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Cracking processes during creep test of ŻS6U superalloy with aluminium coatings

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Properties

ABSTRACT

Purpose: The paper presents the evaluation of the influence of aluminium layers used as protective coatings of aircraft turbine engine blades upon durability of ŻS6U nickel base superalloy under the conditions of short time creep. The conditions of cracks formation and growth in specimens with aluminium coatings have been analysed while taking into account the microstructure properties of coatings as well as the microstructure of specimen core material.
Design/methodology/approach: The creep tests have been performed on MTS apparatus in the conditions corresponding to the extreme operating conditions of aircraft engine blades. The specimens were heated in a resistance furnace up to the temperature of 950ºC and then constant axial force was applied which induced stress σ_o=300 MPa in their cross-section.
Findings: The obtained results have proved a significant influence of the type, protective coating thickness and the specimen core structure upon the secondary creep rate.
Research limitations/implications: To ensure the most effective use of aluminium protective coatings it is important to understand the creep mechanisms in temperature lower than DBTT (ductile brittle transition temperature). Therefore, it is necessary to perform some creep tests in temperatures much lower than 900ºC.
Practical implications: The obtained results could constitute the base for suggesting the guidelines on selecting proper aluminium coatings for specific designs of aircraft engine blades.
Originality/value: It has been found that the reduction of creep durability of specimens made of ŻS6U alloy with diffusive aluminium coatings is caused by the reduction of the lateral surface of specimens core, which effectively transfers loads in creep tests.
Keywords: Creep-resistance; Corrosion; Aluminium protective coatings; Superalloy

1. Introduction

Nickel based high-temperature creep resisting alloys are the basic material in the constructing of aircraft turbine engine components that are supposed to be the most reliable. The parts working under the most critical conditions, such as the combustor or blades, are under the effect of gases of a very high and often variable temperature which, depending on the method of the blade mounting and heat conduction, can reach a value in the order of 700°C÷950°C [1÷3]. The unprofitable effect of high temperature results, inter alia, from the intensification of corrosion processes, changes in the material structure and decreasing of its mechanical properties. At the same time, at a high temperature, plastic strain are created, especially in creep processes.

One of the phenomena, which determine the blades' durability of aircraft turbine engine, is cracking of the protective′, most often aluminium based, coatings applied onto them, where the intermetallic NiAl compound plays a crucial role [4÷6]. A favourable effect of the coatings is conditioned by their adequate selection for concrete design solutions and by specific conditions of the engine operation [7÷10]. In order to effectively use nickel

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superalloys with aluminium coatings, knowledge is necessary of, inter alia, the creep mechanisms which prevail in the specific operating conditions of internal combustion turbines' blades.

2. Accelerated creep tests of ŻS6U supperalloy with an aluminium coating

The research was conducted on a casting, high-temperature creep resisting nickel based alloy, ŻS6U, applied for 1st stage blades of internal combustion turbines, of the following chemical composition: 0,17%C, 1,4%Mo, 2,6%Ti, 0,1%Fe, 8,4%Cr, 9,9%W, 1,1%Nb, 9,6%Co, 5,3%Al, 0,1Si, 0,03S, 0,007P and the rest - Ni. Specimens of a diameter d_o=3.8mm and a measuring base l_o = 30mm were made of rolls subjected to homogenization (1210°C, 4h, air). On the specimens, protective coatings were applied by means of silicoaluminising and chromoaluminising, with the use of a pack-cementation method, with parameters presented in Table 1.

The creep tests were performed in conditions corresponding to the extreme operating conditions of aircraft engine blades. The specimens were heated in a resistance furnace up to the temperature of 950°C and next, constant axial force was applied which induced stress σ_o= 300MPa in their cross-section. The temperature of the specimens was adjusted by means of thermocouples of a Pt-Rh/Pt type. The creep deformation until failure was recorded with an extensometer with a 25 mm measuring base.

For the creep tests, three groups of specimens were prepared as characterized in Table 1.

Strain characteristics of the investigated material (Fig. 1 and 3, Table 1) are depicted by Andrade's formula [11]:

$$\varepsilon = \varepsilon_o + \beta\, t^n + V_u \cdot t \qquad (1)$$

where: ε_o – initial strain, V_u – secondary creep rate, β, n – material constants.

A statistically determined value of V_u (Table 1) characterized the rate of the investigated materials' deformation in the secondary creep phase. The deformation behaviour of the materials in that creep phase was crucial, since it indicated the conditions of cracks formation and growth during the transition to stage III which ended with the specimen's failure and destruction.

The short time creep tests showed that durability of specimens with coatings, both "Si-Al" and "Cr-Al", expressed by means of time until failure (t_z), reduced compared to durability of the reference specimen (no. 1, without a coating, after homogenization) the more, the thicker the aluminium coating was (Fig. 1, Tab. 1). The specimens with a "Si-Al" coating 90 and 140 µm thick, were characterized by lower hardness compared to those with a "Cr-Al" coating of 60 and 90µm thickness.

Lower creep rates (V_u) and longer time until failure (t_z) of the specimens with "Cr-Al" coatings in relation to the specimens with "Si-Al" coatings resulted from the differences in the γ′ phase morphology as well as from the observed in the initial state differences in the morphology of grain boundaries in those materials.

The ŻS6U alloy after homogenization and silicoaluminising was characterized by a cuboidal form of γ′ phase particles of a size of ca. 0.5µm, whereas in the specimens subjected to chromoaluminising, the γ′ phase particles had an irregular form with visible traces of coalescence of those precipitations which caused the particles growth up to the size of ca. 1÷3µm.

The size, morphology and distribution of γ′ phase particles in the nickel supperalloys' matrix determine the form of dislocation boundaries, the latter constituting considerable obstacles for dislocation mobility within the γ/γ′ interface boundaries' regions [11÷15].

A significant factor which caused a reduction of the creep rate of the specimens with "Cr-Al" coatings could have been the presence of a fine dispersive spheroidal γ′ phase in the γ/γ′ interfaces in the specimens core material.

Table 1.
Characterization of materials for the investigations and accelerated creep tests results

Specimen group / number		Material type	Coating thickness [µm]	Durability t_z [min]	$\varepsilon = \varepsilon_o + \beta \cdot t^n + V_u \cdot t$			
					ε_o	β	n	V_u [1/min]
I	1	Without coating (homogenized)	------	1100	0,00244	0,00018	0,30549	0,0000064
II	2	With a Cr-Al coating (6h/1050°C)	60	810	0,00271	0,000066	0,37801	0,0000097
	3	With a Cr-Al coating (16h/1050°C)	90	750	0,00224	0,00006	0,26178	0,0000145
	6	Without coating + OC→ (16h/1050°C)	-----	715	0,00287	0,00020	0,29416	0,0000094
III	4	With a Si-Al coating (4h/800°C+2h/1050°C)	90	700	0,00218	0,00019	0,26448	0,0000159
	5	With a Si-Al coating (8h/800°C+2h/1050°C)	140	470	0,00237	0,00012	0,33243	0,0000148
	7	Without coating +OC→ (4h/800°C+2h/1050°C)	-----	640	0,00246	0,00008	0,36632	0,0000151

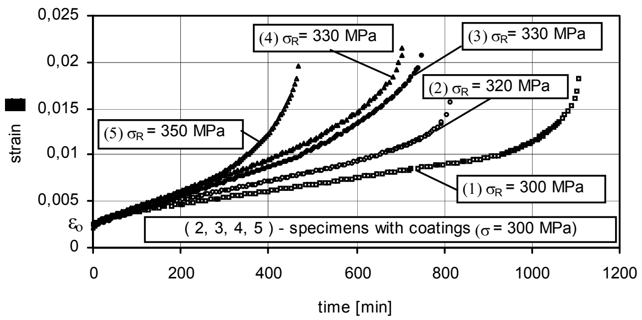

Fig. 1. Characteristics of short time creep of ŻS6U alloy specimens with an aluminium coating. σ_R means stress in the core of a specimen with an aluminium coating

In the substrate material of the specimens, especially those which underwent chromoaluminising, effects were observed of an advanced decomposition of MC carbides (Fig. 2) containing molybdenum and tungsten, i.e. chemical elements which weaken the strength of bondings between those phases. The MC carbides underwent decomposition, which resulted in the formation of fine $M_{23}C_6$ and M_6C carbides.

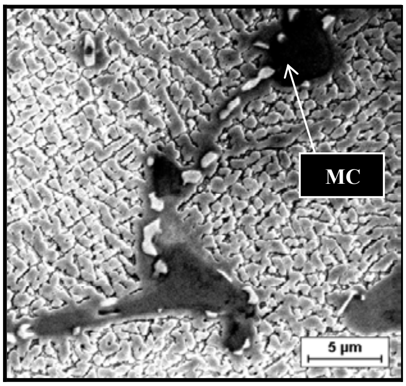

Fig. 2. Microstructure of a ŻS6U alloy specimen after chromoaluminising (16h/1050°C), decomposition effect of MC carbides containing molybdenum and tungsten

Numerous precipitations of fine carbide phases also could have contributed, by slip suppressing, to an increase of durability, under creep conditions, of specimens with "Cr-Al" coatings produced in warm processes.

Metallurgical analyses of the cores of specimens with "Cr-Al" coatings performed on a Hitachi S-4200 scanning microscope showed that the carbides' transition effects, as well as the occurrence of a fine dispersive γ′ phase in the γ/γ′ interfaces, were the consequence of ageing processes in the homogenized ŻS6U alloy, which began already during its heat and chemical treatment. The treatment was characterized by a high soaking temperature (1050°C) and long time (6h and 16h) of diffusion saturation.

Precipitations of fine carbide phases as well as of a superfine γ′ phase were the requisite for suppressing slips within the grain boundaries′ regions and determined the observed reduction of the seconddary creep rate V_u of specimens with "Cr-Al" coatings (Table 1).

The research carried out showed that a crucial factor determining durability under creep conditions was the state of the core material of specimens with protective coatings, including its microstructure which conditioned the course of ŻS6U deformation and cracking. In that regard, important information was obtained by a comparison of accelerated creep characteristics of the specimens without aluminium coatings, examined under the same load (Fig. 3).

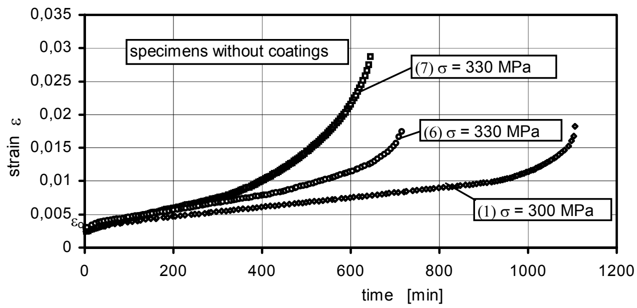

Fig. 3. Short time creep characteristics for specimens of ŻS6U alloy without an aluminium coating.

In the case of the ŻS6U alloy subjected to heat treatment with parameters corresponding to those of chromoaluminising (16h/1050°C), elongation of time until failure (t_z) was observed as well as considerably lower strain (V_u) rates compared to the creep characteristics of the alloy after heat treatment (4h/800°C+2h/1050°C) corresponding to the silicoaluminising process. In the case discussed, differences in the secondary creep rates (Table 1) were observed, with the differences in the specimens' durability determined by a varied size and morphology of the γ′ phase particles, as well as by differences in the morphology of the precipitations on the nickel superalloy grain boundaries.

Analyses of the specimens' microstructures after creep tests showed that the aluminium coatings at the test temperature (950°C) were characterized by high plasticity, since none of the coatings had cracks, except for a crack in the fracture plane. However, numerous voids and microcracks as well as effects of their coalescence, particularly in the regions of grain boundaries and dendrite branches, were found in the cores of the investigated specimens.

Cracks nucleation in the ŻS6U alloy was the effect of a loss of cohesion in the material as a result of slip suppressing along grain boundaries, which led to stress concentration and brittle cracking being the consequence of overcoming the cohesion force on the carbide/layered γ′ phase interface (Fig. 4).

In the specimens without protective coatings, apart from the already discussed processes, structure degradation was observed in close-to-surface regions (Fig. 5). Under creep conditions, a film of oxides (mark 1, Fig. 5) of a complex chemical composition was formed, composed of Cr, Al, Ni, Ti and Mo, W. In subsuperficial regions, due to a reduced concentration of elements forming the oxide phases, dissolution of the γ′ phase particles (mark 2, Fig. 5) took place in the alloy austenitic matrix. In subsequent stages of the creep process, oxygen diffusing into the substrate through a film of scale caused oxidation of the clearly formed matrix grain boundaries. This led to the occurrence of tensile stresses in those regions and additionally, initiated the processes of the ŻS6U alloy cracking (Fig. 5).

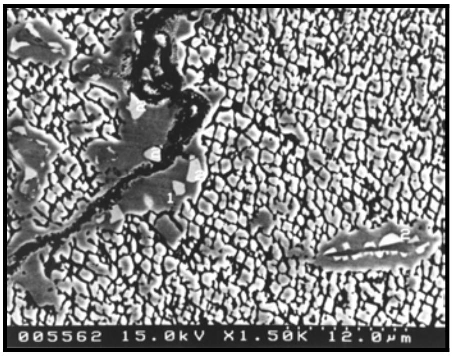

Fig. 4. Microstructure of the ŻS6U alloy after short time creep tests. Microcracks on the carbide/layered γ′ phase interface

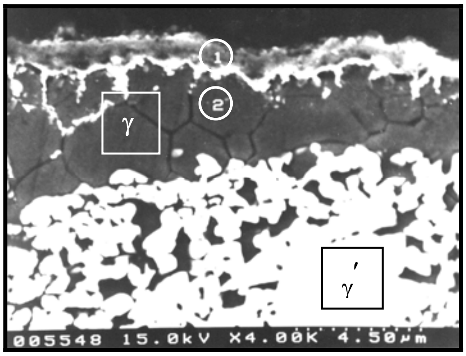

Fig. 5. Microstructure of subsuperficial regions of a specimen without an aluminium coating after short time creep tests

3. Conclusions

Reduction of durability of the ŻS6U alloy specimens with diffusive aluminium coatings under accelerated creep conditions at a temperature of 950^{0}C is caused by a reduction of the specimens' bearing surfaces and a change of the conditions of load distribution throughout their cross-sections. In this case, the aluminium coating thickness and its plasticity in creep conditions are fundamental.

The short time creep tests of the ŻS6U alloy with diffusive aluminium coatings have shown that when one refers the actual load of a specimen exclusively to the cross-section of its core (Table 1, specimens 3 and 6, specimens 4 and 7), the influence of the aluminium coatings on the alloy durability measured by time until specimen failure is insignificant.

In short time creep tests at a temperature of 950^{0}C, the course of the cracking processes of the ŻS6U alloy with protective coatings is mostly determined by the high-temperature creep resisting properties of the substrate material. In the specimens' cores, cracks initiation and growth are most often observed in the regions of grain boundaries and dendrite branches. However, no occurrence of cracks was found in the diffusive coatings of aluminium.

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