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High-Temperature Precision Forming of Titanium Blades

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Based on the experimental study of superplastic deformation parameters, a technology was developed for producing near-net-shape compressor blade forgings for gas turbine units from Ti-6.2Al-2.5Mo-1.5Cr-0.2Si-0.5Fe. The mechanical properties of these blades are higher than those of blades produced by conventional methods, and the anisotropy coefficient is reduced. The improved properties of the blades can be attributed to the isotropy of mechanical properties resulting from the homogeneous fine-grained equiaxed structure produced throughout the blade volume.

Keywords
mechanical properties, superplasticity, titanium alloy

1. Introduction

MATERIALS used for compressor blades must meet certain requirements of strength, crack resistance, and stability (Ref 1). This paper presents results obtained in a study of the influence of a unique method of superplastic deformation (SPD) on the ductile and strength characteristics, impact toughness, endurance, and anisotropy of the properties of a two-phase titanium alloy. The investigation was carried out using near-net-shape blade forgings of intricate aerodynamic shape, 80 by 190 mm in projection size. Results are compared with results for similar blades produced by conventional hot forging on a mechanical press.

2. Experimental Procedure

The chemical composition (in weight percent) of the tested alloy was Ti-6.2Al-2.5Mo-1.5Cr-0.2Si-0.5Fe. Fine-grained and coarse lamellar microstructures of the blanks were obtained by rolling in the temperature regimes of the two- and one-phase fields, respectively.

The SPD conditions were defined by tensile tests of round specimens with gage dimensions of 5 mm diameter and 25 mm length. Superplastic deformation was carried out on a 630 ton hydraulic press in an induction heating unit mounted on the press. Blanks in the form of measured rods and a die were heated in the ($\alpha + \beta$) region to 30 to 40 °C below the β-transus point: $T = 930 \pm 10$ °C. They were subjected to deformation in the strain rate range of 10^{-3} to 10^{-1}/s. Maximum strain at the trailing edge of a blade did not exceed 80%. The forgings were cooled at a regulated rate of 4 °C/s. After deformation, the forgings were aged at 530 °C in the electric furnace, held for 2 h, and air cooled. Blanks were also conventionally manufactured by forming on a mechanical press in a cold die at a strain rate of 10^0 to 10^1/s and high-temperature annealing at 950 °C.

Mechanical properties were determined on specimens cut from various zones of both types of forgings: the blade root portion and the airfoil portion in different directions (lengthwise and crosswise). All mechanical tests were carried out at room temperature. Tensile tests were conducted on round specimens

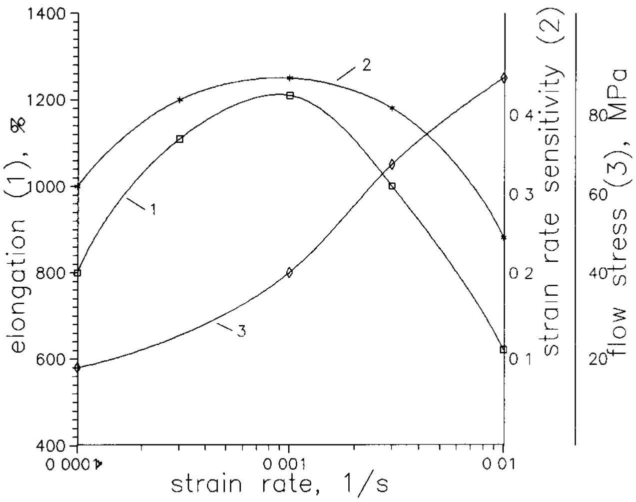

Fig. 1 Dependence of flow stress (3), elongation (1), and strain-rate sensitivity (2) on strain rate for the titanium alloy at 930 °C

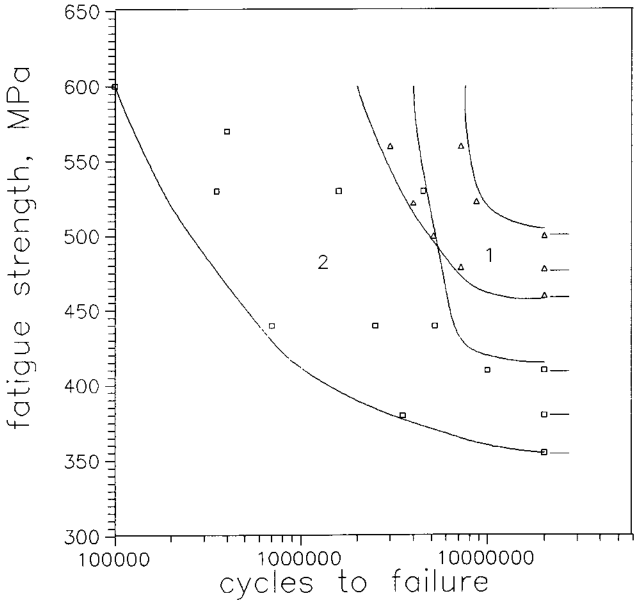

Fig. 2 Fatigue curves for titanium alloy blades produced by conventional processing (2) and by SPD (1)

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with gage dimension of 3 mm diameter and 15 mm length using a crosshead rate of 1 mm/min. Impact toughness was determined on Charpy U-notch and notch fatigue cracked specimens. Fatigue strength was determined on the full-scale blades, which were machined on a vibroelectrodynamic unit at fundamental tone oscillations on the base of $N = 2 \times 10^7$ cycles. Polished etched sections were viewed in an optical microscope.

3. Results and Discussion

3.1 *Mechanical Properties*

In a definite temperature-rate interval, the titanium alloy displayed evidence of superplastic behavior. As shown in Fig. 1, the values of elongation (δ) and strain-rate sensitivity coefficient (m) reached their maximum at temperatures near 930 °C and at a strain rate of 10^{-3}/s. These thermomechanical parameters were used in the technology of near-net-shape blade forging.

Table 1 lists the material characteristics of an airfoil portion of a blade in different directions. Data from ten specimens showed that SPD processing significantly enhances blade properties compared to conventional processing, especially in terms of tensile strength, ductility, and fatigue strength (Fig. 2).

The effect of SPD in terms of enhancement of isotropy of the mechanical properties of blades also was investigated. Increased isotropy of properties is a primary reason for increased machine reliability and service life (Ref 2-4). Homogeneity of properties is an important requirement when the limit of allow-

Table 1 Mechanical properties of titanium alloy blades produced by SPD and by conventional processing (CP)(a)

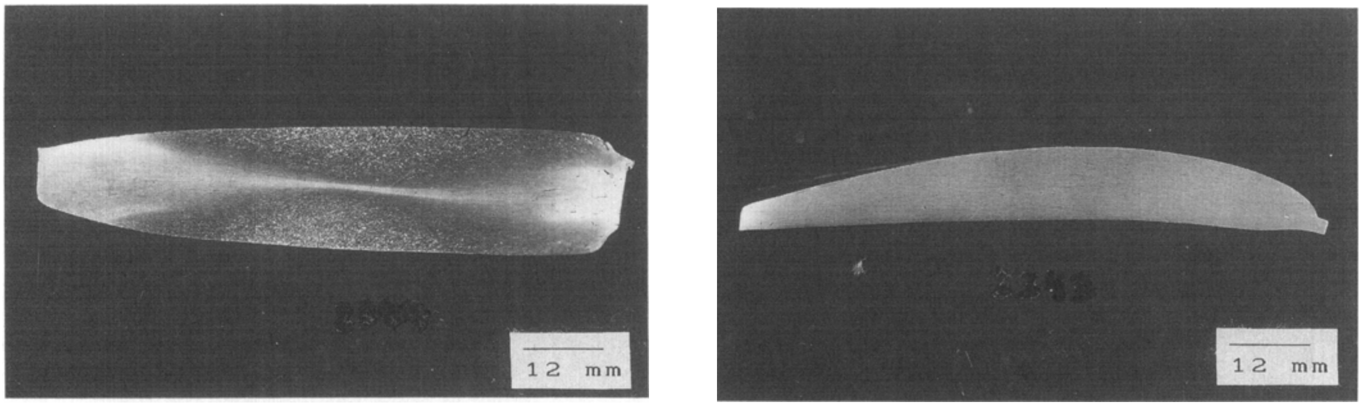
Method of forging	Tensile strength, MPa	Elongation, %	Reduction in area, %	Impact toughness, $J/mm^2 \times 10^2$ U-notch	Impact toughness, $J/mm^2 \times 10^2$ Crack
SPD,	1175-1200	17-19	52-56	54-56	15-18
lengthwise	(1190)	(18)	(54)	(55)	(16)
SPD,	1145-1170	14.5-16	54-57	49-52	15-17
crosswise	(1150)	(16)	(55)	(51)	(16)
CP,	995-1130	13-20	31-37	38-57	9-13
lengthwise	(1080)	(16)	(35)	(50)	(10)
CP,	930-990	13-17	35-42	35-50	12-20
crosswise	(945)	(14)	(38)	(43)	(19)

(a) The ranges of data represent lowest and highest values for ten specimens. Mean values are given in parentheses.

Table 2 Mechanical properties of initial blank and final SPD blades(a)

Material condition	Tensile strength, MPa	Elongation, %	Reduction in area, %	Impact toughness, $J/mm^2 \times 10^2$ U-notch	Impact toughness, $J/mm^2 \times 10^2$ Crack
Rod	920-1100	8-14	15-21	35-47	9-13
(blank)	(1050)	(9)	(20)	(42)	(11)
SPD blade	1160-1200	17-19	39-42	39-42	15-17
	(1195)	(18)	(40)	(41)	(16)

(a) The ranges of data represent lowest and highest values for ten specimens. Mean values are given in parentheses.



(a) (b)

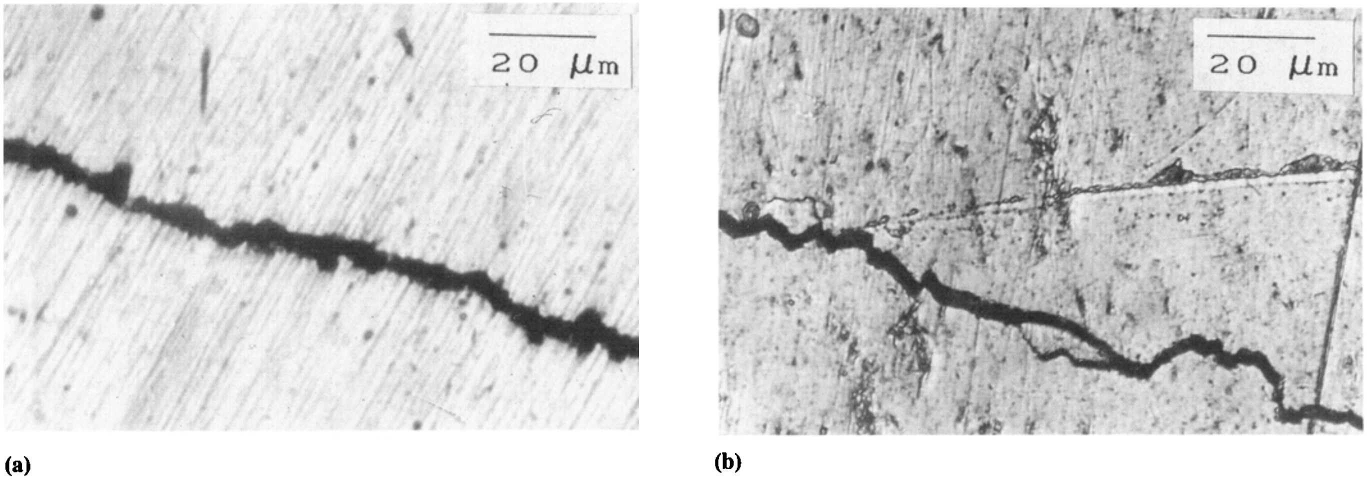
Fig. 3 Macrostructure of the blade forging in cross section. (a) Conventional technology. (b) SPD able level of the material properties is calculated. Test results show that, compared to conventional processing, the scatter of the properties and the anisotropy coefficient, K_a, of SPD blades decreases (Table 1). Thus, for example, the values of K_a (calculated for mean characteristic values) of ultimate strength (σ_u) decreased from 1.2 to 1.03, and K_a of impact toughness of notched fatigue cracked specimens decreased from 1.9 to 1.

The effects of SPD can be used to increase sharply plasticity and strength in two-phase titanium alloys with an initially coarse lamellar structure. The blades were produced from low-plasticity initial rods. Comparative mechanical test data for ten specimens showed that the mean value of performance ductility, ψ and δ, increased by 100%, strength increased by 15%, and impact toughness increased by 30% for blade forgings produced under SPD conditions compared to blades produced from rod blanks (Table 2).

3.2 *Structural Investigations*

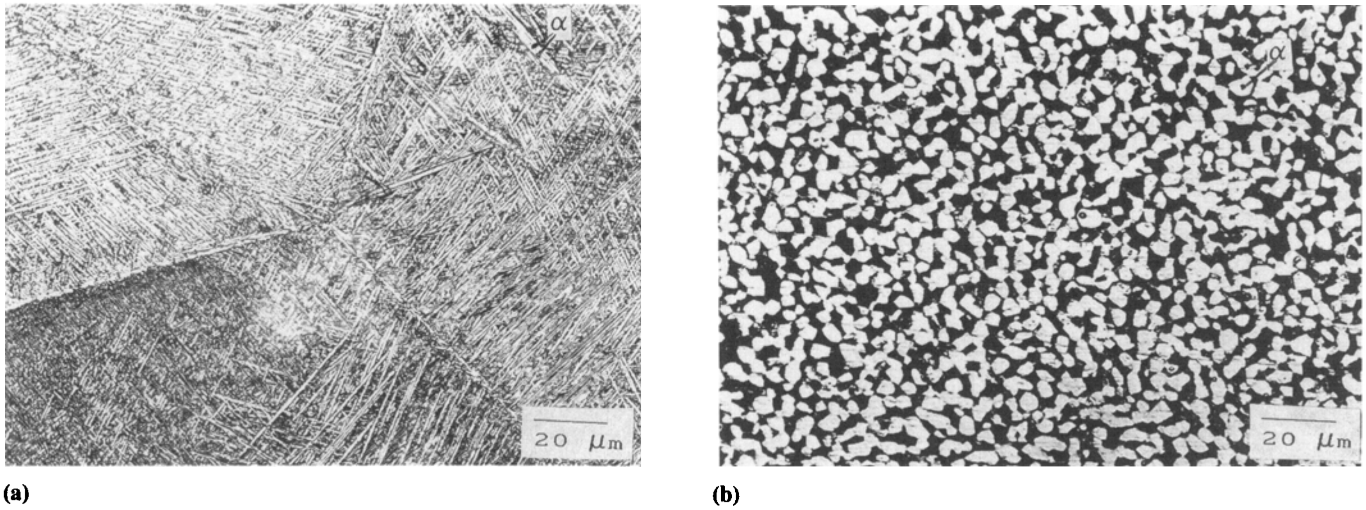
The highest strength and ductile properties have been observed in two-phase titanium alloys with a fine-grained equiaxed microstructure (Ref 5-7). A favorable structure is formed during SPD, with grains becoming finer and more equiaxed. Grains rotate around one another, relative sliding occurs, and dynamic recrystallization is observed (Ref 8). The formation of a fine-grained equiaxed structure by SPD in all the component volumes is one of the main strengthening factors (Ref 1).

Spreading of the initial crystallographic texture occurs during superplastic flow. After 50% SPD, a textureless state with uniformly distributed crystallographic grain orientation throughout the volume is formed (Ref 8). This state provides structural homogeneity and high isotropy of mechanical properties throughout the component volume (Table 1). During conventional forging, a homogeneous structure cannot be achieved because of the sharp decrease in temperature when the blank is transferred from the heating unit to the press, where it contacts a cold die. Also, the deformation rate is high (greater than 200 mm/s), resulting in decreased plasticity in the surface layers and formation of localized areas of heat emission and zones of intensive metal flow (Fig. 3). Blades fabricated conventionally have a vividly pronounced anisotropy of properties. The type of structure that is formed after hot deformation affects alloy



(a)
(b)

Fig. 4 Micrograph of trajectory of crack propagation in nonetched specimens. (a) Conventional technology. (b) SPD



(a)
(b)

Fig. 5 Microstructure of the titanium alloy. (a) Initial blank (rod). (b) SPD blade crack resistance as well. As shown in Fig. 4, after SPD a fatigue crack propagates in a branchlike manner, and secondary cracking is observed. After conventional processing, the crack propagates in a more straight-line way.

The enhancement of properties by SPD in an alloy with an initially coarse lamellar structure is due to the transformation of this structure into a fine-grained one (Fig. 5). Thus, at the first stage of deformation, the fragmentation of plates is the result of the increased dislocation density. The spheroidization that follows and phase transformations complete the structure transformation (Ref 9). In this case, the finer the plates in the initial material, the finer the grains of the α-phase formed. Superplastic flow is the final stage of deformation.

4. Conclusions

This study shows that SPD transforms nonhomogeneous, coarse lamellar structure into a homogeneous, fine-grained, equiaxed structure with α-phase grains between 5 and 10 μm in size, in which α:β volume ratio is equal to 50:50 in all cross sections of the blades manufactured. This type of structure is preferred for blades that operate under great alternating loads.

The experiments and studies performed resulted in the development of precision technology for producing near-net-shape titanium alloy blade forgings under superplastic conditions. The forgings are of high quality and reliability. This technology can be successfully used to produce components with excellent strength, ductility, and fatigue properties.

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