –Mo_2C and VC.

Table 2. Results of hardness measurements in weld cross-sectional area 1 (Technical data of 15CDV6 steel, 2024).

Measurement No	1	2	3	4	5	6	7	8	9	10	11	12
HV0.5	367	349	381	363	400	441	440	424	412	445	431	441

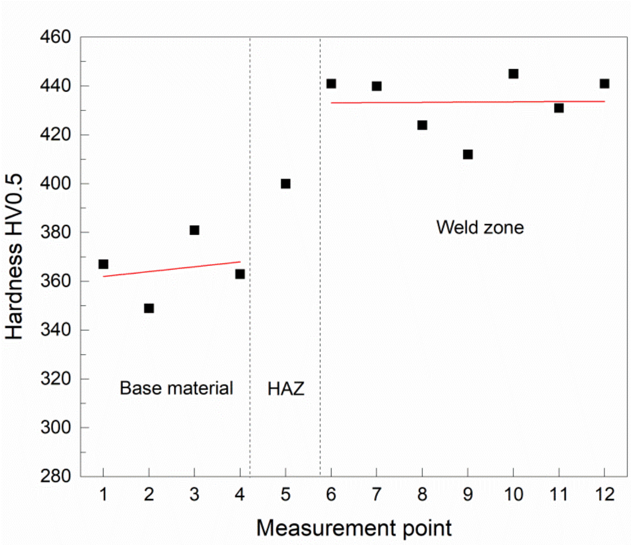

Fig. 10. Hardness profile measured on weld cross-section 1 (as marked on Fig. 3c).

3.3. Tensile properties

Frames used in aerospace structures have complex structures and are heavily loaded. They require high strength under static and variable loads, high rigidity, and the ability to be shaped in such a way as to be functional. The introduction of new structural solutions requires the use of acceptable technologies in aeronautical structures. In light of the above requirements, it is advisable to use the technology of joining individual frame elements using welding and heat treatment technologies that guarantee high strength properties. This also, or even primarily, applies to the material used. The structural steel used is usually heat-treatable steel - most often 30HGSA. Its substitute proposed in this work - 15CDV6 steel - is characterized by similar mechanical properties (Table 3). In addition, it was assumed that a properly performed welding operation allows for the preservation of the 15CDV6 steel's high strength properties without additional heat treatment. To reduce the thermal deformation produced during the high-temperature joining process, a special welding jig developed by SZEL-TECH was used.

Table 3. Ultimate tensile strength (UTS) and elongation of examined steels.

Material	UTS, MPa		Elongation A_{20}, %
	Required*	Measured	Required*
30HGSA	1080-1280	1095	7.1-8.1
15CDV6	980-1180	1178	10.1-10.7

*Required by the PN-EN ISO 6892-2:2011, ISO 204:2023, ASTM E21-20, and ASTM E139-11 standards

The results of mechanical tests at room temperature showed that the ultimate tensile strength of butt (weld at an angle of 90° to the tensile direction) and lap welded joints matches that of the parent material (Fig. 11).

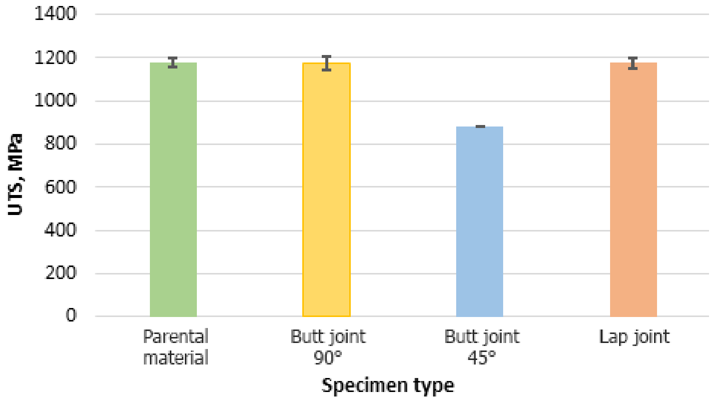

Fig. 11. Ultimate tensile strength of 15CDV6 steel welds.

In testing the mechanical properties of 15CDV6 steel at 200°C, a high reproducibility of the results was obtained (Table 4). There was an approximate 20% reduction in UTS and a slight increase in ductility compared to room temperature (Table 3). Rupture of the specimens occurred in the middle part of the gauge length. The results show that the mechanical properties of welded joints remain high when the operating temperature of the structure is increased.

Table 4. Tensile properties of 15CDV6 steel at 200°C.

Material	Yield strength, MPa		UTS, MPa		Elongation A_{50}, %	
	Measured	Average (standard deviation)	Measured	Average (standard deviation)	Measured	Average (standard deviation)
15CDV6	864	862.8 (3.4)	936	936.0 (3.7)	10.5	11.13 (0.48)
	866		941		11.5	
	858		932		11.0	
	863		935		11.5	

4. Conclusions

15CDV6 steel in the tempered state is a highly weldable material. In the weld metal zone, martensite is formed in the microstructure of the steel with a higher hardness (about 430 HB) compared to the parent material (about 365 HB). Despite the observed difference in hardness in the micro-areas of the welds, like the propensity of the steel to brittle fracture, no cracks were observed in the entire weld volume after TIG welding tests at different cooling rates. The welded joints produced are of very high quality, qualifying them for Group B according to the PN-EN ISO 5817:2007 standard, so they can be used in the production of high priority components - including aerospace.

Based on the analysis of the research results obtained, the following conclusions were made:

- TIG welding process have been performed successfully to join the 15CDV6 steel tubes,
- The TIG process can achieve less heat input and small HAZ compared to other methods used in aviation, e.g. MIG) – this leads us to believe that the thermal stresses near the weld are not high,
- the gradient microstructure of a welded joint is typical of structural steels for tempering,
- the relatively small differences in hardness between the parent material, the HAZ, and the weld metal zone make it reasonable to believe that the resulting joints will effectively and reliably transfer the load between the components of the tubular aerospace structure.

Acknowledgments

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Mikrostruktura i Właściwości Mechaniczne Stali 15CDV6 w Lotniczych Konstrukcjach Kratownicowych Spawanych Metodą TIG

Streszczenie

Pomimo niekwestionowanej dominacji materiałów kompozytowych w budowie lekkich pojazdów latających, konstrukcje stalowe nadal znajdują zastosowanie – szczególnie do mocowania silnika. Redukcję masy konstrukcji uzyskuje się poprzez zastosowanie kratownic rurowych, zwykle wykonanych ze stali konstrukcyjnej do ulepszania cieplnego. Zwiększone wymagania dla tego typu konstrukcji oraz rozwój metalurgii stali stanowią podstawę do wprowadzenia nowych gatunków stali. W artykule przedstawiono wyniki badań spawanej kratownicy wykonanej z zaawansowanej stali 15CDV6, jako potencjalnego zamiennika gatunku 30HGSA. Omówiono mikrostrukturę i twardość charakterystycznych stref złączy spawanych metodą TIG. a także wyniki statycznej próby rozciągania materiału rodzimego oraz połączeń spawanych.

Słowa kluczowe: płatowiec, spawane konstrukcje rurowe, stal 15CDV6, mikrostruktura, właściwości mechaniczne