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Superplasticity in Aeroengine Titanium Alloy VT-9 and its Modified Compositions

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Abstract. The alloy (*Ti*-6.5*Al*-3.3*Mo*-1.6*Zr*-0.3*Si*) is a Soviet composition designated *VT*-9. Excellent superplastic characteristics found by us in this alloy prompted us to explore the possibility of use of *Si*-free *VT*-9 in sheet form for superplastic forming. An optimum thermomechanical processing produced a microstructure that resulted in an elongation of 1700 per cent at a fairly high deformation rate (2 X 10^{-3} sec^{-1}). Thus, the same aeroengine alloy (W-9) can be used for superplastically formed airframe parts in the G-free condition. The present study also shows that for making the forming process commercially viable, deformation temperature could be lowered by temporarily alloying with hydrogen in a particular concentration range (0.1 to 0.2 wt per cent).

1. Introduction

Superplasticity, the ability of a material to flow like molten glass under unusually low loads, has been well documented[1-7] in the work-horse titanium alloy *Ti*-6*Al*-4*V* (*Ti-6-4*). Superplasticity is usually characterised by two parameters : (a) the strain rate sensitivity index *m* ($\sigma = K \dot{\epsilon}^m$, where σ is flow stress, $\dot{\epsilon}$ is strain-rate) and (b) the total tensile elongation. High *m* values (0.7-0.9) and large elongations (500-1000 per cent) have been reported'-' for *Ti-6-J*. Our interest in exploring the possibility of developing superplasticity in VT-9 alloy (*Ti*-6.5*Al*-3.3*Mo*-1.6*Zr*-0.3*Si*) arose from our effort to establish the isothermal/superplastic forging parameters in this alloy. While isothermal forging at superplastic strain rates led to improvement in mechanical properties[8], L. A. Elagina, et al.[9] observed homogenity of microstructure due to superplastic flow during isothermal forging. No systematic study revealing true potential of this alloy under conventional superplastic deformation is available. Excellent superplastic properties in terms of total tensile elongation and *m* value obtained by us in this alloy prompted us to modify the alloy for sheet metal'superplastic forming.

The element *Si* is invariably added in titanium alloys to improve creep resistance at elevated temperatures'". On the other hand, superplastically formed sheet products like necele centre beam frame[11], door panel, single piece pressure vessels[12] are not used at high temperatures. As such our next step was to optimise superplastic parameters in Si-free VT-9 alloy. While extensive work had been done on different aspects of superplasticity in titanium alloys, no systematic study is available on the optimisation of thermomechanical treatments required for producing favourable (fine and uniformly equiaxed) microstructure in sheets. This was attributed to easy availability of acceptable superplasticity in standard mill processing[13] IMI, Titanium Limited, however, claimed to have developed optimum mill processing parameters", but the details are not available. Therefore, this aspect was also included in our work.

Finally, in order to make superplastic forming more commercially viable, we proposed to lower the forming temperature which in turn increases die life, reduces contamination and stops grain coarsening. Reduction of deformation temperature is possible by increasing the proportion of more deformable beta phase (diffusivity in beta-Ti is almost two orders of magnitude higher than in alpha-*Ti*[15]. This objective could be achieved by addition of beta-stabilising elements such as (a) *Fe*, Co, *Ni* which also increase diffusivity[16] and (b) the interstitial element hydrogen. While the former elements alter the alloy composition, the latter method is a form of temporarily alloying with hydrogen which may be removed completely by vacuum annealing at 923*K*[17]. Wert & Paton[18] reported lowering of superplastic forming temperature of *Ti-6-4* to 114% but the comparison with base metal does not seem to be proper due to wide differences in grain size. Lederich, et al[17]. on the other hand, reported lowering of the forming temperature in *Ti-6-4* by hydrogen charging. In the present work a systematic study was undertaken for the first time to evaluate superplastic forming parameters with various levels of hydrogen in *Si*-free *VT-9* alloy.

2. Experimental Procedure

2.1 Material

Two alloys, namely VT-9 of the standard composition and Si-free *VT-9*, as shown in Table 1, have been used in this investigation, Melting of ingots, forging and rolling were done in our laboratory. Processing details for *VT-9* ingots has been described elsewhere'*. The thermomechanical treatments employed for *Si*-free *VT-9* involved hot rolling of forged slab in the (alpha + beta) range.

2.2 Hydrogen Charging in Si-free VT-9

The hydrogen charging unit was designed and fabricated at DMRL. The unit consists of a stainless steel tube chamber over which a sliding tubular furnace with controls is mounted. Two inlets have been provided for argon and hydrogen gas, the proportion being controlled by two flow rate meters and the mixed gas comes out through a

Table 1. Chemical compositions (weight per cent)

Alloy	Al (%)	Mo (%)	Zr (%)	Si (%)	β-Trans (K)
Standard VT-9	6.6	2.9	1.7	.23	1253
Si-free *VT-9*	6.3	2.7	1.72	—	1263

vacuum oil bubbler. The hydrogen concentration was determined by weighing the specimens before and after charging to an accuracy of 0.1 mg using an electronic balance.

2.3 Tensile Testing

Tensile testing was carried out in a 10 ton floor model Instron machine under argon atmosphere. The hydrogen charged samples were coated with glass[19] so that hydrogen could be retained in the sample. Details of incremental cross-head velocity tests and total elongation tests and dimensions of test pieces are described elsewhere'.

2.4 *Pressure Bulge Test*

Pressure bulging of hydrided sheet was performed by clamping the sheet between a Nimonic bottom die and the top ram of a 20 ton hydraulic press. High purity agron gas from a cylinder was blown over the sheet to form the shape.

2.5 Metallograph)

Standard polishing techniques were used and etching was done in a solution of composition $5HF + 10HNO_3$ + 30 lactic acid.

3. Results and Discussions

3.1 VT-9 Alloy

Flow stress vs strain-rate and strain-rate sensitivity index m vs strain-rate curves were generated in the temperature range I 123 to *1293K* for three microstructures i.e. mixed, equiaxed and acicular (Fig. I). All the three microstructures recorded high m values (0.7-0.85). Extensive tensile elongation (1300 per cent at 1173*K* at a strain-rate 8.3 x 10^{-4} sec^{-1}) was achieved only in the equiaxed microstructure. Large stretchability at various combinations of temperatures and strain-rate are illustrated in Fig. 2. Total elongation in the other two microstructures remained low (I 6 I per cent for acicular and 180 per cent for mixed) inspite of their high m values. The reason may be attributed to the unfavourable lamellar shape of grains which resist grain boundary sliding/rotation so essential for superplasticity. The lamellar grains were, however, modified to

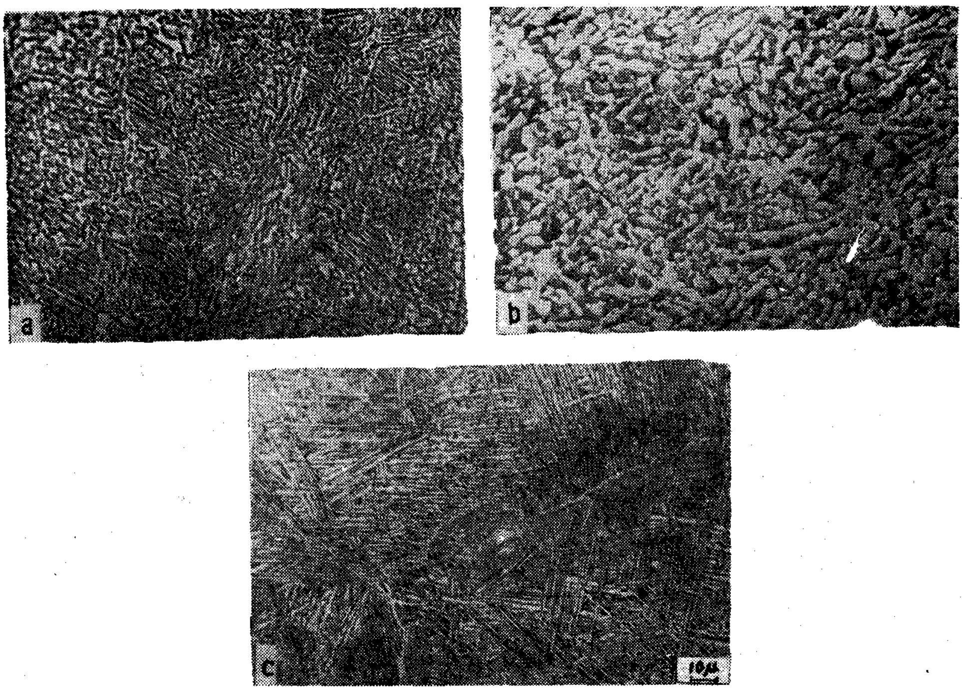

Figure 1. *Ti*-6.5*Al*-3.3*Mo*-1.6*Zr*-0.3*Si* alloy in three different microstructural conditions : (a) Mixed, (b) Equiaxed, and (c) Acicular.

equiaxed shape by deformation as shown in Figs. 3 (b) and (e). The equiaxed microstructure, however, remained equiaxed after deformation (Figs. 3 (c), and (f)). Strain-induced grain coarsening is also apparent from Fig. 3.

3.2 Si-free VT-9

A comparison of *m* values between *VT*-9 and Si-free *VT-9* as shown in Fig. 4 reveals the superiority of Si-free *VT-9* : the peak ***m*** value at 1123*K* is higher for Si-free alloy at the higher testing temperature of 1 173*K*, although the peak m value for both the alloys is nearly the same, the strain rate at peak *m* value has shifted to higher strain rate for the Si-free alloy. It is also clear that at 1173*K* the strain rate range for the higher *m* value is much broader for the Si-free alloy.

Microstructures obtained by various thermo-mechanical routes are shown in Fig. 5. Amongst these, Ci microstructure is uniformly equiaxed with the lowest aspect ratio. This structure recorded a maximum tensile elongation of 1725 per cent at 1 173*K* and a strain rate of 10^{-3} sec^{-1}, as illustrated in Fig. 6.

A comparison of properties for the equiaxed microstructure shown in Table 2 again underlines the superior superplastic characteristics of Si-free composition. The high

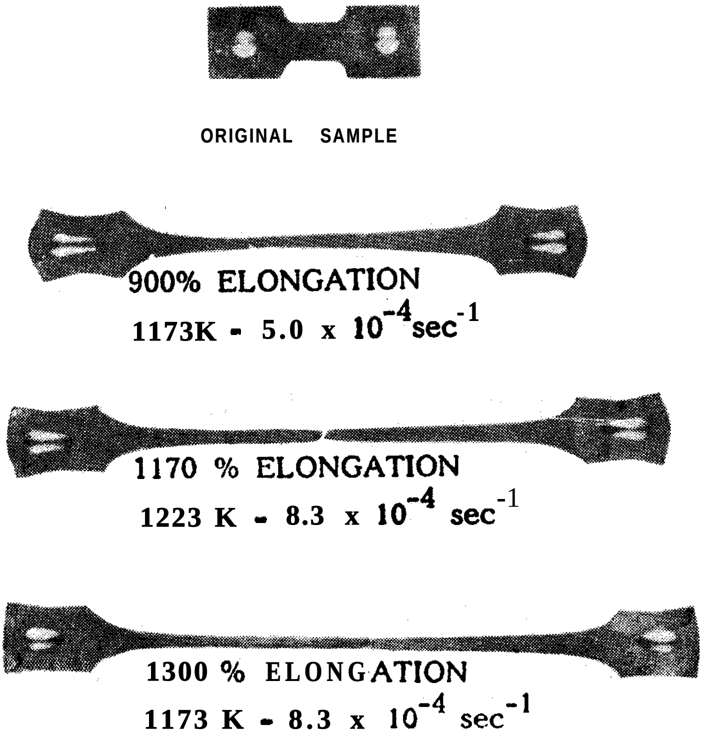

Figure 2. Total elongation of equiaxed *Ti*-6.5*Al*-3.3*Mo*-1.6*Zr*-0.3*Si* alloy at various combinations of temperature and strain-rate.

strain-rate (2 x 10^{-3}) at which 1700 pre cent elongation has been obtained is unmatched by any other titanium alloy. This implies that the forming time in this alloy would be the shortest which renders the alloy a better choice for superplastically formed components.

3.3 Hydrogen Charged Si-free VT-9

A plot of flow stress vs strain-rate for base Si-free ***VT-9*** alloy and the hydrogen charged alloys as shown in Fig. 7 shows that **the flow** stress level of 0.1 I wt. per cent hydrogen charged alloy at 1023*K* nearly matches that of the base alloy at **1123*K*.** Fig. 8 similarly shows matching of m vs $\dot{\epsilon}$ plot of the base alloy tested at 1123*K* with that of the 0.11 wt. per cent hydrogen charged alloy at ***1023K.***

The fact that extremely high elongation could not be obtained in hydrided sheets (Table 3) does not, however, take away the practical benefits of lowering the forming temperature. In practical forming operation, strains do not usually exceed 150 per cent. The total elongations in hydrogen charged alloy as shown in Table 3 are higher than 150 per cent. More over, contrary to large strain induced grain coarsening observed in

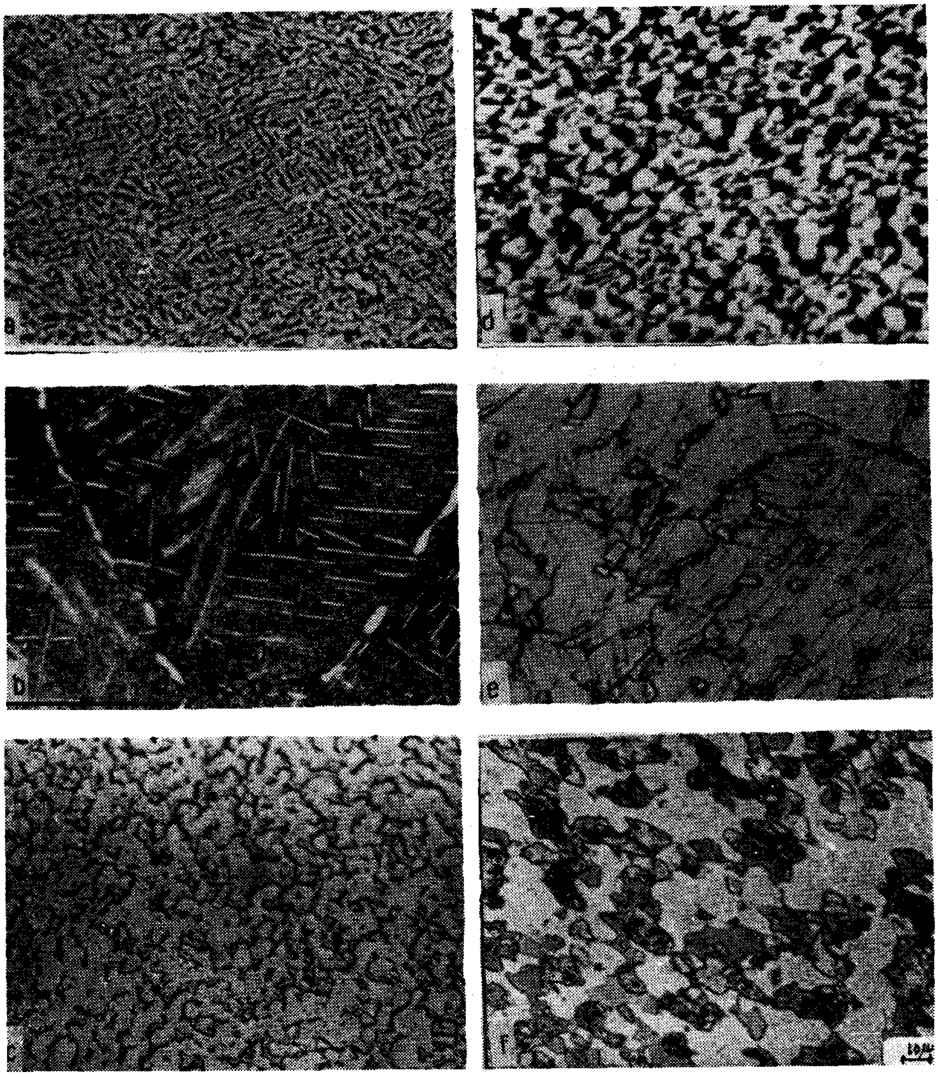

Figure 3. Microstructural changes with/without deformation : (a-c) grip and (d-f) gage sections of mixed acicular and equiaxed microstructures respectively.

conventional superplastic deformation (Fig. 3), the microstructure, in the hydrogen charged alloy, remains refined, if deformed, at 1023*K* as shown in Fig. 9, thus improving the post-forming properties. Strain-induced grain coarsening was absent even at the higher deformation temperature of 1073*K*.

The choice of proper hydrogen concentration and temperature of deformation depends on the specific requirement. For better die life and obtaining microstructural refinement, the opimal combination is deformation temperature of 1023K with 0.1 wt.

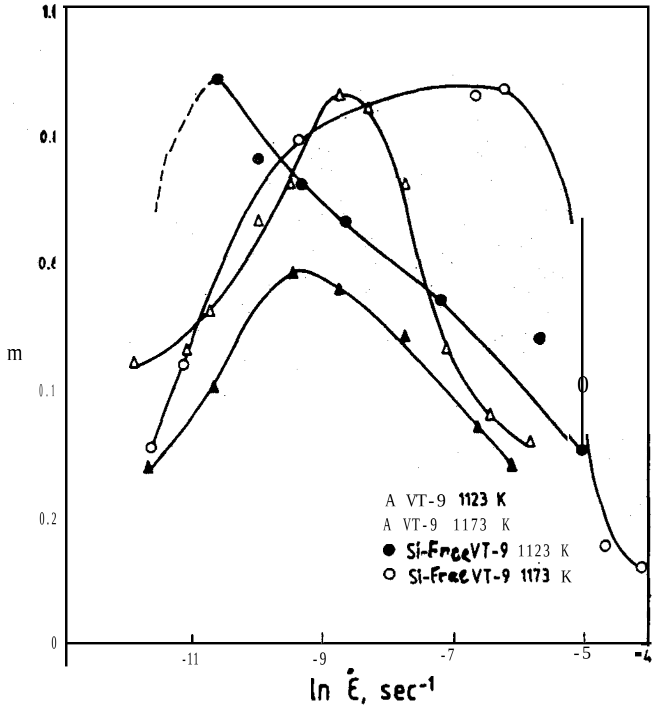

Figure 4. Comparison of ***m* vs ln** $\dot{\epsilon}$ plots for VT-9 and *Si*-free Q-9.

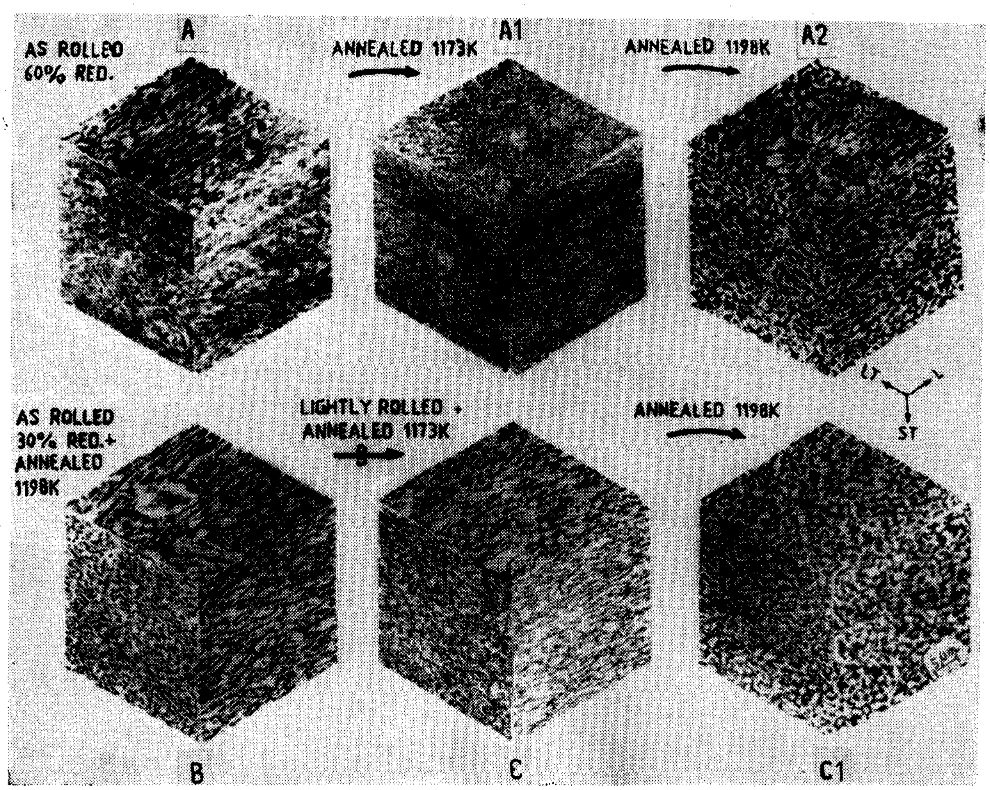

Figure 5. Microstructures of S-free *VT*-9 under different thermomechanical processing.

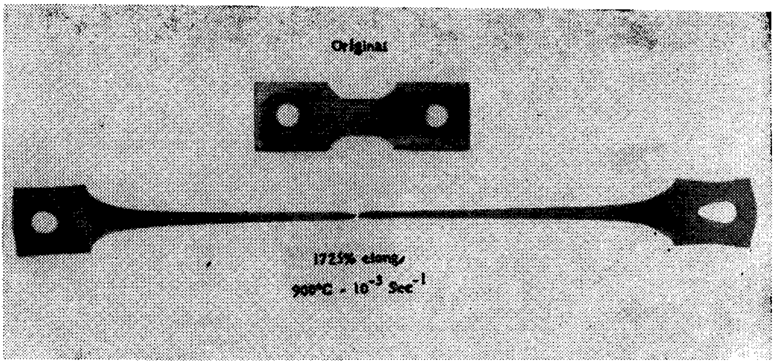

Figure 6. Maximum total elongation in S-free *VT*-9.

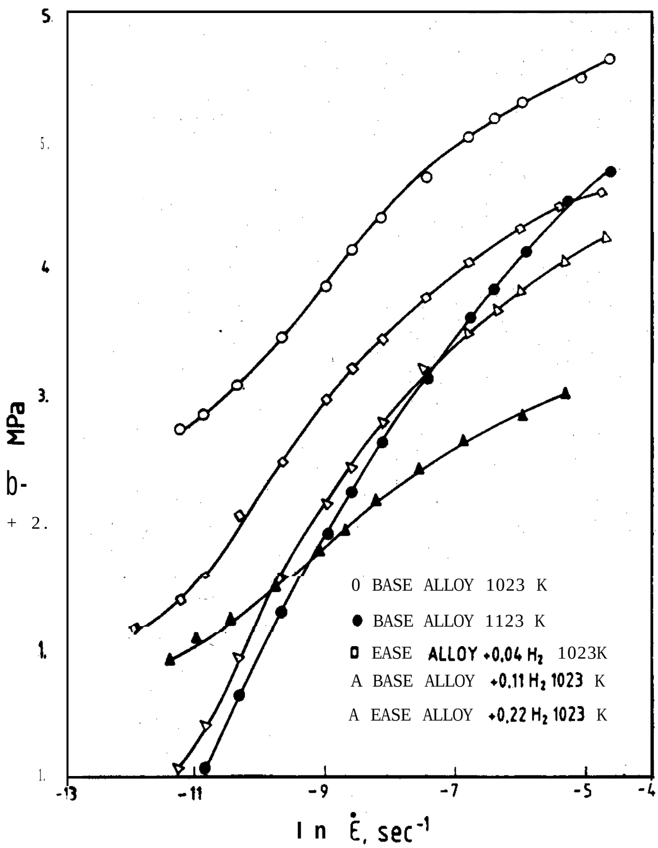

Figure 7. Comparison of ln σ vs ln $\dot{\epsilon}$ plots for base alloy (S-free *VT*-9) with hydrogen charged alloys at $1023 K$.

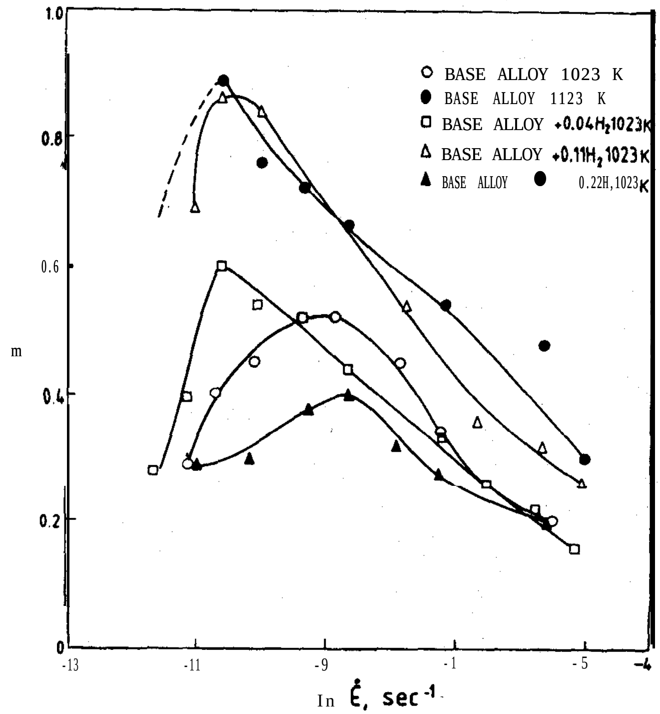

Figure 8. Comparison of m vs In $\dot{\epsilon}$ plots for base alloy with hydrogen charged alloys at $1023K$.

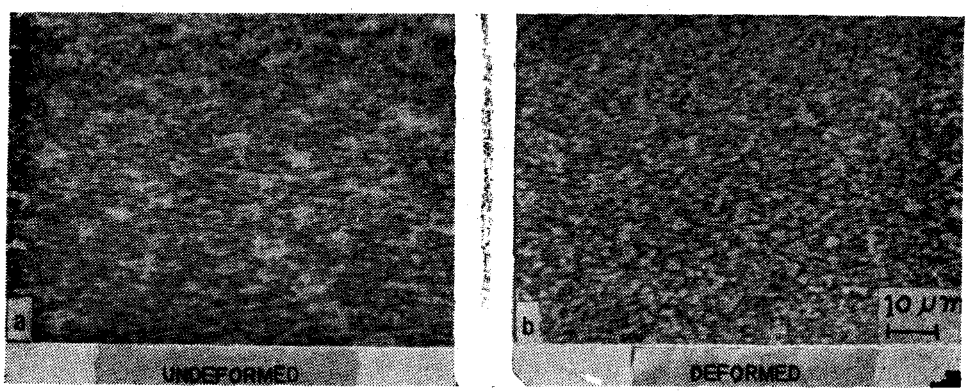

Figure 9. Microstructural refinement in hydrogen charged (0.1%) S-free *VT-9* sample **after** deformation.

per cent hydrogen concentration. On the other hand, for reducing flow stress and forming time, 0.1 to 0.2 per cent hydrogen and deformation temperature of $1073K$ are

Table 2. Improvement in tensile elongation and strain-rate in *Si*-free *VT*-9

	VT-9		*Si*-free *VT-9*	
Test temperature (K)	Strain-rate at max elong (sec^{-1})	Max. elong (%)	Strain rate a max elong (sec^{-1})	Max. elong. (%)
1123	8.3×10^{-4}	500	1 x 10-s	825
1173	8.3×10^{-4}	1300	1×10^{-3}	1725
			2×10^{-3}	1700
1223	8.3×10^{-4}	1170	1×10^{-3}	1189

Table 3. Superplastic properties with different amounts of hydrogen

Test temperature (K)	Hydrogen (wt %)	Initial strain-rate (sec^{-1})	Total elongation (%)
1023	0.11	4.2×10^{-4}	680
	0.2	2.1×10^{-4}	312
1073	0.05	5×10^{-4}	375
	0.1	6.2×10^{-4}	401/463
	0.11	1×10^{-3}	550
	0.19	4.2 × 10’”	641

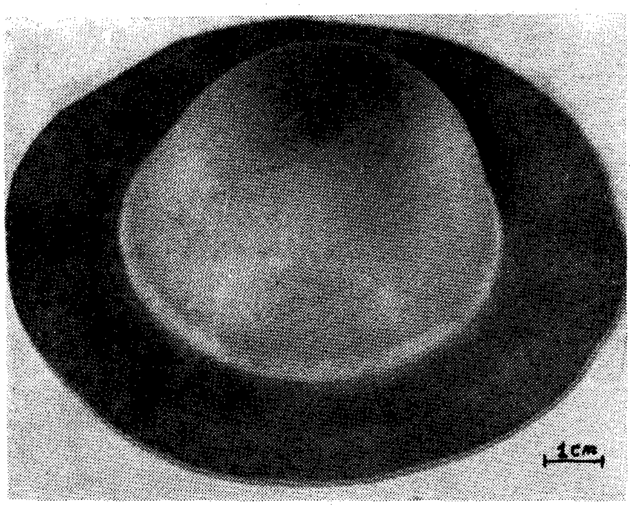

Figure 10. Hemispherical shape formed by blowing argon gas at 1073 K under a pressure of 30 Kg/cm^2 on 0.2% H_2 charged Si-free *VT-9*.

recommended. Superplasticity as well as microstructure degraded with increased hydrogen content (> *0.2* per cent) and temperature (> 1123K)

Figure 10 shows a hemispherical shape formed by blowing argon gas at a pressure of 30 bar over a 0.2 per cent hydrogen charged *Si*-free *VT-9* sheet at 1073*K*.

4. Conclusions

1. Titanium alloy *VT-9* exhibits striking superplastic effects in the fine, equiaxed microstructural condition.

2. Satisfactory superplastic characteristics are observed even when the *VT-9* alloy is treated to develop an acicular microstructure.

3. Total elongation and the deformation rate are higher for the *Si*-free *VT-9*, making this alloy best suited for commercial superplastic forming.

4. Proper thermomechanical processing of sheet is necessary to achieve a fine equiaxedl globular microstructure, which is the microstructure capable of producing extensive elongations.

5. Superplastic forming temperatures can be brought down by 100-150*K* by temporarily alloying with hydrogen.

6. While strain-induced grain coarsening is always noticed after superplastic deformation at conventional temperatures, grain refinement is observed, after low temperature deformation, in the hydrogen charged alloy.

7. Blow forming of hemispheres is possible at low deformation temperatures (1073*K*) by introducing 0.2 per cent H_2 in the Si-free *VT-9* sheet.

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