Thermal-Mechanical Fatigue Property of Ni-Base Single Crystal Superalloys TMS-82+ and TMS-75*

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The effect of hold time \( t_h \) on the thermal-mechanical fatigue property (TMF) of two nickel-base single crystal superalloys TMS-82+ and TMS-75, which are second- and third-generation single crystals, respectively, was investigated. Cycles to failure for both alloys decreased drastically with the increase in the hold time. The TMS-75 showed a longer life than the TMS-82+ at \( t_h = 0 \). The TMS-82+ showed a longer life than the TMS-75 at \( t_h \neq 0 \), which could be attributed to the higher tensile strength at 400 °C and higher stress relaxation resistance at 900 °C in the TMS-82+. From microstructural studies, a slightly rafted \( \gamma'/\gamma'' \) structure was observed in the TMS-82+ for TMF with a hold time. This work indicates that the TMS-82+ is appropriate to be served in gas turbine engines under specific conditions such as electric power generation.

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1. Introduction

It has been requiring to increase the thermal efficiency of gas turbine engines in order to inhibit from discharging the carbon dioxide gas into global environment. In gas turbine engines, the thermal efficiency is limited by the durable temperature of blades and vanes which are made primarily of nickel-base superalloys. Therefore, the creep, fatigue and corrosion properties at high temperatures are important for the use of nickel-base superalloys in gas turbine engines. This report focuses on the thermal-mechanical fatigue properties of two nickel-base single crystal superalloys developed at National Institute for Materials Science.

2. Experimental Procedure

TMS-82+ and TMS-75 are second- and third-generation nickel-base single crystal superalloys, respectively. The chemical composition and heat treatment for the two superalloys are specified elsewhere. The volume fraction of the \( \gamma' \) phase is about 60% and the average size of \( \gamma' \) precipitates is 0.4 μm. The other second-generation single crystal superalloy, CMSX-4 was used as a reference under specific experimental conditions.

Round bar were worked to smooth TMF specimens of 5 mm in diameter and 15 mm in parallel part length. TMF testing was carried out on a hydraulic-servo system fatigue machine (MTS type 810) with a capacity of ±50 kN. Static tensile testing was conducted for TMS-82+, TMS-75 and CMSX-4 at 400 °C in air. To simulate the actual conditions of blades and vanes, the following experimental conditions were selected: temperature range, 400 °C ≤ 900 °C in air; total strain range, \( \pm 0.64% \); frequency, \( (0.1 + t_h) \) (h)/cycle, where \( t_h \) is the hold time at the maximum testing temperature \( t_h = 0, 0.17, 1, \) and 10h; wave form, triangular + trapezoidal; phase, out-of-phase.

Microstructural observations by optical and scanning electron microscopy (SEM) were carried out for ruptured specimens.

3. Results and Discussion

The cycles to failure against the hold time are plotted in Fig. 1. It can be seen that the fracture lives of TMS-82+ and TMS-75 decreased drastically with increasing the hold time. The TMS-75 showed a longer failure life than the TMS-82+ at \( t_h = 0 \), whereas the TMS-82+ showed a longer rupture life than the TMS-75 at \( t_h \neq 0 \). The relationship between the normalized cycles to failure, that is, the ratio of cycles to failure with a hold time to cycles to failure without a hold time, and the hold time is shown in Fig. 2, which demonstrates that the TMS-82+ shows longer rupture life than the TMS-75 at \( t_h \neq 0 \). The effect of the hold time on the stress-strain hysteresis loop is illustrated in Fig. 3, where

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loops at incipient, medium and final cycles for TMS-82+ with a hold time of 10h are chosen. It can be seen that the amplitude of the stress relaxation is increased with the increase in fatigue cycles.

The tensile properties of TMS-82+, TMS-75 and CMSX-4 are shown in Table 1, where proof stress, tensile strength, elongation, and reduction of area are listed. The relationship between the cycles to failure and tensile strength at 400°C is illustrated in Fig. 4. Despite the fact that experimental data are insufficient in number, it could be concluded that the rupture life of an alloy with a hold time becomes longer with the increase in the tensile strength at 400°C, while this trend does not hold in the case of \( t_h = 0 \). This implies that an alloy with high tensile strength at 400°C in tensile deformation testing may lead to superior TMF properties. Thus, the longer rupture life of the TMS-82+ at \( t_h \neq 0 \) than the TMS-75 would be attributed to the higher strength in the TMS-82+ in the tension phase. The stress relaxation in the compression phase plays an important role, as previously reported.6) The stress-strain hysteresis loops of the TMS-75 (Fig. 5a) and the TMS-82+ (Fig. 5b) were recorded at half-cycles to failure under identical testing conditions. It can be seen that the TMS-82+ has higher stress relaxation resistance in the compression phase than the TMS-75. A higher stress

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temperature</th>
<th>Proof strength</th>
<th>Tensile strength</th>
<th>Elongation</th>
<th>Reduction of area</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMS-75</td>
<td>400</td>
<td>878</td>
<td>913</td>
<td>6.8</td>
<td>12.6</td>
</tr>
<tr>
<td>TMS-82+</td>
<td>400</td>
<td>947</td>
<td>961</td>
<td>5.5</td>
<td>13.3</td>
</tr>
<tr>
<td>CMSX-4</td>
<td>400</td>
<td>983</td>
<td>1022</td>
<td>6.8</td>
<td>11.2</td>
</tr>
</tbody>
</table>

CMSX-4 is a registered trademark of the Cannon-Muskegon Corp. in U.S.A.
relaxation resistance corresponds to a smaller plastic strain gained in the tension phase and a longer TMF rupture life.\(^6\)

The change in the TMF property with the stress relaxation behavior in the TMS-75 and the TMS-82+ confirmed the previous result.\(^6\)

On the optical micrographs, some coarse slip bands formed in the TMS-75 (Fig. 6a), while no such slip bands were observed in the TMS-82+ (Fig. 6b). Crack propagation is approximately perpendicular to the loading stress axis. Microstructural observations by SEM after failure showed that the TMS-75 under a similar condition showed no rafted structure (Fig. 7a), whereas the TMS-82+ with a hold time exhibited a slightly rafted structure (Fig. 7b).

Some gas turbine engines are frequently switched on and off to adjust the electric power supply. The TMF property of TMS-82+ has been presently shown to be better than that of the TMS-75 under an out-of-phase TMF condition at \(t_0 = 1\) h.

The characteristics of the TMS-82+ are advantageous for blades and vanes in gas turbine engines.

### 4. Conclusions

The following conclusions are reached based upon the investigations of the thermal-mechanical fatigue properties of alloys TMS-82+ and TMS-75:

1. Although the TMS-82+ showed a worse property for TMF without a hold time, it exhibited a better TMF property than the TMS-75 for TMF with a hold time.
2. The TMS-82+ showed higher tensile strength at \(400\) °C and higher stress relaxation resistance at \(900\) °C than the TMS-75, which led to a smaller plastic deformation in tension and a longer rupture life in the TMS-82+.
3. The number of slip bands was relatively smaller in the TMS-82+ than in the TMS-75 under identical conditions, and a slightly rafted \(\gamma/\gamma'\) structure was observed in the TMS-82+ for TMF with a hold time.

### REFERENCES