Production Engineering Archives

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)
Exist since 4th quarter 2013
Available online at www.qpij.pl/production-engineering-archives

A brief overview and metallography for commonly used materials in aero jet engine construction

Juraj Belan[1], **Alan Vaško**[1], **Lenka Kuchariková**[1]

[1] University of Žilina, Faculty of Mechanical Engineering, Department of Materials Engineering, Univerzitná 8215/1, Žilina 01026, Slovakia, e-mail: juraj.belan@fstroj.uniza.sk

Article history
Received 16.09.2017
Accepted 23.12.2017
Available online 31.01.2018

Keywords
aluminium alloy
titanium alloy
nickel-base alloys
metallography procedures
B/W and colour contrast

Abstract

Aluminium, titanium, and nickel base alloys are mostly and widely used for aircraft jet engine construction. A proper evaluation of its microstructure is important from working safety point of view. To receive a well prepared sample of microstructure, some important steps have to be undertaken. Except for proper grinding and polishing of a sample, structure developing is a significant step, too. In order to develop microstructure various chemical reagents were used to achieve the best results for microstructure evaluation. The chemical reagents were used according to the previous knowledge and some new ones were also tested. Aluminium AK4-1č, titanium VT – 8, and nickel VŽL – 14 and ŽS6 – U alloys were used as an experimental materials. Alloy AK4-1č is used for fan blade production with working temperatures up to 300°C. It is a forged piece of metal machined down into final shape by five-axe milling machine. Alloy VT – 8 is used for high pressure compressor rotor blade production with working temperatures up to 500°C. Blades are forged as well and finally grinded. Finally nickel base alloys VŽL – 14 and ŽS6 – U are used for turbine blade production with working temperatures up 950°C. Blades for turbine are casted into mould with reducible models.

1. Introduction

A safety and economic factors need to be taken into account while selecting proper materials for airplane construction. There are only a few materials~~,~~ which have satisfactory ratio between low weight and high strength as well as durability in various ways of loading. However, aircraft materials also need to have resistance against surrounding conditions which may vary. The construction materials selection for aircraft industry is extremely challenging and requires a good knowledge of materials characteristics with small scattering of its values.

Aircraft construction materials are divided into two main categories: materials for airplane body construction (Fig. 1a) and jet engine materials (Fig. 1b). Materials for each group have individual requirements such as construction limits defined by mechanical, chemical and as well as heat demands for every single component. For a typical construction, the following limits are considered: weight, Young's modulus, failure strength, fatigue limit, corrosion resistance, and, of course, the price.

Aircraft industry is characterised by a considerable range of airplanes varying mainly in design, size and their purpose, which is linked to costumers' needs and their economic situation. From this standpoint, this segment can be divided into four specific groups: light airplanes, bizjets (or business airplanes), civil airplanes, and military airplanes.

The requirements connected with materials used for light airplanes (Cessna e. g.) construction are not so high, with lower price as the most important one. Quality steel and aluminium alloys are considered to be sufficient materials.

In the case of business airplanes (HAWKER Beechcraft Premier e. g.) material costs are not so significant and that is why, for example, composites with carbon fibre are used.

For civil airplanes (Boeing 747 e. g.) the price should be minimal as well as their weight. However, the issue of safety should not be overlooked. Aluminium alloys and composites are commonly used for body construction.

And finally, the last category includes military airplanes (Boeing F/A 18 e. g.). Working conditions for these airplanes are specific and, therefore, materials used for their production must be of top quality. Composite materials used for the body.

New materials are being constantly invented, which is especially visible in various combinations of composite materials. Taking into consideration materials used nowadays, three main material groups can be distinguished. The first group comprises aluminium alloy, the second - titanium alloys, and third one - Ni-base superalloys.

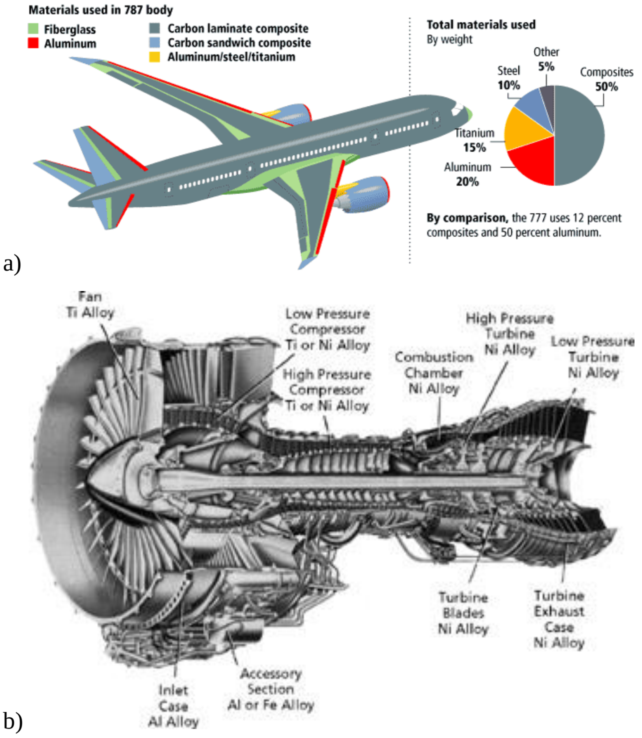


Fig. 1 Overview of materials used at plane body construction (a) and materials used in aero jet engine construction (b) (CAMPBELL F. C. 2006)

Aluminium alloys are used in room temperature and in cryogenic applications. The research focused on further reducing the density, improving the elevated temperature capabilities and the corrosion resistance of the alloys. Titanium alloys are used where lighter aluminium alloys no longer meet strength, corrosion resistance and elevated temperature requirements. A major effort was to increase the service temperature of titanium alloys. Near α type alloys with improved elevated temperature capabilities were introduced and even titanium aluminides are more promising. In the temperature of 800°C these intermetallic have the potential to partly replace Ni-base superalloys. Ni-base superalloys are the primary materials in aero-engines in the environment where high temperature capability and high strength are required. Single-crystal turbine blades represent today's state-of-the-art technology (PETERS M., LEYENS C. 2009). Surely, without the knowledge of structural and mechanical fundamentals progress is impossible. This article is a part of research connected with high loaded materials used for automotive and aircraft industry (BELAN J., ET AL. 2016, TILLOVÁ E., ET AL. 2011, JAMBOR M., ET AL. 2017, ULEWICZ R., TOMSKI P. 2017, KUCHARIKOVÁ L., ET AL. 2017). It considers materials especially used in aero jet engine construction, such as aluminium, titanium, and nickel alloys.

2. Experimental

Aluminium alloy AK4 – 1č, titanium alloy VT – 8, and nickel base alloys VŽL – 14 and ŽS6 – U were used as experimental materials. All these materials two main groups, materials with working temperature up to 500°C, and materials with working temperature over 500°C.

2.1. Materials with working temperature up to 500°C

Over 70% of the structural weight of modern civil aircraft, such as Airbus A330/A340, or Boeing 777, is attributed to high strength aluminium alloys. The attractiveness of aluminium stems from the fact that its price is relatively low. It is also a light metal that can be heat treated to fairly high strength levels, and it is one of the most easily fabricated of high performance materials, which usually correlates directly with lower costs. Aluminium–copper (2XXX series) and aluminium–zinc (7XXX series) alloys are the primary alloys used in airframe structural applications.The2XXXalloys are used in damage tolerance applications, such as lower wing skins and fuselage structure of commercial aircraft, while the 7XXX alloys are used where higher strength is required, such as the upper wing skins. The 2XXX alloys also have a slightly higher temperature capability (572 vs. 482°C) (CAMPBELL F. C. 2006). An aluminium alloy AK4 – 1č (or AK4 – 1) is mechanically worked alloy corresponding to 2XXX grade of aluminium alloys – ASTM AA2618. It is suitable for long time using for temperature up to 300°C. This alloy is used for a production of compressor blades or discs, engine pistons and forged components. Alloy AK4 – 1č has unique mechanical properties which predetermines it for being used in high temperature (in measure of aluminium alloys, of course). The chemical composition can be found in Table 1.

Table 1. AK4 – 1 and AK4 – 1č chemical composition (wt. %). Content of Al is a balance

Alloy	Cu	Mg	Ni	Fe	Si	Zn	Mn	Cr
AK 4 – 1	2.2	1.6	1.25	1.2	max. 0.35	max. 0.3	max. 0.2	max. 0.1
AK4 – 1č	2.0 - 2.6	1.2 - 1.8	0.9 - 1.4	0.9 - 1.4	0.1 - 0.25	0.1	-	0.1

Titanium alloys are used mainly for compressor components (discs, blades, stator blades, driving elements, and engine bonnet). Working temperatures are up to 550°C when an intensive reaction of titanium with oxygen and nitrogen starts. It is necessary to use a protective coating to prevent oxidation (silicon diffusion coating) when titanium alloys are designed to work at higher temperatures (SOKOLOVSKÁ Ž. 1995).

According to some sources, replacing steel with titanium alloys in aero jet engine results in saving components weight around 30-40 % (MOISEYEV V. N. 2006). Titanium is becoming more important as an airframe material. Due to their outstanding resistance to fatigue, high temperature capability and resistance to corrosion, titanium alloys comprise approximately 42% of the structural weight of the new F-22 fighter aircraft, over 4082 kg in all. In commercial aircraft, Boeing 747-100 contained only 2.6% titanium, while a newer Boeing 777 contains 8.3%. New applications for titanium include landing gears, traditionally made from high strength steels. For example, to save weight and eliminate the risk of hydrogen embrittlement, the beta alloy Ti-10V-2Fe-3Al is used for landing gear components in Boeing 777. Titanium alloys are also used extensively in lower temperature regions of jet turbine engines. In commercial aircraft engines titanium alloys are used in the fan, the low pressure compressor, and in about 2/3 of high pressure compressors (CAMPBELL F. C. 2006).

Deformable titanium alloy VT8 is based on the Ti–Al–Mn–Si system. It belongs to two - phase martensite - type ($\alpha + \beta$) - alloys (MOISEYEV V. N. 2006) and its $K_\beta = 0.3$ (MOISEYEV V. N. 2004, SIENIAWSKI J., ZIAJA W., KUBIAK K., MOTYKA M. 2013). The alloy is used mainly as-annealed, but can be subjected to hardening heat treatment (quenching and aging) in small cross-sections of up to 40 mm. Titanium alloy VT – 8 is high strength and hardened alloy with $\alpha + \beta$ phases in microstructure. Temperature of $\alpha \rightarrow \beta$ transformation is 1000°C. Commonly used as a heat resistant alloy, for long time loading at temperature up to 500 °C. VT – 8 titanium alloy is used for rotor blades of high pressure compressor production in DV – 2 jet engine. Chemical composition is shown in Table 2.

Table 2. Chemical composition of titanium VT – 8 alloy

Ti	Al	Mo	Zr	Si	Fe	C	O / H	N
Bal.	5.8 - 7.0	2.8 - 3.8	Max. 0,5	0.2 - 0.4	Max. 0,3	Max. 0.1	0.015	Max. 0.05

2.2. Materials with working temperature over 500°C

There are different processes running in materials at higher temperature. Here are some examples of them:

- increasing concentration of vacancies,
- high speed of diffusion processes (processes controlled by diffusion become more important),
- good possibilities for phase transformations,
- processes related to grain boundary (grain boundaries become more weak, migration of grain boundaries, recrystallization / growing of grains),
- processes related to dislocation movements (dislocation shin up, new slip systems become active, slip system changing),
- over aging and coarsening of precipitates,
- higher oxidation and oxygen penetration at grain boundaries.

For these reasons, unique construction materials, such as nickel base superalloys, are used for construction of most stressed parts of jet engine, namely, turbine blades. Nickel base superalloys were used in various structure modifications, e.g., as cast polycrystalline, directionally solidified, single crystal and in materials produced by powder metallurgy last year.

Superalloys are often divided into three classes, based on the major alloying constituent: iron-nickel-base, nickel-base and cobalt-base. Iron-nickel base superalloys are considered to have developed as an extension of stainless steel technology. Superalloys are highly alloyed and a wide range of alloying elements is used to enhance specific microstructural features (and, therefore, mechanical properties). Superalloys can be further divided into three additional groups, based on the primary strengthening mechanism:

- solid-solution strengthened,
- precipitation strengthened,
- oxide dispersion strengthened (ODS) alloys.

Solid-solution strengthening results from lattice distortions caused by solute atoms. These solute atoms produce a strain field which interacts with the strain field associated with the dislocations and acts to impede the dislocation motion. In precipitation strengthened alloys, coherent precipitates resist dislocation motion. At small precipitate sizes, strengthening occurs by dislocation cutting of the precipitates, while at larger precipitate sizes strengthening occurs by Orowan looping. Oxide dispersion strengthened alloys are produced by mechanical alloying, and they contain fine incoherent oxide particles which are harder than the matrix phase, and inhibit dislocation motion by Orowan looping.

Alloy ŽS6-U is heat resistant nickel base superalloy with significant creep resistance. It is commonly used for turbine blade of first turbine stage production. Its chemical composition is in Table 3.

Table 3. Chemical composition ŽS6 – U alloy (wt. %)

C	Cr	Co	Al	Ti	Mo	W	Nb	Fe	Mn
0.13 - 0.20	8.0 - 9.5	9.0 - 10.5	5.1 - 6.0	2.0 - 2.9	1.2 - 2.4	9.5 - 11.0	0.8 - 1.2	max. 1.0	max. 0.4

Alloy VŽL 14 is also nickel base heat resistance superalloy used for blades of gas turbine production. Its working temperature is up to 800°C. Chemical composition is presented in Table 4.

Table 4. Chemical composition and mechanical properties of VŽL – 14 alloy (wt. %)

C	Cr	Al	Ti	Mo	Fe	Mn/Si	W
0.05 - 0.08	18 - 20	1.2 - 1.5	2.5 - 3.1	4.5 - 5.5	8 - 10	max. 0.4	max. 0.005

2.3. Experimental methods

Selected experimental materials were prepared with regular procedure and etched with various etching reagents. There were etching reagent for black/white and colour contrast used for better description of structural parts. Reagents used are listed in Table 5. Various reagents were used with the aim to describe their effect on materials, and to determine which one is the best to use for revealing structural parameters.

Table 5. Black/white reagents and reagents for colour contrast used for experimental materials evaluation.

Reagents for aluminium alloys etching (KONEČNÁ R. 2010, MICHNA Š., ET AL. 2015)			
Reagent	**Composition**	**Etching**	**Application**
Keller	1.3 ml HF 1.5 ml HCl 2.5 ml HNO_3 95.5 ml dest. water	Immerse for a few seconds till minute.	Developing of microstructure and structure parts recognition of Al alloys.
Dix a Keith	0.5 ml HF 99.5 ml dest. water	Immerse for a few seconds till minute.	Etching of single structural parts of Al alloys.
Tucker	15 ml HCl 5ml HNO_3 5 ml HF 75 ml dest. water	Immerse for a few seconds till minute.	Etching of Al alloys.
Selected reagents for titanium alloy			
10 % fluorhydric acid	10 ml HF 90 ml dest. water	Immerse for a few seconds.	Developing of Ti alloys structure.
Kroll	1,5 ml HF 4 ml HNO_3 94 ml dest. water	Immerse for a few seconds till minute.	Suitable for developing of α + β structure.
	1 ml HF 2 ml HNO_3 50 ml H_2O_2 47 ml dest. water	Immerse for a few seconds till minute.	Most used reagent for common Ti alloys.
Selected reagents for nickel base superalloys			
Kalling's reagent	5 g $CuCl_2$ 100 ml HCl 100 ml ethanol	Immerse or spread for a few seconds till minute.	Etching of Ni superalloys.
Marble	10 g $CuSO_4$ 50 ml HCl 50 ml dest. water	Immerse or spread for 5-60 sec. A few drops of H_2SO_4 increases reagent effect.	Etching of Ni superalloys. Good for grain boundaries and structural phases.
Colour contrast reagents			
Weck - Aluminium	4 g $KMnO_4$ 1g NaOH 1000 ml dest. water	Pour over a dry sample and let it react for 20 sec. till 1.5 minute.	Colour etching of Al alloys.
	8 g $KMnO_4$ 2 g NaOH 200 ml dest. water	Etching for 20 sec. till 1.5 minute.	Colour etching of Al alloys, increasing of dendrite segregation.
Weck – Ti	2 g NH_4FHF 50 ml alcohol 100 ml dest. water	Etching for a few seconds till minutes.	Colour etching of Ti alloys.
Beraha III	Base solution: 50 g NH_4FHF 400 ml HCl 600 ml dest. water 1 g $K_2S_2O_5$	Wet etching for 30 sec. till 5 minutes.	Colour etching of Ni superalloys.

3. Results and discussion

There were used various types of reagent on selected experimental materials. Microstructure observations were done on microscope in light field, polarised light, and colour contrast. Polarised light is useful for determination phases with different crystal lattice of structural phases that a matrix has.

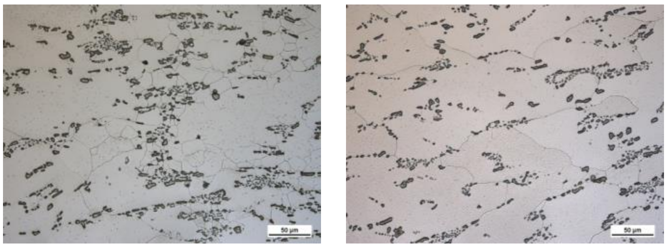
3.1. Results for aluminium alloy

Dix a Keith. Etching of AK4 – 1č was provided by immersing of sample for 15, 35 a 60 seconds. At first etching Al_2Cu precipitate boundary was clearly visible and heterogeneous microstructure was revealed, Fig. 2a (various shape and size of grains).

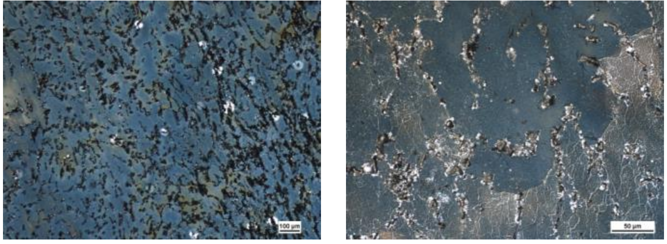
Keller. Because of aggressive composition of reagent the etching time was shorter, 15 seconds. This reagent provides better results, sharp grain boundaries and it precipitates, Fig. 2b.

Tucker. Specimen was etched for 10 seconds. The precipitates of Al_2Cu were after this time etched out and grain boundaries were clearly visible. This reagent caused a colour contrast of single phases, Fig. 2c, d.

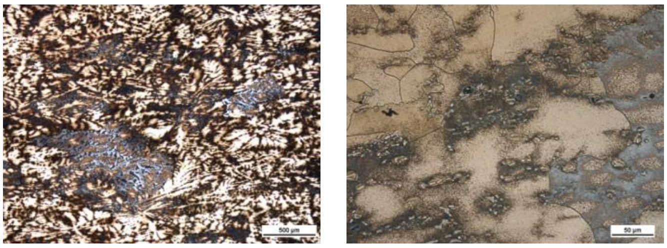
Reagent $KMnO_4$ + NaOH + H_2O. The way of etching is similar as in case of Weck – Aluminium (which does not bring satisfaction result for AK4 – 1č etching) that is 20 seconds. This reagent increases a dendritic segregation (clearly visible at lower magnification, Fig. 2e) and grain boundaries, at higher magnification Fig. 2f. Generally, all the reagents mentioned are suitable for developing and observing ~~of~~ aluminium alloy AK4 – 1č. Reagent Tucker is a very aggressive one because of etching out of Al_2Cu phase. However, the grain boundaries were clear visible and colour contrast appeared. Therefore, it is suitable reagent for the observation of grain boundaries and colour contrast development. The use of colour contrast reagents produced confusing results. While Weck – Aluminium results were poor, reagent $KMnO_4$ + NaOH + H_2O produced satisfactory results in the dendritic segregation and grain boundaries identification therefore it is considered the best.



a) Dix and Keith, 60 sec. b) Keller, 15 sec.



c) Tucker, 10 sec d) Tucker, 10 sec., detail



e) $KMnO_4$+NaOH+H_2O, 20 sec. f) $KMnO_4$+NaOH+H_2O, 20 sec., detail

Fig. 2 Microstructure of aluminium AK4 – 1č alloy.

3.2. Results for titanium alloy

10% fluorhydric acid. This reagent is very common for titanium alloys etching. The time of etching was 5 seconds. It reveals a duplex α + β structure of VT – 8 titanium alloy with worm shape of α – phase, Fig. 3a. With the use of polarised light it become α – phase multicoloured, Fig. 3b.

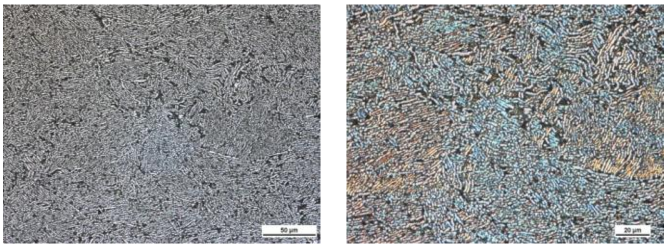
Kroll. This reagent gives almost the same results as 10% fluorhydric acid.

Weck – Titanium. Even when etching time was around 10 minutes, the reagent did not produce positive results. The microstructure did not have any significant colour contrast and even when using polarised light it was not satisfactory, with very poor colour contrast for β – phase, Fig. 3c, d.

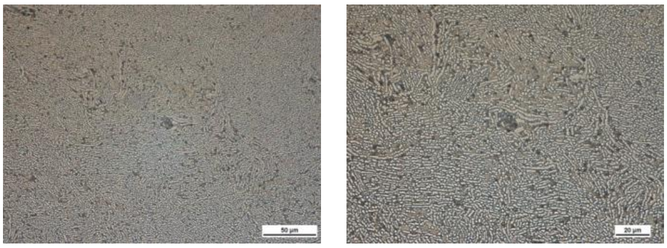
3.3. Results for nickel base superalloys

Marble is very common reagent for etching in the case of such a kind of material. The etching time was ten for ŽS6 – U alloy and twenty-five seconds for VŽL – 14 alloy. After etching dendritic segregation and inter dendritic phases occurred, mainly carbides were clearly visible, Fig. 4a, b. At higher magnification eutectic γ/γ′ formation are visible at ŽS6 – U alloy.

Reagent $FeCl_3$ + HCl + H_2O. Etching time was 10 seconds at ŽS6 – U alloy up to 2 minutes at VŽL – 14 alloy. This reagent is not a proper one for VŽL – 14 alloy. Microstructure was flat without significant effect, with only a few signs of dendritic segregation. However, ŽS6 – U alloy was satisfactory. Carbides were enhanced as well as grain boundaries, Fig. 4c, d.



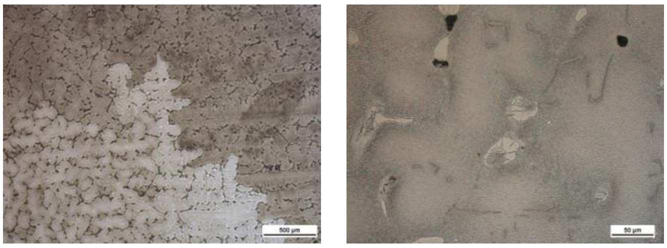
a) 10 % HF, 5 sec. b) 10 % HF, 5 sec., polarised light



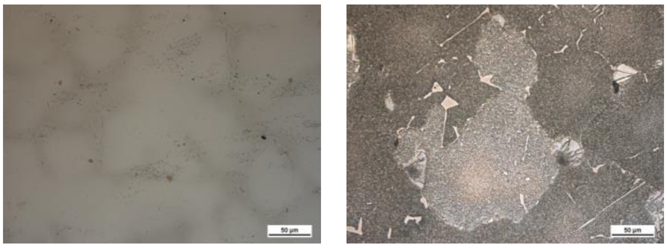
c) Weck - Ti, 10 min. d) Weck - Ti, 10 min., detail

Fig. 3 Microstructure of titanium VT – 8 alloy.

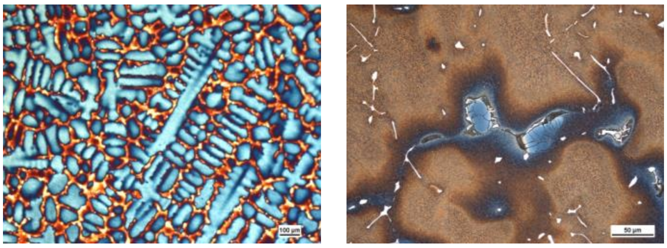
Beraha III. The way of using this reagent is quite different from the previous one. A sample surface is covered with water and into water is dropped reagent. Sample is moving from side to side for equal etching effect. Etching time is 1 minute at VŽL – 14 alloy and 4 – 5 minutes at ŽS6 – U alloy. Result is very colourful dendritic structure, Fig. 4e, f.



a) Marble, VŽL – 14 alloy, 25 seconds b) Marble, ŽS6 – U alloy, 10 seconds



c) $FeCl_3$ + HCl + H_2O, VŽL – 14, 2 min. d) $FeCl_3$ + HCl + H_2O, ŽS6 – U alloy, 10 sec.



e) Beraha III., VŽL – 14 alloy, 1 minute f) Beraha III., ŽS6 – U alloy, 4 – 5 min.

Fig. 4 Microstructure of VŽL – 14 and ŽS6 – U nickel base superalloys.

4. Conclusion

The aim of article was to help to decide which reagent is proper for the selected materials mainly used at aero jet engine construction preparation. From a number of reagents, very common ones were selected for a specific material type and its effect was evaluated on microstructure developing.

Aluminium alloy AK 4-1č is possible to be etched with Dix and Keith and Keller reagents where a classical contrast was obtained. To obtain a colour contrast $KMnO_4$ + NaOH + H_2O is considered the best.

With titanium alloy VT – 8, reagent of fluorhydric content fine, such 10 % HF, Kroll and HF + HNO_3 + H_2O_2 + H_2O.

For etching nickel base superalloys such VŽL – 14 and ŽS6 – U are reagent Marble, Kalling's reagent, and reagent of content $FeCl_3$ + HCl + H_2O and HCl + H_2O_2 are relatively satisfactory. Colour etching of these alloys is possible to obtain with Beraha III. reagent. The best results were obtained in VŽL – 14 alloy.

Acknowledgments

The project presented in this article is supported by Scientific Grant Agency of Ministry of Education of The Slovak Republic and the Slovak Academy of Sciences, No. 1/0533/15, No. 049ŽU-4/2017.

References

BELAN J., KUCHARIKOVÁ L., VAŠKO A., CHALUPOVÁ M., ŠVECOVÁ I. 2016. *Employing various metallography methods at high temperature alloy fatigue tests evaluationl*. Production Engineering Archives, Vol. 13, No. 4, 11-15.

CAMPBELL F. C. 2006. *Manufacturing Technology for Aerospace Structural Materials*, Elsevier Ltd., Amsterdam.

KONEČNÁ R. 2010. *Practical Metallography*. VEGA. Žilina: University of Žilina.

KUCHARIKOVÁ L., TILLOVÁ E., MATVIJA M., BELAN J., CHALUPOVÁ M. 2017. *Study of the precipitation hardening process in recycled Al-Si-Cu cast alloys*. Archives of metallurgy and materials, Vol. 62, Iss. 1, 397-403.

MICHNA Š., ET AL. 2005. *Aluminium Handbook*. Adin, 1st Edition, Prešov.

MOISEYEV V. N. 2006. *Titanium Alloys: Russian Aircraft and Aerospace Application*, CRC Press, Taylor & Francis Group LLC.

MOISEYEV V. N. 2004. *Structural titanium alloys in modern mechanical engineering*. Metal Science and Heat Treatment, Vol. 46, No. 3-4, 115-120.

PETERS M., LEYENS C. 2009. *Aerospace and Space Materials*, Materials Science and Engineering - Volume III, Edit. Rees D. Rawlings, EOLSS Publishers Company Limited.

SIENIAWSKI J., ZIAJA W., KUBIAK K., MOTYKA M. 2013. *Microstructure and Mechanical Properties of High Strength Two-Phase Titanium Alloys*, Titanium Alloys – Advances in Properties Control, Edit. Sieniawski, J., Ziaja, W., IN-TECH Open Acces.

SOKOLOVSKÁ Ž. 1995. *Construction materials for aircraft jet engine*, 1st Edition, VVŠL, Košice.

TILLOVÁ E., CHALUPOVÁ M., HURTALOVÁ L., BONEK M., DOBRZAŃSKI L. A. 2011. *Structural analysis of heat treated automotive cast alloy*, Journal of achievements in materials and manufacturing engineering, Vol. 47, No. 1, 19-25.

ULEWICZ R., TOMSKI P. 2017. *The effect of high-frequencies loading on the fatigue cracking of nodular cast iron*, METALURGIJA, Vol. 56, Iss. 1-2, 33-36.

航空喷气发动机结构中常用材料的简要概述和金相

關鍵詞

铝合金
钛合金
镍基合金
金相学程序
黑白和色彩对比

摘要

铝，钛和镍基合金大多被广泛地用于飞机喷气发动机的构造。从工作安全角度来看，对其微观结构进行适当的评估是重要的。要获得准备好的微观结构样品，必须采取一些重要步骤。除了对样品进行适当的研磨和抛光，结构的发展也是一个重要的步骤。为了开发微观结构，使用各种化学试剂来获得用于微观结构评估的最佳结果。化学试剂根据以前的知识使用，一些新的也被测试。铝AK4-1č，钛VT - 8和镍VŽL - 14和ŽS6 - U合金被用作实验材料。合金AK4-1č用于风扇叶片生产，工作温度高达300°C。这是用五轴铣床加工成最终形状的锻造件。合金VT-8用于高压压气机转子叶片的生产，工作温度高达500°C。刀片也是锻造的，最后磨削。最后镍基合金VŽL-14和ŽS6-U用于涡轮叶片生产， 工作温度高达950°C。涡轮叶片铸造成可缩模型。