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Manufacturing Advantages of Superplastically Formed Fine-Grain Ti-6Al-4V Alloy

Peter N. Comley

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Superplastic forming (SPF) of Ti-6Al-4V has traditionally been performed at 900 °C. Although SPF equipment and dies have been developed to withstand this high temperature, their life is limited and maintenance is high. In addition, the formed sheets need chemical milling after processing to remove a significant layer of alpha case, and parts require hand polishing due to a rough die surface caused by high temperature oxidation. The recent development of a Ti-6Al-4V alloy with a grain size of around 1 μm has led to the possibility of superplastic forming at a much lower temperature than regular Ti-6Al-4V. In addition, the forming speed can be increased. This work looks at some of the SPF attributes of fine-grain titanium, in particular, the optimum forming temperature, the thinning characteristics, alpha case formation, and forming speeds. The authors also address manufacturing advantages, such as die life, equipment needs, and operator comfort. Some prototype and preproduction aircraft components on Boeing airplanes are presented. The results show that the new fine-grain material could significantly lower the cost of SPF Ti-6Al-4V part production for the aerospace industry.

Keywords alpha case, forming speed, fine-grain Ti-6Al-4V, SP700, SPF, superplasticity, titanium, VSMPO

1. Introduction

Superplastic forming (SPF) of the widely used titanium alloy Ti-6Al-4V has been an aerospace manufacturing process since the early 1980s, and the forming temperature of this alloy has been standardized at 900 °C. There has been much development in die materials, platens, and heater design in the last 20 years to withstand the operating conditions of SPF at this high temperature, but it is evident that die life is limited, and platens and heaters continue to need replacement on a frequent basis. Rather than continuing to seek newer and better materials to work at 900 °C, the Boeing Company has been working with VSMPO (Verkhnaya Salda, Russia) to develop a new processing route for Ti-6Al-4V to make it superplastic at a lower forming temperature.

It is well known that grain refinement will give optimum properties at lower temperatures (Ref 1, 2). For example, Boeing manufactures an SPF part in SP700 (Ti-4.5Al-3V-2Fe-2Mo) (Ref 3), a titanium alloy developed by JFE (Yokohama, Japan). This alloy has a grain size of about 3 μm, compared with 6 μm for conventionally processed Ti-6Al-4V, and the alloy is highly superplastic at 775 °C. The alloy is no longer available in the United States and Europe, but based on production experience over the last three years, there are a number of reasons why forming at this temperature will bring tangible benefits to the production of SPF titanium parts.

Work by Salishchev (Ref 4) showed that it is possible on a laboratory scale to achieve submicron grain sizes in Ti-6Al-4V by special processing. Accordingly, VSMPO was contracted to determine if grain refinement of Ti-6Al-4V was possible in the manufacture of full-size production sheet and to find what the grain size would have to be for the material to show good SPF properties at 775 °C. VSMPO refined their sheet manufacturing process to create a 1 μm grain size material. Boeing has procured several thicknesses of 1.2 × 3.6 m sheet of this material, called "fine-grain Ti-6Al-4V" and has now tested the SPF properties and formed prototype parts.

2. Results and Discussion

2.1 SPF Properties of Fine-Grain Ti-6Al-4V

Figure 1 shows the stress versus strain curve for the VSMPO fine-grain Ti-6Al-4V material at 775 °C, together with a comparison of conventional Ti-6Al-4V made by RMI (Niles, OH) at 900 °C. Both coupons were tested at a $3 \times 10^{-4}\ s^{-1}$ strain rate.

Most SPF parts at Boeing are formed with true strains up to 1.1 (200%). It can be seen from Fig. 1 that the SPF properties of fine-grain Ti-6Al-4V at 775 °C are similar to those of regular Ti-6Al-4V at 900 °C. Consequently, Boeing has decided to form fine-grain parts at 775 °C. Material has also been evaluated at 815 °C, which shows that the fine-grain Ti-6Al-4V is highly superplastic, having an elongation of more than 2.2 without apparent necking. Thus, is it possible that complex parts with areas of high elongation that are not readily formable at 775 °C could be better formed at 815 °C.

2.2 Alpha Case

One of the features of superplastic forming of conventional Ti-6Al-4V at 900 °C is that about 25 to 50 μm of alpha case

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Peter N. Comley, The Boeing Company, P.O. Box 3707, m/c 5K-63, Seattle, WA 98124. Contact e-mail: peter.n.comley@boeing.com.

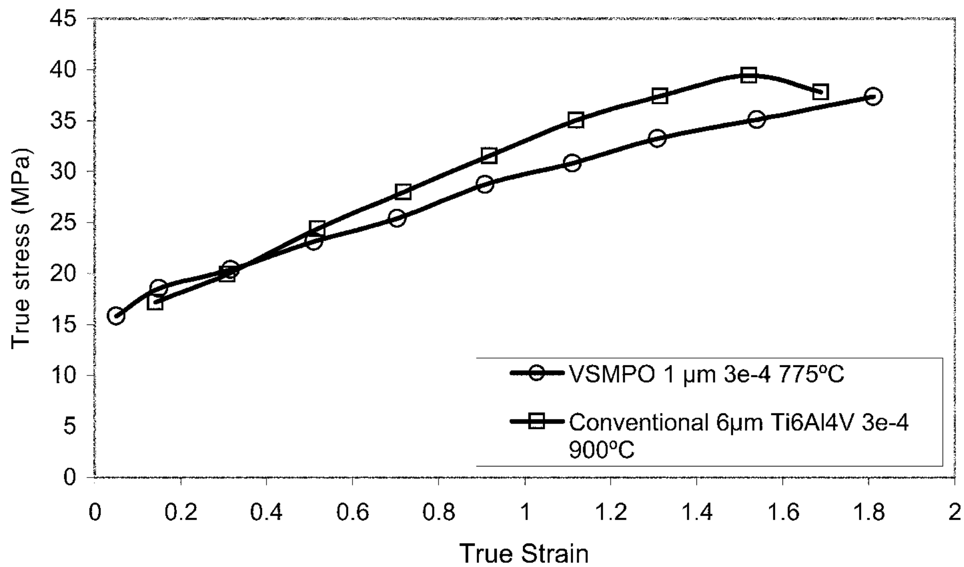

Fig. 1 Stress versus strain for conventional Ti-6Al-4V at 900 °C and VSMPO fine-grain Ti-6Al-4V at 775 °C

forms on the surface. This is taken off by a chemical milling operation that removes 75 μm from each surface. The process is not precise, however, and due to heating by the chemical reaction on the surface, more material is removed from thinner areas of the part than from thicker areas. Therefore, not only does the blank have to be 150 μm thicker than required, but the variation of thickness across the part is worse after the chemical milling process. On the other hand, the fine-grain material develops only about 13 μm alpha case during a typical SPF forming cycle. A flash etch to remove lubricant, plus removing 25 μm surface material by immersion in a tailored HF/HNO_3 solution (chemical mill pickle), is sufficient to remove all the alpha case and oxide-rich surface contamination, as confirmed by a 105° bend test on postformed parts. The "pickling" process does not significantly heat up the titanium, so the removal of material is more uniform than with chemical milling. Consequently, the starting blank thickness of fine-grain Ti-6Al-4V can be at least 0.1 mm less than conventional Ti-6Al-4V for the same final thickness of the part.

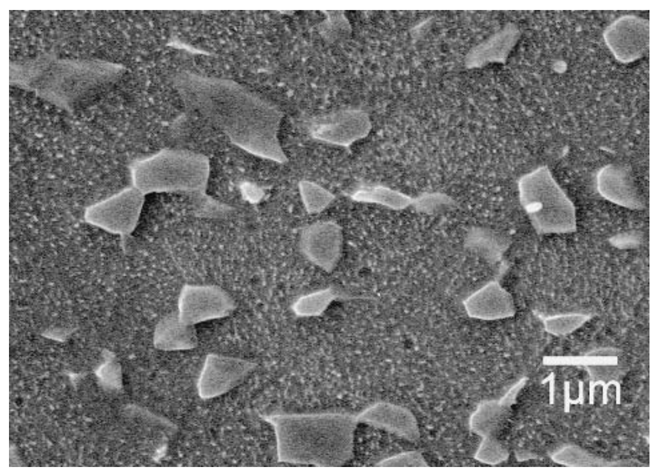

Fig. 2 As-received fine-grain Ti-6Al-4V

2.3 Grain Growth

One concern over using fine-grain material is the grain growth that can be expected during the forming operation. This would affect both the SPF characteristics and post-SPF mechanical properties of the material. Figures 2 to 4 show the grain size of the as-received material and parts made in 31 min and 55 min at 775 °C in the same die. Both alpha and beta phase growth is evident; however, the effect on the SPF properties has not yet been examined.

2.4 Die Life

The cost of SPF dies for titanium is very significant because the stainless steel used is expensive and difficult to machine. The limited production quantity (up to 4000) typical of aerospace means the tools can only be amortized over a small number of parts. The solid lubricant used in SPF quickly builds up on the die surface, and only a limited number of parts can be run at a time before the surface finish on the parts is compromised. Thus, the die undergoes many thermal cycles from room temperature up to operating temperature. Over time this causes cracks, especially around lift holes, die hanging slots, and other features of the die. The thermal cycling also induces die distortion, especially on long flat areas, and the high operating temperature has led some dies to creep so that parts made on them are also distorted. In addition, although the alloy content of the die is chosen to be heat and oxidation resistant, conditions inside the die are such as to cause corrosion and pitting of the surface, even though the outside surface remains smooth. An unfortunate feature of SPF is that this rough surface is reproduced in exact detail on the parts, so the die has to be rigorously cleaned and dressed before a run of parts. Typically, a die for conventional SPF of titanium is expected to last

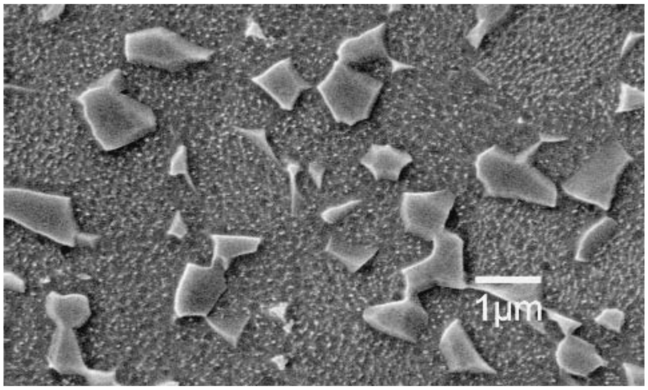

Fig. 3 Fine-grain Ti-6Al-4V after SPF for 31 min at 775 °C

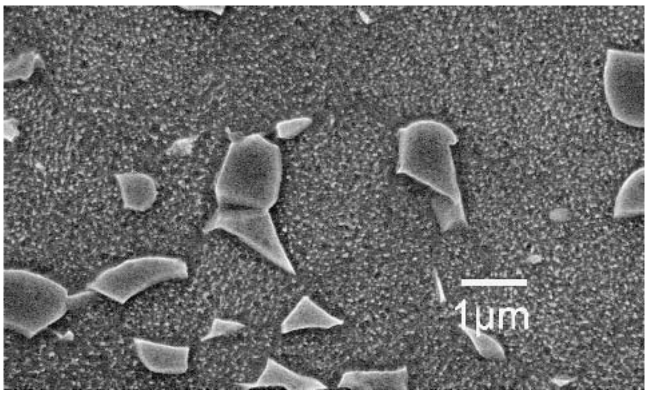

Fig. 4 Fine-grain Ti-6Al-4V after SPF for 55 min at 775 °C

about 70 thermal cycles before it is replaced. Figure 5 shows a typical die surface after three years of SPF production.

Boeing experience using dies for hot forming and SPF of SP700 at 775 °C has shown a marked improvement in the quality and integrity of the die after repeated usage over several years. Examination of a die made for the 757 passenger door thresholds in SP700 shows no cracking or distortion after three years use (Fig. 6). The die was easier to clean between production runs, and the surface finish remained excellent. Because the die surface is smooth, the part surface is also smooth, and there is little or no hand finishing required on these parts. It is anticipated that die life should exceed the normal production life of the aircraft if fine-grain Ti-6Al-4V is used at 775 °C.

2.5 Strain Rate Effects

Fine-grain Ti-6Al-4V can also be formed at a faster rate than conventional Ti-6Al-4V. Figure 7 shows the SPF stress versus strain characteristics at 775 °C for four different forming rates.

Conventional Ti-6Al-4V is usually formed at around 3×10^{-4} s^{-1}. The forming stress at this speed is 35 MPa after a strain of 1.1 (200%). Under the same conditions, fine-grain Ti-6Al-4V has a forming stress of 30 MPa. The forming stress is directly related to the gas pressure required to form a sheet, and so the fine-grain alloy requires less pressure to make components. Alternatively, at a stress of 36 MPa, fine-grain

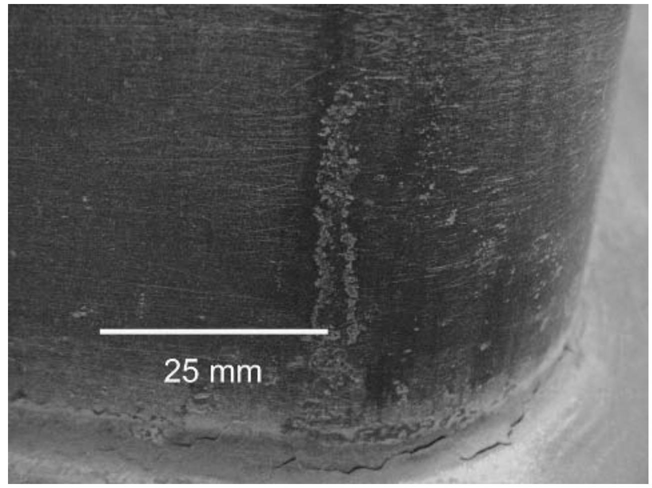

Fig. 5 Die surface after 900 °C SPF

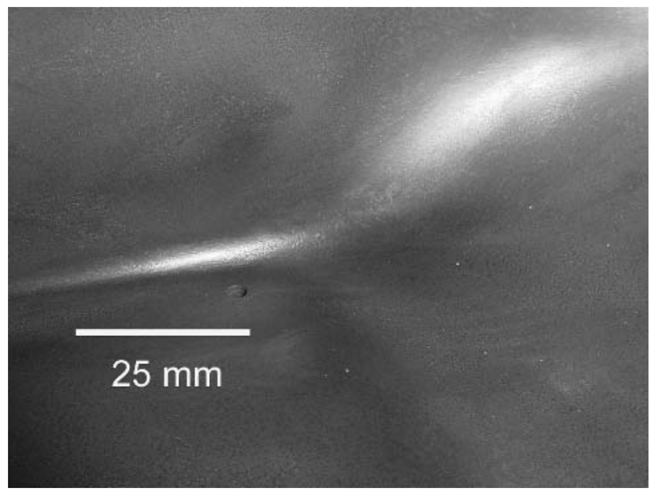

Fig. 6 Die surface after 775 °C SPF

Ti-6Al-4V forms at 6×10^{-4} s^{-1}. Thus, components can be formed twice as fast. Experiments making components at strain rates of 6×10^{-4} and 1×10^{-3} s^{-1} have been successful, with only a small compromise in part thickness distribution. Thus, the forming time can be reduced by up to 67%. In practice, the floor-to-floor cycle time is not reduced as much because loading, heat up, depressurization, and unload times remain the same; nevertheless, productivity can be considerably increased.

2.6 Forming Equipment

Superplastic forming presses are generally regular hydraulic presses with a special heated platen and heat shield package. The heated platen consists of segments of a highly creep- and oxidation-resistant alloy, which are bored to accept electric resistance cartridge heaters. In use, SPF presses are cooled after a run of parts so that the die can be removed for cleaning and then heated again. After a few years of thermal cycling, the platens are distorted and cracked to the point where they need to be replaced. It is expected that thermal cycling to 775 °C will

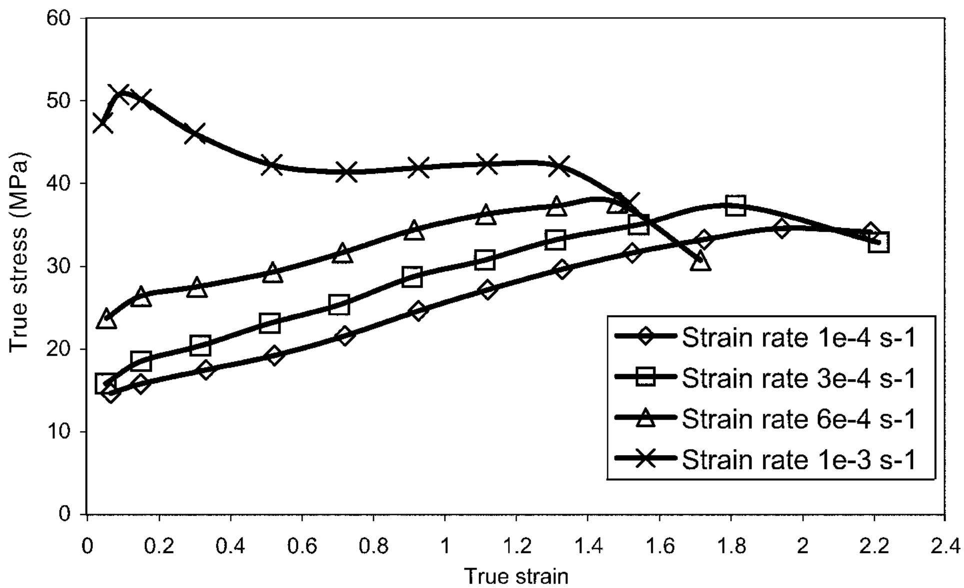

Fig. 7 Stress versus strain for fine-grain Ti-6Al-4V at different strain rates at 775 °C

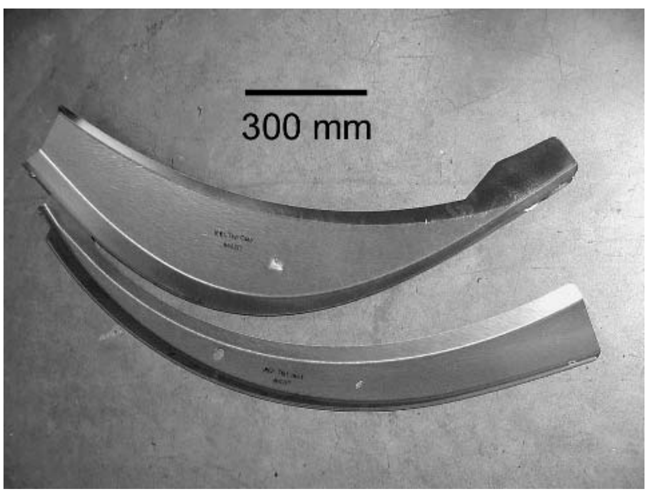

Fig. 8 Thrust reverser webs formed by SPF using fine-grained Ti-6Al-4V

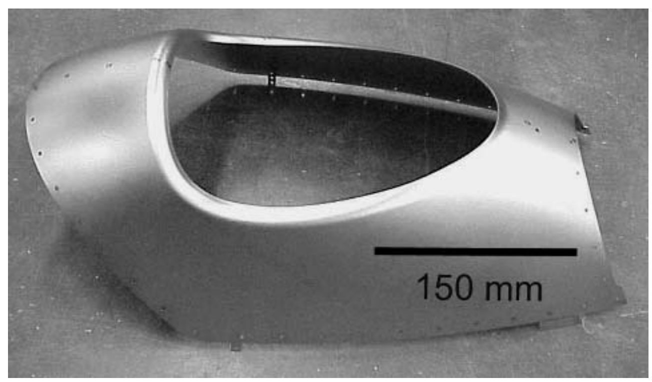

Fig. 9 Auxiliary power unit exhaust fairing formed by SPF using fine-grained Ti-6Al-4V

be less severe than to 900 °C, and based on experience with hot form presses at 760 °C, platen life should be extended by 50% or more.

Due to the low thermal conductivity of the stainless steels used in platens, the heating and cooling rates are programmed to be slow, typically 50 °C/h, to minimize the thermal stresses in the metal. Heating to 775 °C saves 4½ h per thermal cycle while changing dies, and this is significant for the frequent die changes typical of aircraft production. Thus, the utilization of the press is improved.

The electric resistance cartridge heaters in the platens have a limited life in an SPF press due to the high temperature and thermal cycling. The element inside the heater can run 300 °C higher than the platen temperature during heat-up and so can exceed 1200 °C, which is approaching the element melting point. Each thermal cycle allows air into the end of the heater as it expands and contracts. Eventually air reaches the element, causing oxidation and deterioration of performance, with the heater ultimately failing after 15 to 18 months. Press operation at 775 °C will at least double the life of the heaters in an SPF press.

2.7 Operator Safety and Comfort

Production of SPF titanium parts at 900 °C is potentially hazardous to the press operator. Although Boeing uses the highest degree of protective clothing for operators, the heat quickly transfers through gloves and helmets, limiting the time available to reach into a press to remove a part and load a fresh blank to a few seconds. Radiant energy follows a fourth power law with temperature, and a die at 775 °C has only 64% of the radiant energy of 900 °C. It is, therefore, considerably easier and more comfortable for the operator to work around a die at 775 °C, and personal protection equipment lasts longer at the lower temperature.

2.8 Experience on Production Parts

Several demonstration pieces have been made on production dies to demonstrate the advantages of using fine-grain Ti-6Al-4V. Figure 8 shows thrust reverser web details on the 737 aircraft. These are made at the same time on a die. The thickness of the starting blank in conventional Ti-6Al-4V is 2.28 mm to meet the thickness requirements of the finished part. Using fine-grain Ti-6Al-4V, the authors have found that a 1.95 mm gage blank gives the same finished thickness distribution. The forming time required to make the fine-grain Ti-6Al-4V is reduced by 44%. Figure 9 shows a 737 auxiliary power unit exhaust fairing. Using conventional Ti-6Al-4V, the starting blank gage is 2.03 mm, while the fine-grain Ti-6Al-4V is only1.8 mm. Additionally, the forming time is reduced by 34%. Thus, for these and other parts, the use of fine-grain Ti-6Al-4V reduces both forming time and blank gage, increasing productivity on the shop floor.

3. Conclusions

SPF tensile tests of 1 μm Ti-6Al-4V at different temperatures and strain rates has shown that fine-grain Ti-6Al-4V can be used in place of conventional 6 μm Ti-6Al-4V, at 125 °C lower SPF temperature. Prototype parts made on production dies have demonstrated that the following advantages can be realized:

- Chemical milling of postformed SPF parts is not required; instead, a flash etch and 25 μm pickle is sufficient to remove the alpha case.
- Die life is significantly extended, so that only one die is required over the production lifetime of the aircraft.
- Die surface finish is dramatically improved, so that part hand finishing and die rework is reduced.
- Press platen life can be extended by 50% and heater life doubled.
- Parts can be formed up to 44% faster, resulting in higher productivity.
- The starting blank thickness can be reduced by up to 17% to produce parts with the same final thickness.
- Operator comfort and safety during production of parts is increased.

References

1. A Arieli and A Rosen, Superplastic Deformation of Ti-6Al-4V Alloy, *Metall. Trans. A,* Vol 8A, 1977, p 1592
2. A.K. Ghosh and C.H. Hamilton, Influences of Material Parameters and Microstructure on Superplastic Forming, *Metall. Trans. A,* Vol 13A, 1982, p734
3. P.N. Comley, Aerospace Part Production Using SP700, *Mater. Sci. Forum,* Vol 357-359, 2000, p 41-46
4. G.A. Salishchev, R.M. Galeyev, O.R. Valiakhmetov, R.V. Safiullin, R.Y. Lutfullin, O.N. Senkov, F.H. Froes, and O.A. Kaibyshev, Development of Ti-6Al-4V Sheet with Low Temperature Superplastic Properties, *Mater. Proc. Technol.,* Vol 116, 2001, p 265-268