RELATIONSHIPS BETWEEN MICROSTRUCTURE AND MECHANICAL PROPERTIES IN Ti-6Al-2Sn-4Zr-2Mo-0.1Si ALLOY FORGINGS

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INTRODUCTION

During recent years, the increasing demands for higher temperature performance and lower weights of jet engine components have brought about the development and commercial use of near-alpha elevated temperature titanium alloys. As a result, the Ti-6Al-2Sn-4Zr-2Mo-0.1Si (designated as Ti-6242Si) alloy has been mostly used for high temperature applications of titanium alloys \( \text{(1, 2)} \). The use of Ti-6242Si has extended the useful temperature of titanium alloys to the 900°F(482°C) regime; here both creep and fatigue properties at high temperatures are critical factors in determining the life cycle of the components. Very recently, the optimum processing and heat treating conditions have been further established for producing the alloy forgings that extend the use of forgings to higher operational temperatures (i.e., 1100°F/593°C) \( \text{(3, 4)} \). However, in spite of the great importance of the Ti-6242Si alloy in jet engine applications and large influence of the microstructure on mechanical properties, the relationships between microstructure and mechanical properties have not yet been well documented. In particular, very limited information has been made available as to how the change in microstructure varies the creep resistance of the alloy forgings.

Metallurgically, the alloy Ti-6242Si is a near alpha, alpha-beta titanium alloy \( \text{(1)} \). Density of the Ti-6242Si alloy is 0.164 lb/in\(^3\) (4.5 gm/cm\(^3\)), and the (α+β)/β transus temperature is about 1820°F(993°C). The 6% Al addition in the alloy is a potent α-phase stabilizer, while 2% Mo represents a moderate quantity of β-phase stabilizer. The Sn and Zr are relatively neutral with respect to stabilization behavior and are solid solution strengthening elements for both α- and β-phases. Mo is added to increase room- and elevated-temperature strength and stability, while the combination of Al, Sn, and Zr is to improve the creep strength of the alloy. Silicon is a strong β-stabilizer and is more soluble in β-phase than in α-phase. The minor addition of 0.1% Si to this alloy has been shown to significantly enhance the high temperature creep properties of the alloy without any apparent undesirable effects \( \text{(2)} \).

In forging practices, the (α+β)-forging combined with (α+β)-solution treatment has been generally used to manufacture Ti-6242Si alloy forgings. Until recently, however, the β-forgings was used to acicularize the microstructure which resulted in a reduction in LCF and ductility, but increased the creep strength and fracture toughness. Like other titanium alloys, the control of the nature and distribution of both globular-α and transformed products by forging and heat-treating variables are of great importance in determining the mechanical properties of the forgings.

In the present paper, the relationships between microstructure and mechanical properties for the Ti-6242Si alloy pancake forgings are presented. The experimental effort involved the determination of microstructure-
mechanical property correlations and the examination of microstructural features through optical, SEM-, and TEM-microscopies. The variation of creep properties with microstructure was particularly emphasized.

**EXPERIMENTAL VARIABLES**

The starting material for this investigation was 9 inch diameter bar of commercial Ti-6242Si grade. Metallographic examination showed that the starting material had a structure characterized by final processing in the (α+β)-phase field. The chemical composition (wt.%) of the as-received bar (TMCA heat number N-4694) as analyzed by Wyman-Gordon is 5.93% Al, 2.00% Sn, 4.20% Zr, 1.80% Mo, 0.11% Si, 0.08% Fe, 0.03% Cu, 0.099% O₂, 0.011% C, 0.007% N, and 0.0032% H₂. The (α+β)/β transus temperature for this heat bar was estimated to be 1820°F (993°C).

In this investigation, various forge and heat-treat combinations were used to produce the forgings with a wide variety of microstructures and a broad range of creep properties. The forging and heat treating variables for the forgings used have been described previously [4]. Briefly, sixteen pancake forgings were produced. The billet multiples were upset from 4 inches (102 mm) for 69% thickness reduction, both isothermally and conventionally, subtransus and supertransus (from 1750 to 2100°F or 954 to 1149°C) to produce pancake forgings of 1.25 inches (32 mm) thick by 16 inches (406 mm) in diameter. Both (α+β)-preforms (a structure of approximately 70% globular-α in a transformed matrix) and β-preforms (a structure of transformed Widmanstatten colonies and acicular-α) were used. All pancakes were sectioned and subjected to selected heat-treat conditions. The effects of solution treatment at temperatures from 1650 to 2000°F (899 to 1093°C) and times ranging from 1 to 8 hours were investigated. Aging treatments were made between 8 and 16 hours at 1100°F (593°C). The effects of cooling rate from forge temperature and solution-treat temperature were also investigated.

The mechanical property evaluations included creep, room temperature tensile, hot tensile, fracture toughness, and post-creep tensile properties. All of the test specimen blanks were cut along circumferential orientation of the pancakes. The fracture toughness measurements were performed only for the forgings having distinctly different microstructures; compact tension fracture toughness specimens were used. The structural features for each condition were examined using optical, scanning, and transmission electron microscopies. Fractographic analyses were made to examine the topographical features in both broken fracture toughness and creep rupture specimens. In some cases, TEM extraction replica was used to identify the nature and distribution of the precipitates.

**EXPERIMENTAL RESULTS AND DISCUSSION**

**Correlation Between Microstructure and Creep Property**

For some time, the microstructural features at optical magnifications have been used to characterize the mechanical properties of the alloy. Based on the forging microstructural appearance and creep results obtained
in this investigation, the high temperature property (creep) of Ti-6242Si alloy can be broadly grouped into eight microstructural categories depending on the nature of primary-α and transformed products (Figure 1). From a creep standpoint, they can be further divided into three different groups, namely high (A and B), intermediate (C, D, E, and F), and low (G and H) creep resistances.

It is seen from Figure 1 that the microstructures characterized by less-defined fine Widmanstatten patches (A) and pseudo-β structures (B) appear to have the highest creep resistance. In practice, such high creep microstructures can be produced by either β-forging or (α+β)-forgings, followed by (α+β)-solution treatment for β-forgings and β-solution treatment for (α+β) forgings. Cooling rate from β-phase field is important in restricting the size of Widmanstatten packets. Previous work has shown that the size and the orientation of Widmanstatten colonies are dominant factors in the fracture behavior of titanium alloy (3).

Both globular-α (G) and transformed martensitic-α (H) appear to significantly degrade the creep properties. Globular-α microstructures are

Figure 1 Creep strain versus time curves for eight microstructural conditions of Ti-6242Si alloy pancakes
C.C. Chen and J.E. Coyne

Figure 2 Solution-temperature dependence of creep resistance for (α+β) and β-forgings obtained by (α+β)-forging combined with (α+β)-solution treatment, and such a forging and heat treating sequence is most often used for manufacturing the Ti-6242Si alloy forgings. It appears that the conventional practices to spheroidize the primary-α of the alloy forgings has limited the creep capability of the alloy. However, the presence of globular-α is known to significantly improve the low cycle fatigue of the alloy. It also provides a slight increase in both tensile strength and ductility as compared with transformed basketweave microstructure. The martensitic transformed structure is developed by water-quench from β-solution temperature. Such a microstructure is known to be beneficial for high cycle fatigue, and often gives significantly higher strength and lower ductility for the forgings.

The microstructures with intermediate creep resistance (C, D, E, and F) are generally characterized by coarser Widmanstatten-α and colonies and/or pseudo-β microstructures, as compared to the fully transformed microstructures in high creeps. Similar to high creep conditions, these microstructures were developed by either (α+β) or β-forgings followed by either (α+β) or β-solution treatments, but differences in forge temperature, solution temperature, and/or cooling rate were applied. However, a comparison of microstructural appearance in Figure 1 clearly shows that the difference in the microstructural features between high and intermediate creep resistances cannot be distinguished based on the microstructural control at optical magnifications.
Thus, the relationships between creep properties and optical microstructures were limited to only several extremely different conditions, i.e., transformed martensitic-α, globular-α, and Widmanstätten-α microstructures.

**Processing/Structure/Mechanical Property Interactions**

The variations of mechanical properties with microstructures of the Ti-6242Si alloy depend strongly on both forging variables and heat-treating conditions. In particular, the creep properties of alloy forgings have a complicated relation to the heat treat conditions. Although there is no obvious difference in optical microstructures, the changes in solution temperature (Figure 2) and time (Figure 3), intermediate anneal (Figure 4), and cooling method (Figure 5) have significant influence on creep resistance of the alloy forgings. The use of (α+β)-solution treatment significantly degrades the creep properties of (α+β) forgings, and the (α+β)-solution treatment generally gives a better creep strength than that resulting from β-solution treatment for β-forgings.

The creep property appeared to be insensitive to aging time. Within the forge conditions investigated, the type of forging, forge temperature, and preform microstructure were found to have an important effect on creep properties (3). Since solution treatment for this alloy forgings has been generally made at very high temperatures, none of the die temperature, ram rate, cooling method from the press were detrimental to creep resistance.
Earlier investigation \(^{(4)}\) had determined the influence of processing variables on the forging deformation and resultant structures of Ti-6242Si alloy forgings. The results demonstrated that the forging deformation and the resultant structures are strongly dependent on the forge temperature, die temperature and ram rate, and the effect of preform microstructure was particularly emphasized. The deformation characteristics under isothermal forging were quantitatively related to the hot deformation properties of the alloy and the rate-controlling deformation process in (\(\alpha+\beta\))-processing conditions is attributed to the dynamic softening. This means that the structural change occurs during forging deformation.

**Observation of Heterogeneous Precipitates**

As discussed earlier, the creep resistance of the alloy forgings varied strongly with forging schedule and subsequent heat treatment, which cannot be simply interpreted in terms of microstructural features of the alloy forging. A wide range of creep properties are often observable within a given microstructure and the variations in creep can be generally related to the processing histories of the forgings.

Figure 6 presents the effect of the nature and distribution of incoherent precipitates on the creep resistance of the alloy forgings; these submicrostructures were obtained from electrolytically extracted replica. X-ray fluorescent analysis of the particles indicates that these particles are generally rich in silicon and tin (Figure 7). Such undesirable particles are often formed as a result of improper forging and heat treating condi-
tions and do not significantly affect the tensile ductility and strength properties. These particles are not observable at optical magnification and are more confined to the interface region for low creep conditions. Attempts by thin foil TEM failed to correlate these particles to α2-phases. It is also seen from Figure 6 that at high creep conditions, an excellent combination of creep, tensile, and fracture toughness properties could be achieved for the forgings.

Figure 8 further illustrates examples of fracture surface of broken creep-rupture samples and fracture toughness samples at high, intermediate, and low creep conditions. At both high and low creep resistances, the size of prior β-grains and Widmanstatten colonies are shown to control the creep fracture behavior of the alloy (Figure 8a). Similar to that observed for Ti-6Al-4V alloy forgings (9), the higher fracture toughness of fully transformed microstructures appears to associate with the extent of crack branching (Figure 8b).

It has been suggested that the immobilization of mobile dislocations by either fine silicide or silicon atmosphere may dominate the rate controlling creep mechanism for the high temperature titanium alloys containing silicon (7,8). Since Si and probably Sn are effective solid solution strengtheners for creep resistance, the extraction of these elements from solid solutions to form incoherent precipitates due to improper thermomechanical history would obviously affect the state of silicon dissolution, thereby limiting the availability of silicon in solution for improved creep properties.
Figure 6 Optical microstructures at three distinctly different creep resistances and corresponding extraction replicas showing the nature and distribution of precipitates in Ti-6242Si alloy forgings

Creep test condition: $1050^\circ F (566^\circ C) - 25 ksi (172 MPa)$

From the above, it is clearly demonstrated that one of the major factors in limiting the high creep capability of Ti-6242Si alloy is the formation of incoherent precipitates containing Si and Sn, which, in turn, depend critically on the forge and heat treat schedules. The basic problem in the conventional treatments for correlating the microstructure and mechanical properties arises because of the lack in understanding the formation of such heterogeneous precipitates.

Achievable Properties and Process Optimization

At the present, the most common forge and heat treat schedule for the Ti-6242Si alloy comprises: forge at temperatures high in the $(\alpha+\beta)$-field, air cool, solution treat for one hour at temperatures high in the $(\alpha+\beta)$-field, air cool, stabilization age for 8 hours at $1100^\circ F (593^\circ C)$, and air cool. The 0.1% creep strain at $950^\circ F (510^\circ C)/35 ksi (241 MPa)$ test condition for these $(\alpha+\beta)$-forgings requires about 35 and 125 hours, respectively, depending on the specification requirements. As stated earlier, the $\beta$-forgings of this alloy have been very recently used in some cases to acicularize the microstructure and have shown to result in increases in creep strength and fracture toughness with a slight reduction of both strength and ductility. By using the $(\alpha+\beta)$-
solution treatment and aging, the time required to reach 0.1% creep strain for β-forging could be increased from (α+β)-forged condition by a factor of 2 quite easily. The times to reach 0.1% creep at 950°F (510°C)/35 ksi (241 MPa) test condition for transformed microstructures produced by β-forging are in the range of 200 to 400 hours; this is estimated equal to about 35 hours at 1050°F (566°C)/25 ksi (172 MPa) test condition.

By optimizing microstructural and submicrostructural features of the alloy forgings, the present investigation has shown that the creep properties of Ti-6242Si alloys could be maximized for both (α+β)- and β-forgings through processing and structural controls. For (α+β)-forgings, the best creep can be achieved by a β-solution treatment, followed by a conventional aging at 1100°F (593°C) for about 8 hours, and air cooling. The solution treatment should be conducted within the (α+β)-phase range for β-forgings. These processing conditions obviously result in minimizing or eliminating the formation of incoherent precipitates and in achieving the maximum creep properties of the alloy. The range of achievable creep properties through the above processing conditions obtained in this investigation are 70 to 110 hours 0.1% creep and 160 to 200 hours 0.2% creep at 1050°F (516°C)/25 ksi (172 MPa) test conditions, and 30 to 50 hours 0.1% creep and 80 to 100 hours 0.2% creep at 1100°F (595°C)/15 ksi (103 MPa). Other properties associated with these processing conditions are: 130 to 135 ksi (896 to 931 MPa) yield strength, 145 to 155 ksi (1000 to 1069 MPa) UTS, 8 to 13% elongation, and 15 to 25% reduction of area. The fracture toughness values are generally in the range of 70-75 ksi·√in. (77-82 MPa·√m) KIC. Table I illustrates examples of the mechanical properties achievable for Ti-6242Si alloy forgings through various processing controls, and at various property combinations.
SUMMARY

The results of this investigation demonstrated that excellent combination of creep, tensile, and fracture toughness properties of the alloy forgings can be achieved for both \((\alpha + \beta)\) and \(\beta\)-forgings through optimum control of the microstructures, on both a micro- and submicroscale. The creep resistance of the Ti-6242Si alloy forgings has an obvious variation with optical microstructure only at a broad range of microstructural differences. The microstructure characterized by less-defined fine Widmanstatten colonies appears to have the highest creep resistance if proper heat treatment is used. Both transformed martensitic-\(\alpha\) and globular-\(\alpha\) appear to significantly degrade the creep and fracture toughness properties. By eliminating and/or reducing the incoherent precipitates through adequate control of processing variables, excellent creep resistance of Ti-6242Si alloy forgings was achievable.
### TABLE 1

<table>
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<tr>
<th>Forge/ Creep* Time</th>
<th>Creep* Rupture Time</th>
<th>YS</th>
<th>TS</th>
<th>RT Tensile</th>
<th>900°F Tensile</th>
<th>Post-Creep Tensile</th>
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<td>Heat Treat</td>
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<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
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<tr>
<td>(441)/8</td>
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<td>74</td>
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<td>150</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>(441)/8</td>
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<td>69</td>
<td>134</td>
<td>156</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>(441)/(a+b)</td>
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<td>50</td>
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<td>154</td>
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<tr>
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<td>134</td>
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<td>23</td>
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<tr>
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<td>75</td>
<td>136</td>
<td>156</td>
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<tr>
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<td>76</td>
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<td>72</td>
<td>122</td>
<td>141</td>
<td>7</td>
<td>17</td>
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</table>

**Creep condition:** 1050°F (566°C) - 25 kpsi (172 MPa)

**Creep rupture:** 1050°F (566°C) - 50 kpsi (345 MPa)

* Estimated value

### REFERENCES