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Multi-rate Superplastic Forming of Fine Grain Ti-6Al-4V Titanium Alloy

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Most parts made by superplastic forming (SPF) have been formed at an optimum strain rate. The rate is selected to give the best SPF properties of the material. However, it has been proposed that multi-rate forming, where an initial high strain rate is successively reduced as the part is strained, can be used to make high strain parts in a much shorter time than traditional SPF forming. This paper examines the performance of fine grain Ti-6Al-4V alloy at very high initial strain rates, from 10–30 times faster than usual, with step reductions at prescribed levels of strain that still enables a total strain of over 2.1 (800%) to be achieved without degradation of the material. The paper also shows that the forming time to 100% deformation can be reduced from 55 min to 9 min. This technique can be used by industry to enable faster flow times and lower production costs of SPF parts.

Keywords fine grain, forming time, multirate forming, strain rate, superplastic

1. Background

The superplastic properties of SPF materials vary with the strain rate imposed on them. In general, the faster the strain rate, the lower the total elongation to failure. However, very slow strain rates also have lower elongations due to grain growth and other factors. Thus, there is an optimum strain rate for maximum elongation. There is a perception that this coincides with the best SPF properties for any particular material. The strain rate is different for different materials, and for the Ti-6Al-4V titanium alloy, it is around 1×10^{-4} s^{-1}. This strain rate is rather slow for most industrial applications, and the aerospace industry generally forms parts in the 2×10^{-4} s^{-1} to 3×10^{-4} s^{-1} range. To predict how to form a sheet of SPF material, most users have a Finite Element Analysis software package that breaks down a sheet of material into small elements, then analyses the stress and strain conditions on each element. A maximum strain rate is imposed on the fastest forming elements, and a gas pressure/time profile can be generated to make the part. This represents the fastest time a part can be formed, as allowed by the imposition of a constant strain rate.

2. Non-Optimum Strain Rates

As stated above, SPF materials can be deformed at higher strain rates than the optimum. Figure 1 shows a series of curves representing the forming stress required to SPF fine grain Ti-6Al-4V at certain constant strain rates at 775 °C. The coupons were pulled at Batelle's PNNL facility, with careful attention paid to testing conditions, coupon geometry and application of strain rate. The strain rates vary from 3×10^{-5} s^{-1} to 1×10^{-2} s^{-1}. It can be seen that the stress needs to be increased to achieve higher strain rates, and the higher strain rates achieve less total superplastic elongation. A maximum strain of 2.2 (800%) is obtained at 1×10^{-4} s^{-1} strain rate.

A curve can be fitted against the set of different strain rate curves that defines a 'Maximum Stress/Strain' boundary. To the left of the boundary, material can be formed without failure, to the right it will fail prematurely. Figure 2 shows such a boundary. Kraisheh (Ref 1) has proposed that instead of forming at the optimum strain rate, forming could start at a very high strain rate, and then decrease to a lower strain rate as the material stress/strain condition approached the boundary. Then, as this lower strain rate approached the boundary again, the strain rate would be lowered once more. This can be called multi-rate forming.

If the maximum stress/strain boundary were well defined, and enough stress/strain graphs generated, then the multi-rate strain rate could be smoothly and continuously decreased to maintain a material stress/strain condition parallel to and inside the boundary. For this paper, with limited stress/strain data, the multi-rate forming was performed with step changes in strain rate.

3. Multi-Rate Tensile Testing

Figure 3 shows the stress/strain curve for fine grain Ti-6Al-4V at 775 °C subjected to a multiple strain rate tensile test, along with portions of three constant strain rates. The multiple

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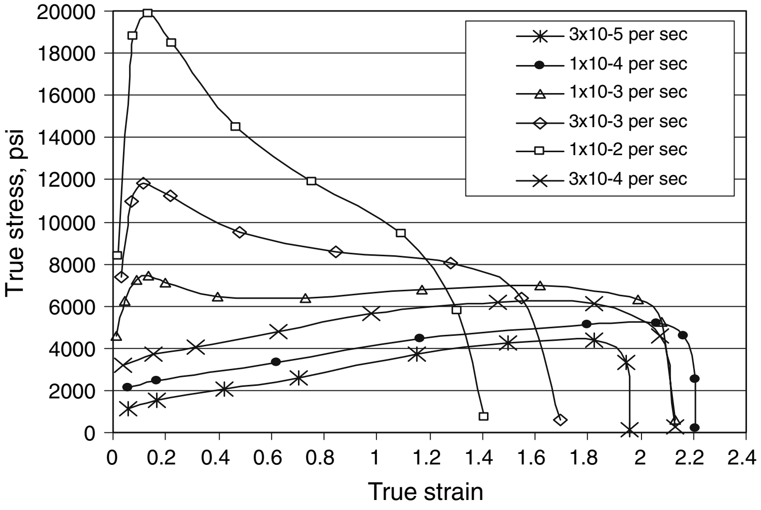

Fig. 1 Stress/strain curves for fine grain titanium at 775 °C at various constant strain rates

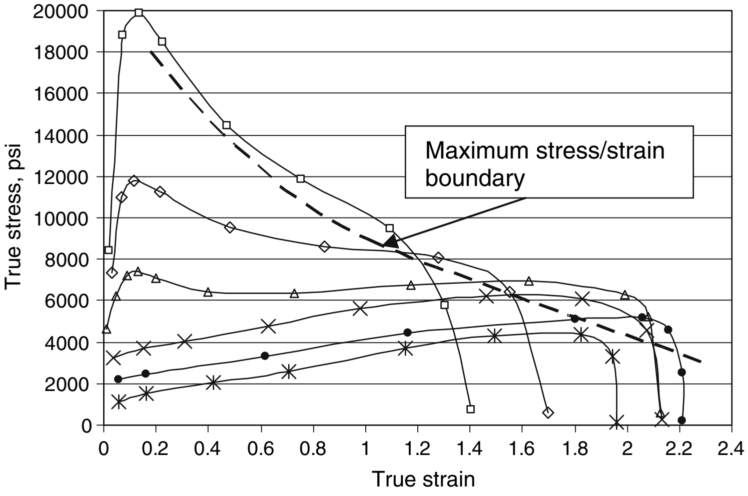

Fig. 2 Maximum superplastic stress/strain boundary for fine grain titanium at 775 °C

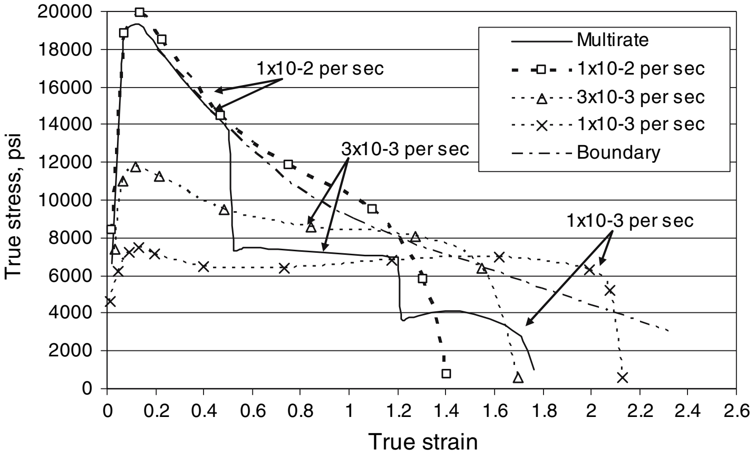

Fig. 3 High speed multi-rate forming stress/strain profile

strain rate test started at 1×10^{-2} s^{-1}, was then changed to 3×10^{-3} s^{-1} at a strain of 0.5, then 1×10^{-3} s^{-1} after a strain of 1.2. These strain changes were chosen as the stress/strain value approached the maximum stress/strain boundary.

Of particular interest is the observation that as the strain rate is 'bumped down' to a lower rate, the forming stress at the new strain rate is lower than it would have been if the test had been conducted at a constant strain rate. For example, after a strain of 0.5, when the strain rate is 3×10^{-3} s^{-1}, the multi-rate stress is about 85% of the equivalent 3×10^{-3} s^{-1} constant-rate stress, and after a strain of 1.2, the stress at 1×10^{-3} s^{-1} strain rate is only about 60% of the constant 1×10^{-3} s^{-1} rate. This phenomenon is worthy of further research, but is likely related to reduced grain growth due to the shorter time required to reach a particular elongation. A further observation is that the total elongation is higher than that achieved with constant strain rates of 1×10^{-2} s^{-1} and 3×10^{-3} s^{-1}, even though the coupon was initially pulled at those strain rates.

Figure 4 shows a similar graph but with a slower multi-strain rate. In this case the initial strain rate was 3×10^{-3} s^{-1}, a factor of 3.3 reduction compared to the previous sample. It should be pointed out that the multi-rate values should not be directly compared with the constant rate ones, as the material was taken from a different heat lot, and had slightly different SPF properties, as evidenced by the difference in the initial curve up to 0.5 strain.

4. Forming Times

The practical consequence of multi-rate forming can be seen in Fig. 5. This shows the two multi-rate curves with initial strain rates of 1×10^{-2} s^{-1} and 3×10^{-3} s^{-1} compared with the SPF titanium industry typical constant forming rate of 3×10^{-4} s^{-1}. The time taken to reach an elongation of 100% is 55 min for the constant strain rate, 9 min for the slower multi-rate and 3 min for the faster multi-rate, while the corresponding times for 200% elongation are 110, 27 and 9 min, respectively. The total elongation of the fast multi-rate curve is about 450%, while the slow multi-rate is 800%. In general, the SPF forming industry does not manufacture many parts in excess of 200% elongation, and most are formed at 100% elongation, or lower.

5. Experimental Part Forming

Although it would welcome a reduction in part cycle time, superplastic forming (SPF) in the aerospace industry would not normally consider a few minutes difference in cycle time significant. In addition, there is usually a constraint of maximum practical gas pressure that can be rapidly applied to a sheet, and those cognizant in the industry know there is also a problem of material pulling in through, or tearing at, the seals if too high a stress is imposed on the forming sheet. Consequently, it was decided for the experiment that the lower multi-rate condition would be used to form a part rather than the higher. This still promised a large reduction in forming time. Figure 6 shows an experimental pan shape used for the demonstration. The pan is 152.4 mm × 152.4 mm (6 in. × 6 in.) in size, with a 50.8 mm (2 in.) depth and 25.4 mm (1 in.) radius on all corners.

Using a Finite Element Program with the data from the stress/strain curves of Fig. 2, a gas pressure versus time curve for a starting gauge of 1.88 mm (0.074 in.) was generated that kept the fastest forming elements at a constant strain rate of 3×10^{-4} s^{-1}. A constraint in the program limits the maximum gas pressure to 2.07 MPa (300 psi), and this was reached at the end of the cycle. The predicted forming time was 47 min and maximum strain was 0.65. A second gas pressure versus time curve was generated for the slower multi-rate forming profile, in which the fastest forming elements would first be strained at a rate of 3×10^{-3} s^{-1}, and then reduced to 1×10^{-3} s^{-1}, after a strain of 0.5. However, in this instance the maximum gas pressure was reached much earlier in the cycle, so the strain rate was only at 3×10^{-3} s^{-1} for a short while. Nevertheless, the predicted forming time was only 9 min. These predicted profiles are shown in Fig. 7.

Test pan blanks were loaded into the press at 775 °C and formed according to the profiles. Both pans formed satisfactorily in the predicted times, and it was noted that the possible problem with material pulling into the die did not occur with the multi-form rate part. Figure 8 shows a quadrant of the pan with points selected for thickness mapping. Previous experience with superplastic materials suggests that a faster forming time leads to a greater thickness reduction in the part, and a more pronounced variation of thickness between thick and thin areas. Figure 9 shows the average thickness distribution at

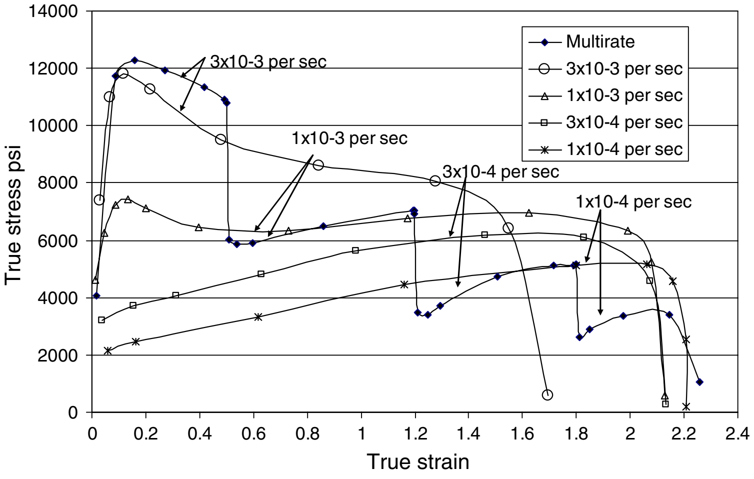

Fig. 4 Low speed multi-rate forming stress/strain profile

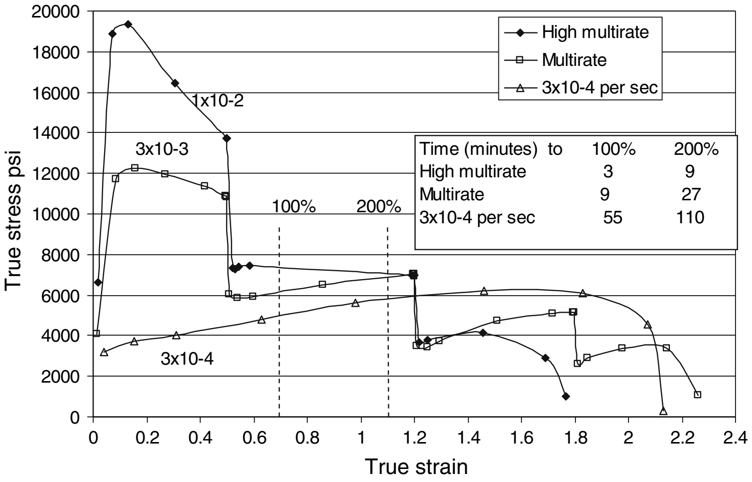

Fig. 5 Forming time comparisons to different strains

Fig. 6 Experimental pan shape

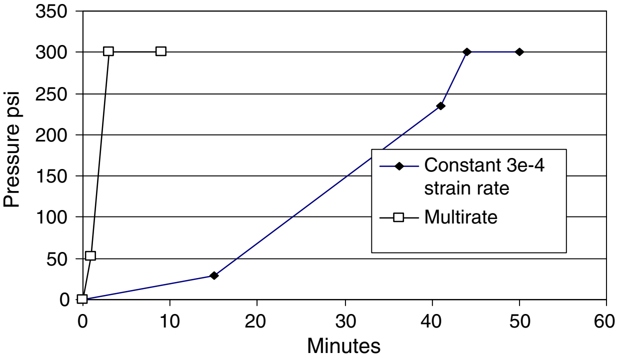

Fig. 7 Pressure/time profiles for constant and multi-rate strain rates

those points for the four quadrants, and it can be seen that in fact for this example there is no significant difference in thickness profile between the two parts.

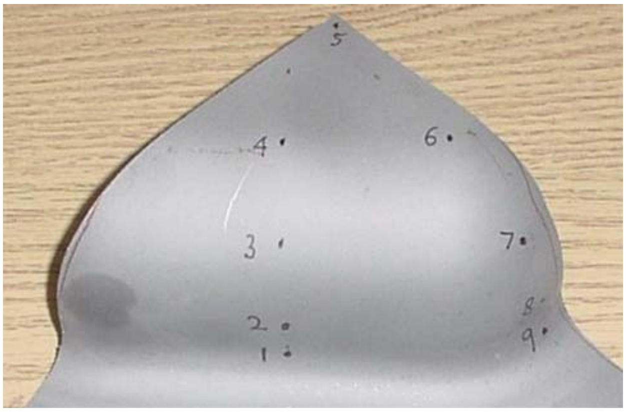

Fig. 8 Node identification for thickness mapping

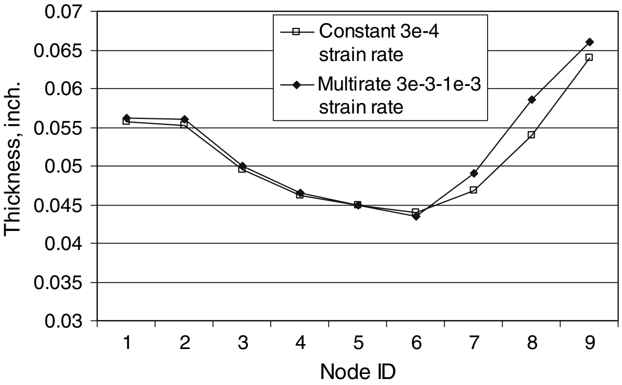

Fig. 9 Thickness distribution comparison between different strain rate forming

6. Conclusions

It has been shown that an empirical maximum stress/strain curve can be drawn on a series of constant strain rate curves that defines the boundary between successful SPF and premature failure at higher than normal strain rates. Using this boundary condition, fine grain titanium can be formed at an initial strain rate many times higher than traditionally used in industry, as long as the rate is subsequently reduced before the stress/strain condition reaches the boundary. There is experimental evidence that the stress using multi-rate is lower than the equivalent constant strain rate at any given strain. It is shown that an experimental pan shape that is representative of an aerospace part can be formed in 9 min, compared with 47 min for traditional forming. It is further shown that there is no detriment to the final thickness distribution of material after this fast forming time. It is anticipated that this technique can be applied to other superplastic materials in common use in industry.

Reference

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