ARCHIVES
of
FOUNDRY ENGINEERING
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 10
Issue Special1/2010
371-376

72/1

# Vacuum brazing of TiAl48Cr2Nb2 casting alloys based on TiAl ($\gamma$) intermetallic compound

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Received 05.03.2010; accepted in revised form 23.03.2010

## Abstract

A growing interest in modern engineering materials characterised by increasingly better operational parameters combined with a necessity to obtain joints of such materials representing good operation properties create important research and technological problems of today. These issues include also titanium joints or joints of titanium alloys based on intermetallic compounds. Brazing is one of the basic and sometimes even the only available welding method used for joining the aforesaid materials in production of various systems, heat exchangers and, in case of titanium alloys based on intermetallic compounds, turbine elements and space shuttle plating etc. This article presents the basic physical and chemical properties as well as the brazability of alloys based on intermetallic compounds. The work also describes the principle and mechanisms of diffusion-brazed joint formation as well as reveals the results of metallographic and strength tests involving diffusion-welded joints of TiAl48Cr3Nb2 casting alloy based on TiAl (γ) phase with the use of sandwich-type layers of silver-based parent metal (grade B- Ag72Cu-780 (AG 401)) and copper (grade CF032A). Structural examination was performed by means of light microscopy, scanning electron microscope (SEM) and energy dispersion spectrometer (EDS). Furthermore, the article reveals the results of shear strength tests involving the aforementioned joints.

**Key words:** diffusion brazing; intermetallic compound; casting alloy; microstructure; shear strength.

## 1. Introduction

Fast-developing aviation, automotive and power-generation industries are increasing demand for new engineering materials which could resists such extreme operation conditions as high operating temperature, considerable stresses or operation in fume-affected environment. Highly desirable properties of such materials should include high hardness and strength, corrosion resistance (also when exposed to aggressive fumes) but also, first of all, low density. The application of engineering materials combining all these features would ensure long and failure-free life of components used in equipment and machinery operating under most adverse conditions.

Since mid-1990's it has been possible to observe an increasing interest in titanium alloys based on Ti-Al-type, particularly $Ti_3Al$ ($\alpha_2$) and TiAl ($\gamma$), ordered intermetallic phases as well as that in duplex alloys containing both of the aforementioned phases [1,2]. Such alloys form a new generation of metals (also known as "intermetallics"), combining the properties of metals and ceramics, thus characterised by corrosion- and heat-resistance, high-temperature creep resistance, high hardness, and yet, by low density. The most popular of Ti-Al compounds is phase $\gamma$ (TiAl) characterised by high melting point (1460 °C), relatively low density ($3.8 \cdot 10^3$ kg/m3), high relative strength, high creep and oxidation resistance and no susceptibility to spontaneous combustion, disadvantageous feature of technical titanium. The aforesaid phase is also characterised by high hardness and low plasticity – its elongation at ambient temperature stands at mere $1 \div 3$ % and decreases significantly in presence of even slight impurities. In addition, TiAl phase ($\gamma$) undergoes significant grain growth, which in practice, impedes or even renders treatment impossible. For this reason, in most cases it is its casting alloys that find technical application. In order to improve the properties of TiAl phase (γ) its alloys are usually added with three groups of elements improving plasticity (chromium, manganese and vanadium), high-temperature creep resistance and corrosion resistance (niobium, tantalum, tungsten and molybdenum) and those causing grain size reduction (boron, carbon, silicon, oxygen and lanthanides).

The industrial application of any structural materials requires the latter to be subject to various technological processes e.g. joining into a functional whole. As there is no practical possibility to weld casting alloys based on intermetallic compounds, brazing of the former appears to be the most promising and, in some cases, the only welding-like joining method.

Similarly as in case of technical titanium and its conventional alloys, the casting titanium alloys based on intermetallic compounds are difficult to braze [3-6]. One of the most convenient technical method used for joining these increasingly popular structural materials characterised by advantageous specialist properties is diffusion welding. This method, combining the qualities of brazing and diffusion welding, is usually referred to as ”a brazing process, in which the mechanism of braze formation is based predominantly on the phenomenon of diffusion between joined materials and a brazing filler metal” or as ”a brazing process, in which the phenomenon of diffusion is decisive for the chemical composition and physical properties of a braze obtained by melting an added brazing filler metal or an alloy formed on the contact point of joined elements” [3-7]. The above definitions divide diffusion brazing into two types. In the first type the filler metal is supplied from the outside and a liquid brazing filler metal is formed as a result of the mutual diffusion of components of the filler metal and the parent metal. The other type consists in brazing without a filler metal supplied from the outside. A braze-forming liquid brazing filler metal is formed in the contact point of joined materials as their specific components undergo mutual diffusion. Such a phenomenon occurs only in case of material systems whose components (or the materials themselves) form phase equilibrium systems with a eutectic mixture or continuous solid solution with a minimum on the liquidus curve. It is then that an alloy of eutectic composition or solid solution composition with a minimum constitutes a brazing filler metal [3-7].

Depending on the mechanism of formation and structure of a brazed joint, diffusion brazing can be divided into low- and high-temperature brazing. In the former, as a result of diffusion of the components of brazing filler metal and those of joined material one may observe the generation of intermetallic phases of melting points higher than that at which the brazing process is conducted (Fig, 1). In the latter case, the brazing process is performed in such a manner that the joint is free from intermetallic phases and the joint area is a solid solution [17].

The analysis of available scientific and technical publications reveals that the problem of diffusion welding of titanium, and, in particular, of its casting alloys based on intermetallic compounds, has not been sufficiently investigated and is presented only generally [3-7,9].

This work contains the results of tests concerned with diffusion brazing of TiAl48Cr2Nb2 casting alloy based on TiAl (*γ*) phase [15]. The research aimed to determine the impact of material and technological parameters of diffusion brazing conditions on structure and mechanical properties and thus to develop the most convenient technological conditions of joining.

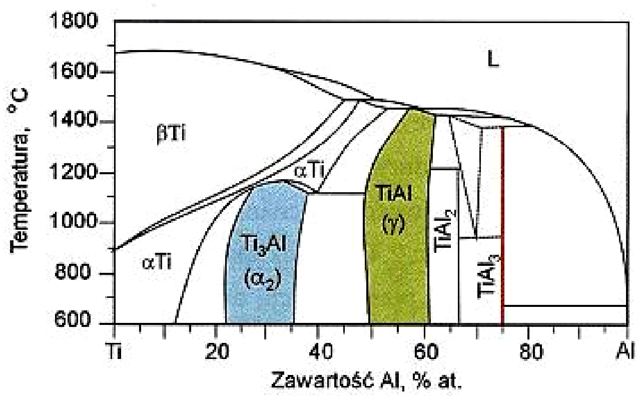


Fig.1. Ti-Al equilibrium system [1]

# 2. Own research

## 2.1. Parent and filler metals used in tests

The tests involved the application of cast rollers (∅ 13 x 120 mm) made of an TiAl48Cr2Nb2 alloy based on phase TiAl (γ) (max. content of impurities C, S and Si 0.6%).

The filler metals used for interlayers in diffusion brazing of the aforesaid casting alloy were eutectic silver-based filler metal (grade B-Ag72Cu-780 (AG 401)) acc. to PN-EN 1044 and copper grade (CF032A) acc. to PN-EN 1412.

## 2.2. Production of test joints

The samples used for shear tests and structural examination of brazed joints of TiAl48Cr2Nb2 alloy were cylindrical in shape (∅ 13 x 12 mm). The elements of butt-brazed joints were placed freely coaxially in the vertical position. This type of sample (cylindrical) supported by appropriate fixture makes it possible to perform pure shear of a brazed joint in strength tests.

In order to increase the faying surface and diffusion length of the components of parent metal and interlayer, prior to brazing the surfaces of the elements were subject to grinding with abrasive paper of the final designation of 800. Directly before brazing the elements were first etched in hydrofluoric acid and nitric acid solutions, and then in NaOH solution. Shape-matched to joint, the interlayers of copper foil and those of brazing filler metal (grade B-Ag72Cu-780) were degreased in acetone and placed (two samples of the total thickness of 0.1mm) between joined elements.

All the samples were brazed in vacuum (range: $10^{-4}\div10^{-5}$ mbar) in S 16 TORVAC-made vacuum furnace.

The brazing temperature and time were determined on grounds of available reference publications and through the analysis of phase titanium-copper interaction on the basis of their phase equilibrium systems [3-14]. In case of the copper interlayer the applied brazing temperature amounted to 1000 and 1050 °C, whereas joints made with B-Ag72Cu-780 alloy were produced at 850, 900 and 950 °C. In all cases the hold time was between 1 and 30min. For comparison purposes one brazing process was performed using nickel for an interlayer. It is advisable that due to the sensitivity of intermetallic phase γ-based alloy to the generation of brittle phases containing interlayer components, the hold time at brazing temperature should be relatively short.

In each case heating up to the brazing temperature was performed with 20-min-long isothermal holding at 700 °C in order to conduct desorption of gases from the surface of brazed elements and obtain the same temperature throughout the samples.

The visual inspection of obtained joints revealed their good quality in case of joints produced with B-Ag72Cu-780 interlayer at 850, 900 and 950 °C and with copper interlayer at 1000 and 1050 °C. It was also ascertained that the application of longer hold time (20 ÷ 30 min) resulted in complete reacting of interlayer metal with the base of the parent metal and formation of a very brittle braze of shear strength amounting to several MPa. In turn, the samples of TiAl48Cr2Nb2 alloy brazed using nickel as an interlayer completely failed to form a joint.

## 2.3. Structures of brazed joints of TiAl48Cr2Nb2 casting alloy

The samples for microscopic metallographic examination were subject to grinding with abrasive paper of denotation of 80, 320, 1000 and 2500 and next to polishing by means of polishing cloth with an addition of diamond and corundum polishing slurries of grain sizes of 3 and 0.05 μm respectively.

The metallographic examination involved the joints which, while subject to parallel conducted mechanical tests, demonstrated the highest strength properties.

The microstructure of the brazed joints was revealed through etching of the samples in the water solution of $FeCl_3$. The metallographic examination was carried out in the bright field using a Leica-manufactured metallographic light microscope MeF4A; the metallographic examination of brazed joints of TiAl48Cr2Nb2 alloy was performed both for the joints brazed using the interlayers of copper and those of B-Ag72Cu-780 alloy. The microstructural examination revealed significant morphological differences of joint structures in case of the joints produced using B-Ag72Cu-780 alloy as the interlayer. The aforesaid differentiation was manifested by an increase in the width of diffusion layers of the joints corresponding to increasing temperature and hold time (Table 4). In case of the joints produced using the copper interlayer, the structural morphology did not reveal significant changes related to temperature and hold time at brazing temperature (Table 5). Due to the elaborate structure of the joints it was necessary to conduct additional microstructural examination by means of an electron microscope with the analysis of the chemical composition of individual components of the structure. The results concerning the joint made with B-Ag72Cu-780 brazing filler metal are presented in Tables 6 and 7, whereas those related to the joint produced with copper as brazing metal are provided in Tables 8 and 9. The metallographic tests were conducted by means of a Hitachi-made SEM VP S-3600N scanning electron microscope (SEM) with variable vacuum, collaborating with an energy-dispersive X-ray spectroscope (EDS) manufactured by THERMO NORAN and equipped with a System Six analyser. The surface of plane sections of the joints was observed using secondary electron image (SEI) and backscattered electron image (BSE) technologies. The SEI images present the structural topography whereas the BSE ones reveal differences in the chemical composition of phases.

The test results related to the structure and chemical composition of the individual structural components reveal the complex chemical composition of individual phases and highly diversified structure of diffusion layers, particularly in the line of alloying and mutual diffusion of parent metal and brazing filler metal components. It was also possible to observe a strong impact of sulphur pollution on the generation of separate phases with a high sulphur content (up to 4% at. S)

Despite a short hold time (5min) at relatively low brazing temperature (850°C) it is possible to observe that diffusive phenomena dominate in the join formation process. Even the areas close to the axial part of the braze contain elements coming the parent metal (Nb, Cr). This fact indicates considerable dynamics of diffusion and release phenomena proceeding during the brazing process. In order to determine the kinetics of diffusion processes and the impact of individual phases on the strength properties of the joint it is necessary to precisely analyse the chemical composition of individual phases on the cross-section of the braze and those on the fractograph of the joints; the aforesaid analysis following the shearing test

Table 4. Microstructure of diffusion-brazed TiAl48Cr2Nb2 alloy joints with B-Ag72Cu-780 interlayer

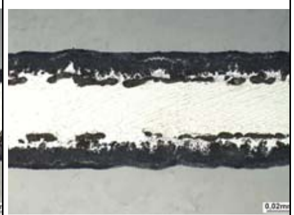
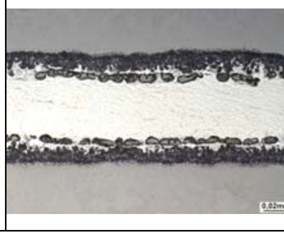
| Temp °C | Brazing time | |
|---|---|---|
| | 1 min | 5 min |
| 850 |  |  |
| 900 |  |  |
| 950 |  |  |

Table 5. Microstructure of diffusion-brazed TiAl48Cr2Nb2 alloy joints with copper interlayer

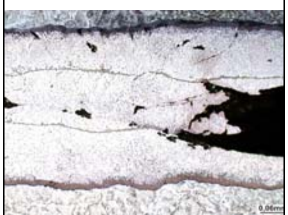
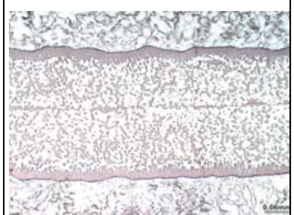
| Temp °C | Brazing time | |
|---|---|---|
| | 1 min | 5 min |
| 1000 |  |  |
| 1050 | No joint obtained |  |

Table 6. Microstructure of TiAl48Cr2Nb2 alloy joint brazed with B-Ag72Cu-780 alloy at 850°C for 5 minutes

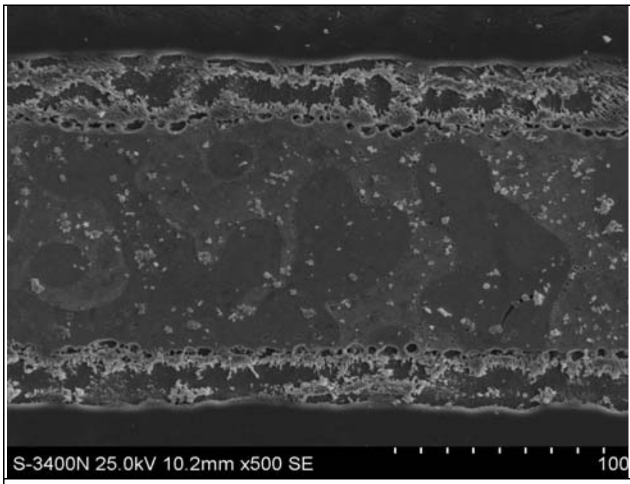
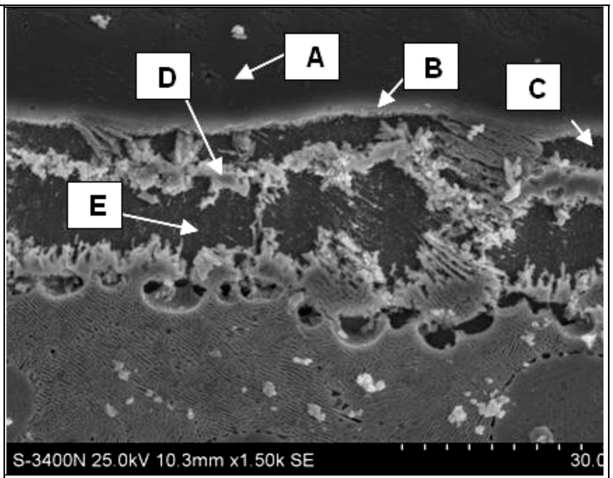
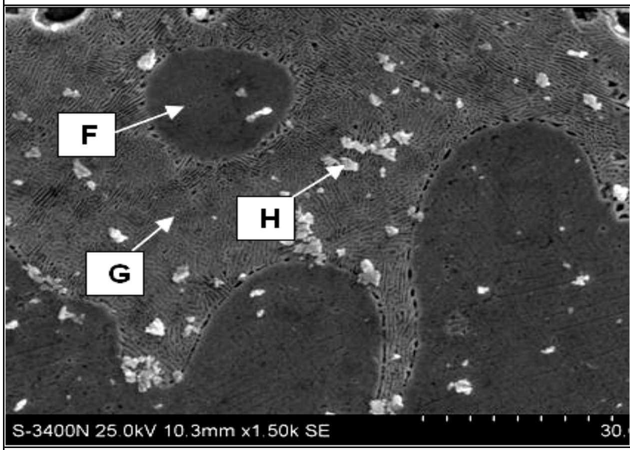
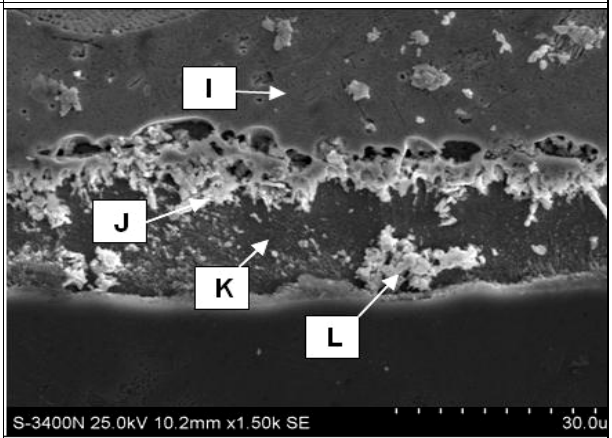
| | |
|---|---|
|  |  |
| Brazed joint | Upper part of joint |
|  |  |
| Central part of joint | Lower part of joint |



Table 7. Results of spectral chemical analysis (EDS) of phases in structure of joint made of alloy based on TiAl (γ) intermetallic phase brazed with B-Ag72Cu-780 filler metal at 850°C (denotation of phases corresponds to phases from Table 6).

| Phase denotation | Chemical composition, % at. | | | | | | |
|---|---|---|---|---|---|---|---|
| | Al | Ti | Cr | Nb | Cu | Ag | S |
| A | 45.7 | 49.6 | 2.6 | 2,1 | – | – | – |
| B | 8.1 | 37.7 | 2.3 | – | 49 | 2.9 | – |
| C | 46.2 | 47.2 | 5.0 | 1,6 | – | – | – |
| D | 5.6 | 4.9 | – | – | 7.9 | 77.3 | 4.3 |
| E | 13.4 | 22.3 | 3.6 | – | 57.6 | 3.1 | – |
| F | 5.0 | – | – | – | 6.1 | 89.0 | – |
| G | 3.7 | – | – | – | 6.1 | 86.0 | 4.3 |
| H | 3.8 | – | – | – | 6.0 | 86.5 | 3.7 |
| I | 3.5 | – | – | – | – | 96.4 | – |
| J | 5.2 | 4.6 | 2.1 | – | 7.1 | 81.0 | – |
| K | 6.1 | 7.1 | 3.2 | 1,0 | 16.6 | 66.0 | – |
| L | 16.5 | 22.4 | 2.5 | 2,0 | 51.8 | 4.8 | – |

## 2.4. Shear strength tests of brazed joints made of titanium and its alloy based on TiAl (γ) phase

The strength properties of brazed cylindrical samples were determined by means of an Instron-manufactured testing machine (model 4210) through shearing the samples in special shearing shackles designed in such a manner that during shearing the samples were exposed to shearing forces only i.e. without bending (Fig. 2) .

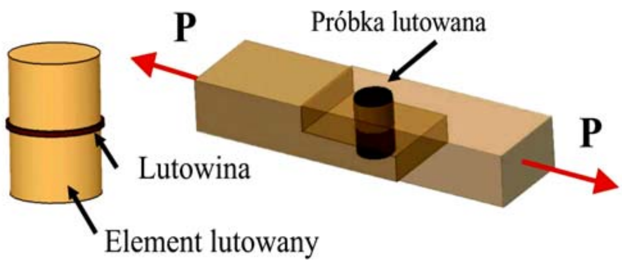
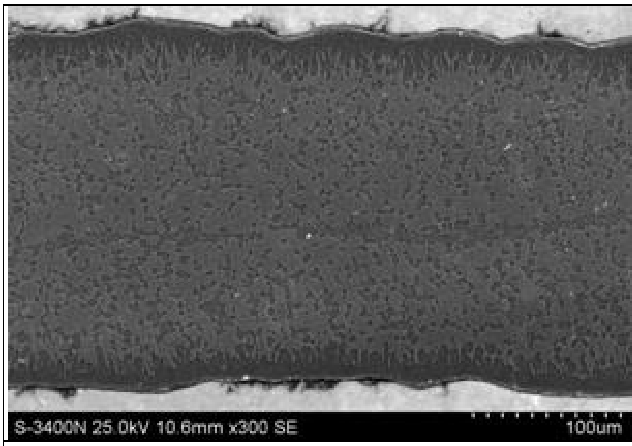
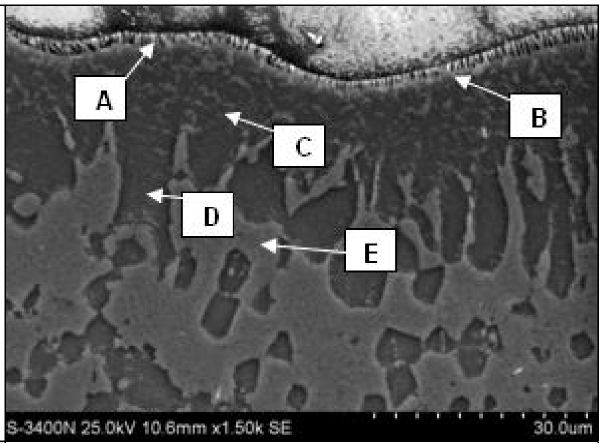



Fig. 2. Sample for static shearing test

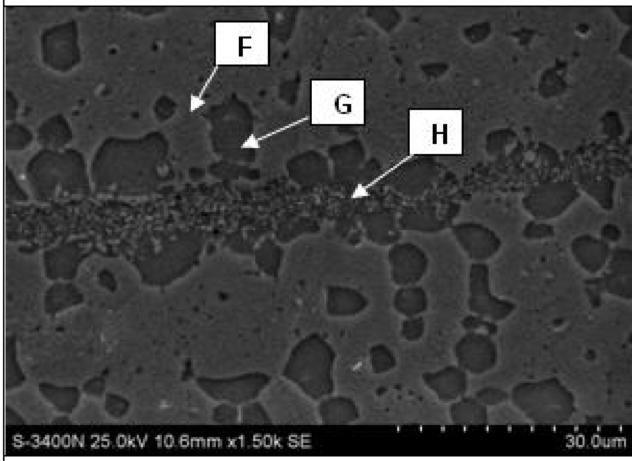
Table 8. Microstructure of brazed joint made of TiAl48Cr2Nb2 alloy with copper at 1050°C for 5 minutes and chemical composition of individual elements of structure



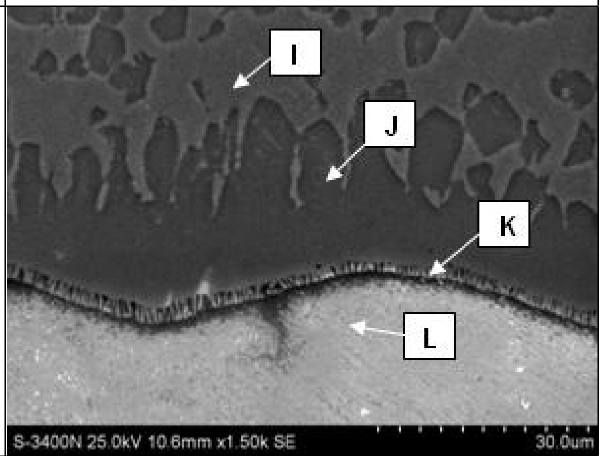
Brazed joint



Upper part of joint



Central part of joint



Lower part of joint

Table 9. Results of spectral chemical analysis (EDS) of phases in structures of joint made of alloy based on TiAl (γ) intermetallic phase brazed with copper filler metal at 1050°C (denotation of phases corresponds to phases from Table 8)

| Phase denotation | Chemical composition, % at. | | | | |
|---|---|---|---|---|---|
| | Al | Ti | Cr | Nb | Cu |
| A | 44.2 | 47.9 | 2.5 | 1.8 | 3.5 |
| B | 41.3 | 43.6 | 1.8 | 2.0 | 11.3 |
| C | 31.0 | 34.6 | 1.6 | 1.3 | 31.4 |
| D | 28.0 | 33.5 | 1.8 | 1.6 | 35.1 |
| E | 28.0 | 32.7 | 2.6 | 1.5 | 35.2 |
| F | 21.6 | 26.1 | 0.4 | — | 51.8 |
| G | 28.5 | 30.8 | 2.9 | 3.2 | 34.5 |
| H | 26.0 | 31.0 | 2.9 | 2.9 | 37.4 |
| I | 21.5 | 26.0 | 0.4 | — | 52.0 |
| J | 28.3 | 31.6 | 2.8 | 1.9 | 35.5 |
| K | 28.3 | 34.6 | 1.9 | 1.4 | 33.7 |
| L | 42.3 | 54.2 | 1.4 | 2.1 | — |

In case of diffusion brazed joints made of TiAl48Cr2Nb2 alloy with the use of copper as interlayer at the process temperature of 1000°C and hold time of 1min the shear strength proved to be very low i.e. did not exceed 30.7 MPa and was even lower i.e. stood at 17.6 MPa for the hold time of 5 min. The joints produced at 1050 °C were characterised by considerably higher strength amounting to 95.3MPa for the hold time of 1min and 77.7MPa for that of 5mins. The obtained results exclude the application of copper as interlayer in the diffusion brazing of TiAl48Cr2Nb2 alloy.

In each test case and combination of material and technological parameters the brazed joints of TiAl48Cr2Nb2 alloy demonstrated similar, inversely proportional dependence of shear strength on hold time at brazing temperature (Fig. 3 and 4). The highest strength was characteristic of the joints brazed with B-Ag72Cu-780 filler metal used as an interlayer. The application of the hold time of 1min at 900°C resulted in obtaining joints of strength amounting to 149MPa. Extending hold time up to 5mins decreased shear strength to mere 69.7 MPa. In turn, the joints produced at 950 °C at the same hold times (1 and 5mins) revealed the sheer strength values of 21.7 and 12 MPa respectively, whereas those brazed at 850 °C reached the values of 137 and 87.7 MPa.

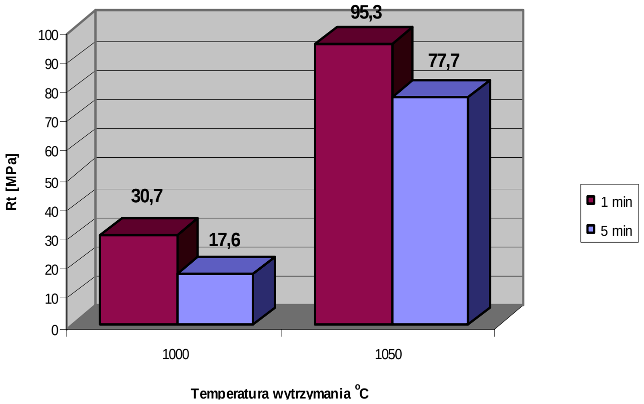


Fig. 3. Shear strength of TiAl48Cr2Nb2 alloy joints produced with Cu foil

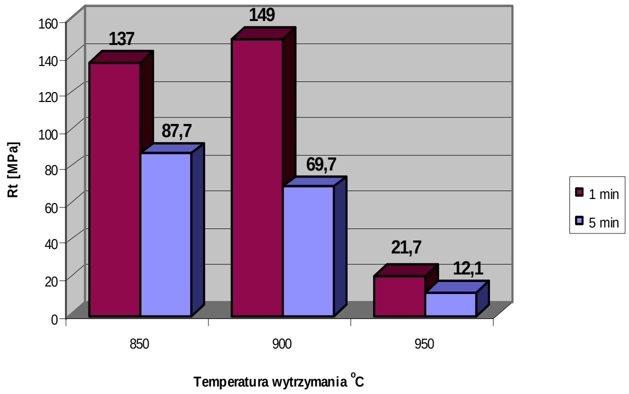


Fig. 4. Shear strength of TiAl48Cr2Nb2 alloy joints produced with B-Ag72Cu-780 filler metal foil

## 3. Conclusions

1. The conducted material and technological tests enabled obtaining qualitatively proper diffusion brazed joints of TiAl48Cr2Nb2 alloy with the use of B-Ag72Cu-780 filler metal interlayers; the applied brazing temperature amounted to 850 ÷ 950 °C with hold time being 1 ÷ 5 min.
2. The highest shear strength of TiAl48Cr2Nb2 alloy joints amounting to 149 MPa was obtained while using B-Ag72Cu-780 filler as interlayer, process temperature of 900 °C and brazing time of 1min.
3. The strength of brazed joints of TiAl - $\gamma$ (TiAl48Cr2Nb2) alloy demonstrates strong dependence on brazing time and temperature.
4. At brazing temperature the components of TiAl48Cr2Nb2 alloy reveal very high activity in relation to interlayer components forming with them intermetallic phases responsible for strength properties of obtained joints.

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