ANALYSIS OF CREEP TESTS OF THE IN 792-5A ALLOY

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Abstract
IN 792-5A, a variant within the IN 792 alloy series, is a high-temperature cast nickel alloy strengthened by the presence of precipitates of the $\gamma'$ phase and carbides. This alloy is currently used, for instance, as the material of cast blades for jet engines. The companies UJP PRAHA a.s and PBS Velká Bíteš a.s. have joined their research capacities in a project aimed to identify the properties of the alloy with focus on its heat treatment. Within the project, creep tests of the IN792-5A alloy as cast and following three-step heat treatment were performed in cooperation with the Institute of Physics of Materials, Academy of Sciences of the Czech Republic. Such heat treatment was found to extend appreciably the alloy’s creep life. In the as-cast state the alloy fails to meet the requirements for its lifetime. The present contribution discusses the causes of the differences in the creep behaviour of the IN792-5A alloy between the two structure states. The structure of the alloy and the crack formation and propagation were investigated on sections perpendicular to the fracture plane. The fracture planes were also analysed.

Key words: Ni superalloys, investment castings, creep properties, microstructure

1. Introduction
Cooperation between the companies UJP PRAHA a.s and PBS Velká Bíteš a.s. in the study of mechanical properties of nickel alloys has a long tradition. The IN792-5A alloy was included in the research programme as early as 2003. Extensive investigation was performed into the variants of heat treatment and long-term stability of the material's microstructure. Mechanical properties of the alloy in its various structure states were also examined. No substantial differences in the short-time mechanical properties were observed between alloy samples in the as-cast state and in the state following heat treatment [1]. Therefore, creep tests were performed by the Institute of Physics of Materials, Academy of Sciences of the Czech Republic, with focus on differences in the high-temperature creep resistance of the IN792-5A alloy in the as-cast state and following heat treatment. In this context, the feasibility of omitting the heat treatment step from the alloy treatment process was considered.

Test specimens for the creep tests were supplied by PBS Velká Bíteš. Metallographic sections for microstructure investigations and longitudinal sections through the fracture plane for examination of the relations between the deformation and disturbance process and the microstructure of the alloy were prepared from selected specimens damaged during the tests. The fracture planes were subjected to fractographic examination.
2. Properties of the IN792-5A alloy

The chemical composition of the IN792-5A alloy melt used is given in Table 1.

**Table 1**: Chemical composition (wt.%) of the IN792-5A alloy

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>Ti</th>
<th>Fe</th>
<th>W</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.08</td>
<td>12.5</td>
<td>1.90</td>
<td>3.42</td>
<td>4.01</td>
<td>0.22</td>
<td>4.01</td>
<td>8.91</td>
</tr>
<tr>
<td>Ta</td>
<td>4.00</td>
<td>0.020</td>
<td>0.03</td>
<td>≤0.001</td>
<td>≤0.02</td>
<td>≤0.005</td>
<td>0.018</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

The alloy was examined in its as-cast (AC) state and following heat treatment (HT) consisting of the following regime:

\[1120^\circ C/2h/air + 1080^\circ C/4h/air + 845^\circ C/24h/air\]

Selected mechanical properties of the alloy are given in Table 2.

**Table 2**: Mechanical properties of the IN792-5A alloy

<table>
<thead>
<tr>
<th>Structure state</th>
<th>Testing temperature[°C]</th>
<th>Rm [MPa]</th>
<th>Rp0,2 [MPa]</th>
<th>A [%]</th>
<th>Z [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>20</td>
<td>1028.75</td>
<td>880.94</td>
<td>5.76</td>
<td>10.72</td>
</tr>
<tr>
<td>HT</td>
<td>20</td>
<td>1045.48</td>
<td>949.80</td>
<td>3.49</td>
<td>10.03</td>
</tr>
<tr>
<td>AC</td>
<td>750</td>
<td>1021.90</td>
<td>799.30</td>
<td>5.17</td>
<td>8.29</td>
</tr>
<tr>
<td>HT</td>
<td>750</td>
<td>1052.70</td>
<td>891.20</td>
<td>9.87</td>
<td>16.07</td>
</tr>
</tbody>
</table>

The differences in the mechanical properties between the structure states are not very pronounced: the as-cast alloy samples exhibit a lower tensile yield strength Rp0,2, elongation A5, and contraction Z at 750°C.

Light microscopy (LM) photographs exhibit a regular casting structure of the dendritic cells, whose boundaries consist of coarse particles of carbides and the \(\gamma'\) primary phase (Figs 1 and 3). Casting defects were found in some points. Scanning electron microscopy (SEM) photographs display the morphology and distribution of the \(\gamma'\) phase precipitated inside the dendritic cells (Figs 2 and 4). The samples were etched electrolytically in an oxalic acid solution.

Metallographic sections of the as-cast alloy display \(\gamma'\) phase particles possessing rectangular to irregular shapes with diameters in the order of tenths of a micrometre. The arrangement of the particles is irregular, the particles form small clusters. A better arrangement and uniformity of the \(\gamma'\) phase particles is found in the alloy following heat treatment. The dendritic cell boundaries are less clear-cut due to a partial decay of the coarse particles of the eutectic \(\gamma'\) phase. The particles exhibit a slightly rounded square-shaped cross section whose edge is approximately 0.5 to 1 µm long and constitute a nearly regularly arranged net with a quadrat network. Tiny particles of the secondary \(\gamma'\) phase can be observed among the particles mentioned.
3. IN792-5A alloy creep tests

In order to decide whether the heat treatment step can be omitted from the processing or not, creep tests to fracture at 850°C were performed by the Institute of Physics of Materials, Academy of Sciences of the Czech Republic in Brno [2] on as-cast specimens and on specimens that had been subjected to heat treatment. Four test stress levels were used, viz. 300, 340, 360, and 400 MPa. Two specimens were tested at each stress level. The results are shown in Figs 5 and 6 below.

![Fig. 5: Dependence of the time to fracture (a) and stationary creep rate (b) on stress at 850°C for the IN792-5A alloy in the as-cast state („bez TZ”) and following 3-step heat treatment („TZ”) [2]](image-url)
The lifetime data for the IN792-5A alloy following heat treatment are in accordance with the data obtained for that structure state recently [3,4]. The results indicate, however, that the creep resistance at high temperatures is markedly poorer for the as-cast alloy than for the alloy after heat treatment. The time to fracture is 2 to 8 times shorter (in dependence on the stress level), as is the elongation to fracture (about 2-fold) and contraction (about 2 to 3-fold). The stationary creep rate is comparable for the two classes of specimens. Also, elongation to fracture for a given structure state exhibits a low dispersion and is nearly constant over the stress range applied. The dispersion of the contraction data is larger and the data increase slightly with extending time to fracture (with decreasing stress). The deformation vs time curves display a rather sharp transition between the 2nd stationary creep phase and fracture. This is particularly apparent for the as-cast alloy. Also, the first creep stage is rather short, and specimens of the as-cast alloy are deformed to a lesser extent at that stage.

The causes of the appreciable difference in the creep lifetime of the IN792-5A alloy between the as-cast state and the state after heat treatment will be discussed in the next part of this contribution.

4. Analysis of IN792-5A alloy specimens damaged during the creep tests
The damaged specimens were viewed first at a low magnification. The samples looked very similar, their surface was oxidized, contraction was low, the fracture plane was perpendicular to the direction of tension and exhibited dendritic structure patterns. The observed differences were not very marked: The edges of the specimens of the as-cast alloy were more jagged, the fracture was smoother and more perpendicular to the direction of tension. The specimens of the alloy subjected to heat treatment provided a wavier fracture plane, and cracks perpendicular to the direction of tension could be observed on the surface beneath the fracture plane even at a low magnification.

4.1 Structural analysis
Test specimens possessing the shortest and longest lifetimes, both of the as-cast alloy and the alloy subjected to heat treatment, were selected for the analysis. Metallographic sections in the specimen axis perpendicular to the fracture plane were prepared from them.
The most marked effect observed on the longitudinal sections of the as-cast alloy specimens was the occurrence of cavities, presumably casting defects, which, however, were no sources of cracks. SEM photographs (larger magnification) displayed cracks parallel to the fracture line in the vicinity of the fracture. The cracks initiated and propagated as interdendritic fracture (Figs 7 and 8), especially along the boundaries of the eutectic $\gamma'$ phase. Cracks initiated on the boundaries of the carbide particles or directly inside the coarse $\gamma'$ phase particles were also observed (Fig. 9). Thin needles that may be TCP phase particles [5] were also found near those coarse particles in the vicinity of the fracture. Since the needles were too thin for a point analysis of the chemical composition by the EDS method, linear analysis with multiple passage of the electron beam perpendicularly to the needle selected was performed. This analysis revealed that the phase was rich in chromium, suggesting [5] that the needles could consist of the TCP phase. No rafting formation was exhibited by the tiny $\gamma'$ phase particles inside the dendritic cells.

As a dominant phenomenon, the sections of specimens subjected to heat treatment exhibited extensive cracks, also at large distances from the fracture plane (Fig. 11). A detailed observation revealed that most of the cracks were intergranular cracks (Fig. 12) rather than interdendritic cracks. This was also apparent at the fracture line. In some suitably oriented grains, $\gamma'$ phase particles inside dendritic cells displayed the formation of rafting.

Fig. 7: Section of the as-cast crept specimen, interdendritic fracture (LM)

Fig. 8: Section of the as-cast specimen, fracture along the boundary of the $\gamma'\gamma$ eutectic (SEM)

Fig. 9: Section through an as-cast specimen, fracture inside the $\gamma'\gamma$ eutectics (SEM)

Fig. 10: Section through an as-cast specimen, fracture along the boundary of the $\gamma'\gamma$ eutectics,
4.2 Fractographic analysis

Fractographic analysis of the fracture planes in the SEM photographs supported the observations made on the longitudinal sections of the specimens (despite the occurrence of oxides on the fracture planes). The fracture planes of the as-cast specimens displayed many elongated particles (of carbides) as well as broader particles (coarse $\gamma'$ phase particles) which were cracked or decohesively separated (Fig. 13). They could also be observed on the bottom of the ductile dimples.

The fracture planes of the heat-treated specimens were more oxidized. Despite this, some phenomena could be observed. The fracture plane was less uniform, some secondary cracks, apparently intergranular ones (Fig. 14) were present. Traces of carbides were also found in some points.

5. Summary of results and discussion

The observed creep lifetimes of the IN792-5A alloy at 850 $^\circ$C following heat treatment are in accordance with those found recently [3,4]. Such specimens exhibited intergranular fracture, which also agrees with recent findings [4].
The measurements performed show that the creep resistance of the as-cast IN792-5A alloy at 850°C is very low – markedly lower than that of the heat-treated alloy. Structural and fractographic analyses suggest that this low creep resistance is due to a heterogeneity of the structure of the cast alloy. Crack initiation and propagation are interdendritic by nature, hence, they are present at the boundaries where precipitated tantalum carbides and eutectic particles of the $\gamma'$ phase occur. The chemical heterogeneity of the structure is also manifested by the fact that the creep test is accompanied by precipitation of thin needles, presumably of the TCP phase, near the coarse particles of the eutectic $\gamma'$ phase. It should be stressed that the number of electron vacancies $N_v$, representing the tendency of nickel alloys to form the TCP phase, is 2.12, which is a safe level. The phases were never observed before during any detailed structural analysis. Hence, it is likely that the particles were formed in the heterogeneous segments of the structure, at the boundaries of the dendritic cells which are rich in chromium, stimulated by the tensile stress and high temperature during the test.

The effect of the TCP phase on the creep behaviour of various modifications of the IN792 alloy obtained by directional solidification has been examined in ref. [5]. The TCP phase acts indirectly, viz. by depleting the $\gamma$ matrix of elements reinforcing the solid solution, resulting in a higher rate of deformation. In this work the observed rate of deformation was identical for the two states of the alloy. Since the observed occurrence of the TCP phase in the structure near the fracture line and at a larger distance from it was rare, it is reasonable to assume that it will not affect appreciably the deformation or fracture during the high-temperature creep resistance test.

Conclusion

Creep resistance tests were performed on samples of the IN 792-5A alloy in the as-cast state and following heat treatment. The heat-treated alloy was found to satisfy requirements for its industrial uses. The as-cast IN 792-5A alloy exhibits a markedly lower creep resistance. This is due to a heterogeneity of the structure and chemical composition emerging during the casting process.

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REFERENCES


