METALLOGRAPHY OF ALLOYS USED IN AIRCRAFT JET ENGINE CONSTRUCTION

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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 safety working point of view. For receiving of good prepared sample of microstructure have some important steps be done. Except proper grinding and polishing of sample is structure developing significant step too. For microstructure developing were various chemical reagents used with aim to achieve the best results for microstructure evaluation. The chemical reagents were used upon the previous knowledge's and some new ones were also tested. Aluminium AK4-1č, Titanium VT – 8, and Nickel VŽL – 14 and ŽS6 – U alloys were used as experimental materials. Alloy AK4-1č is used for fan blade production with working temperatures up to 300°C. Alloy VT – 8 is used for high pressure compressor rotor blade production with working temperatures up to 500°C. Finally Nickel base alloys VŽL – 14 and ŽS6 – U are used for turbine blade production with working temperatures up 950°C.

Keywords: aluminium alloy, titanium alloy, nickel alloys, microstructure preparation, chemical reagents, BW and colour contrast.

1 Introduction

A safety and economical factors needs to be taken into account at selection of 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 at various ways of loading. However, aircraft materials also must have resistance against surrounding conditions which are varying. The construction materials selection for aircraft industry is very challenging and needs a good knowledge of materials characteristics with small scattering of its values.

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

The aircraft industry is characterised with large variety of airplanes, mainly its design variety, size and its purpose all related to costumers needs and costumer's economical situation. From this point of view can be this segment divided into four specific groups: light airplanes, bizjets (or business airplanes), civil airplanes, and military airplanes.

The demands on materials used for light airplanes (Cessna e. g.) construction are not so high, important is mainly lower price. Quality steel and aluminium alloys are just fine.

At business airplanes (HAWKER Beechcraft Premier e. g.) are material costs not so significant and that is why, for example, composites with carbon fibres are used

For civil airplanes (Boeing 747 e. g.) the price should be minimal and its weight too, but remember to safety. Aluminium alloys and composites are for body construction commonly used.

And finally, military airplanes (Boeing F/A 18 e. g.). Working conditions for these airplanes are so specific and therefore materials used for its production must be top. For body are composite materials used.

New materials are still invented, especially various combination at composite materials. But what about materials used today. Of course, without knowing of structural and mechanical fundamentals cannot be progress. This article is a part of research work about high loaded materials used for automotive and aircraft industry [1 - 9], considering materials especially used at aero jet engine construction, such as aluminium, titanium, and nickel alloys.

2 Experimental materials and methods

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 represents materials of 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

Aluminium alloy AK4 – 1č (or AK4 – 1) is mechanically worked alloy. It is suitable for long time using for temperature up to 300°C. This alloy is used for production of compressor blades or discs, engine pistons and forged components. Alloy

AK4 – 1č has an unique mechanical properties what predetermine it for high temperature using (in measure of aluminium alloys of course). The chemical composition is in **Table 1.** and mechanical properties in **Table 2.**

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
AK4 – 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

Table 2. Mechanical properties, creep yield strength $R_r.10^2/0,2$ and creep strength $R_{mT}.10^2$ [10]

Temperature [°C]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]	$E.10^3$ [MPa]	σ_c [MPa]	$R_r.10^2/0,2$ [MPa]	$R_{mT}.10^2$ [Mpa]
50	275	415	26	16	72	140		
100	270	395	26	16	70	135		
150	270	360	26	14	67	124	270	300
200	245	315	24	10	64	95	150	190
250	180	280	29	7	59	70	70	90
300	135	150	34	8	50	50	25	45

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 starts an intensive reaction of titanium with oxygen and nitrogen. It is necessary to use of protective coating against of oxidation (silicon diffusion coating) when titanium alloys are designed to work at higher temperatures [10].

According some references, replacing of steel by titanium alloys in aero jet engine brings saving of components weight around 30 – 40 % [11].

Titanium alloy VT – 8 is high strength and hardened alloy with α + β phases in microstructure. Temperature of α → β transformation is 1000°C [12]. 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 and elementary mechanical properties are in **Table 3.**

Table 3. Chemical composition and mechanical properties of titanium VT – 8 alloy [13]

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
Mechanical properties at 20°C				Tensile strength, [MPa]	Specific elongation, [%]	Impact strength, [J /cm^2]	Reduction of area, [%]	Density, [kg/m^3]
				930 - 1230	6 - 9	20 - 30	15 - 30	4520

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, re-crystallization / 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 [14].

From this reasons are unique construction materials, such as nickel base superalloys, used for construction of most stressed parts of jet engine – turbine blades. Nickel base superalloys were used in various structure modifications: as cast polycrystalline, directionally solidified, single crystal and in last year's materials produced by powder metallurgy.

The superalloys are often divided into three classes based on the major alloying constituent:

iron-nickel-base, nickel-base and cobalt-base. The iron-nickel base superalloys are considered to have developed as extension of stainless steel technology. Superalloys are highly alloyed and a wide range of alloying elements are 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 contain fine incoherent oxide particles which are harder than the matrix phase, and inhibit dislocation motion by Orowan looping [15].

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 [16]. Its chemical composition and some mechanical properties are in **Table 4.**

Table 4. Chemical composition and mechanical properties of ŽS6 – U alloy (wt. %) [17]

C	Cr	Co	Al	Ti	Mo	W	Nb	Fe	Mn	Si
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	max. 0.4

Tensile strength, [MPa]	Specific elongation, [%]	Reduction of area, [%]	Impact strength, [J /cm^2]	Density, [kg/m^3]
952 – 995	3.2 – 4.8	7	7.5 – 12.5	8400

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 and mechanical properties are in **Table 5.**

Table 5. Chemical composition and mechanical properties of VŽL – 14 alloy (wt. %) [18]

C	Cr	Al	Ti	Mo	Fe	Si	Mn	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. 0.4	max. 0.005

Tensile strength, [MPa]	Specific elongation, [%]	Reduction of area, [%]	Impact strength, [J /cm^2]	Density, [kg/m^3]
900 – 1000	14 – 22	18 – 22	40 – 80	8170

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. Used reagents are listed in **Table 6.** Various reagents were used with aim to describe its effect on materials and which of them is the best to use for revealing structural parameters.

Table 6. Black/white reagents and reagents for colour contrast used for experimental materials evaluation.

Reagents for aluminium alloys etching [19 - 20]			
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.

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Kroll	1,5 ml HF 4 ml HNO_3 94 ml dest. water	Immerse for a few seconds till minute.	Suitable for developing of $\alpha + \beta$ 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	Base	Wet	Colour
III	solution: 50 g NH_4FHF 400 ml HCl 600 ml dest. water 1 g $K_2S_2O_5$	etching for 30 sec. till 5 minutes.	etching of Ni superalloys.

3 Experimental 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 as matrix has.

3.1 Results for aluminium alloy

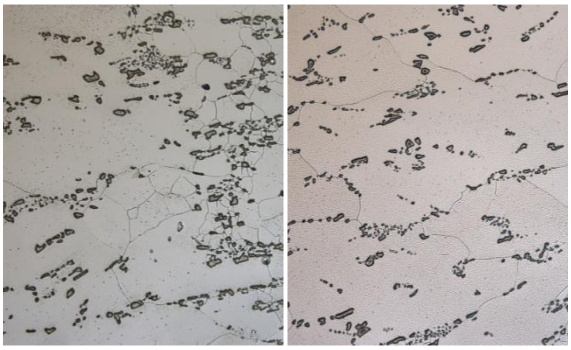
Dix a Keith. Etching of AK4 – 1č was provided by immersing of sample for 15, 35 a 60 seconds. At first etching was Al_2Cu precipitate boundary clear visible and was revealed heterogeneous microstructure, **Fig. 1a** (various shape and size of grains).

Keller. Because of aggressive composition of reagent was etching time shorter, 15 seconds. This reagent provides better results, sharp grain boundaries and precipitates, **Fig. 1b.**

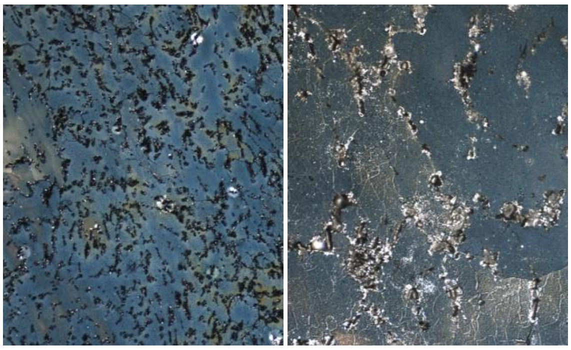
Tucker. Specimen was etched for 10 seconds. The precipitates of Al_2Cu were after this time etched out and grain boundaries were clear visible. This reagent caused a colour contrast of single phases, **Fig. 1c, d.**

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) for 20 seconds. This reagent increases dendritic segregation (clear visible at lower magnification, **Fig. 1e**) and grain boundaries, at higher magnification **Fig. 1f.**

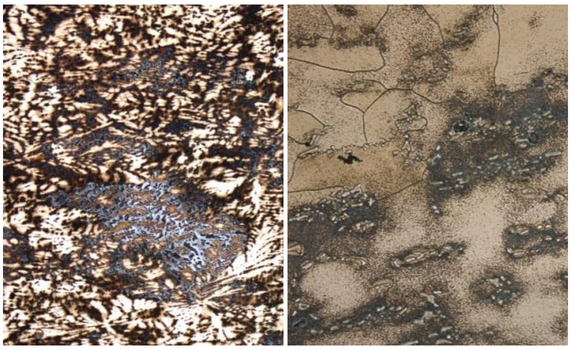
Generally, all mentioned reagent are suitable for developing and observing of aluminium alloy AK4 – 1č. Reagent Tucker is very aggressive one because of etching out of Al_2Cu phase. However, the grain boundaries were clear visible and colour contrast has appeared. So this is good reagent for grain boundaries observing and colour contrast developing. Using of colour contrast reagents have bring confused results. Whereas Weck – Aluminium results were poor, reagent $KMnO_4$ + NaOH + H_2O has nice results in the dendritic segregation and grain boundaries identification. This reagent is considered as 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. 1 Microstructure of aluminium AK4 – 1č alloy.

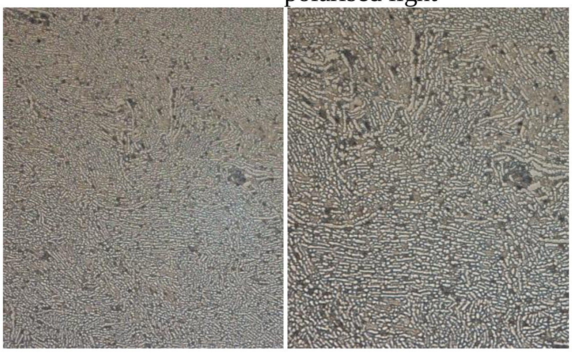
3.2 Results for titanium alloy

10 % fluorhydric acid. this reagent is very common for titanium alloys etching. 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. 2a.** With using of polarised light become α – phase multicoloured, **Fig. 2b.**

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

Weck – Titanium. Even when we used etching time around 10 minutes this reagent did not bring positive results. The microstructure was without any significant colour contrast and even using of polarised light was not satisfactory, very poor colour contrast for β – phase, **Fig. 2c, 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. 2 Microstructure of titanium VT – 8 alloy.

3.3 Results for nickel base superalloys

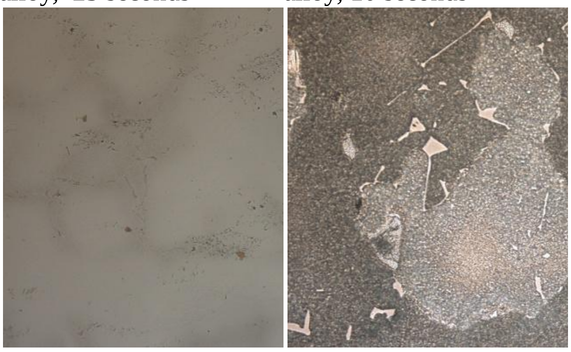
Marble is very common reagent for etching such of this kind of material. Time of etching was used 10 for ŽS6 – U alloy and 25 seconds for VŽL – 14 alloy. After etching is dendritic segregation and inter dendritic phases, mainly carbides clear visible, **Fig. 3a, b.** At higher magnification are eutectic γ/γ′ formation visible at ŽS6 – U alloy.

Reagent $FeCl_3$ + HCl + H_2O. Etching time was 10 seconds at ŽS6 – U alloy till 2 minutes at VŽL – 14 alloy. This reagent is not a right one for VŽL – 14 alloy. Microstructure was flat without significant effect, just a few signs of dendritic segregation. However, ŽS6 – U alloy was doing nice. Carbides were enhanced as well as grain boundaries, **Fig. 3c, d.**

Beraha III. The way of using this reagent is a quite different from previous reagent. Sample's 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. 3e, f.**

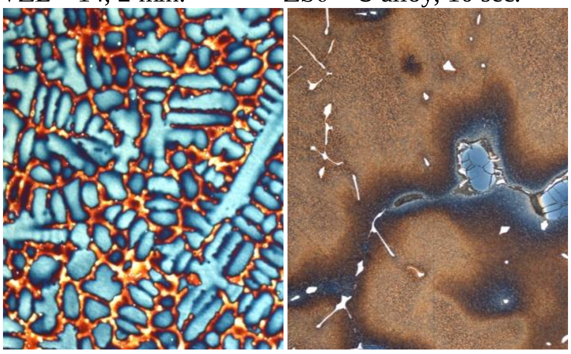
a) Marble, VŽL – 14 alloy, 25 seconds

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

Conclusion

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

Aluminium alloy AK 4-1č is possible to etched with Dix and Keith and Keller reagents where we obtain a classical contrast. To obtain a colour contrast is $KMnO_4 + NaOH + H_2O$ consider as 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 $HCl + H_2O_2$ doing pretty well. Colour etching of these alloys is possible to provide with Beraha III. reagent. The best results were obtained at VŽL – 14 alloy.

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