Effect of hot working temperature on the weldability of Ti-6Al-4V alloy

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The resulting microstructure and mechanical properties of Ti-6A1-4V alloy depend to a great extent on the temperature at which working is carried out. Two components namely 650mm diameter Rings and 650mm diameter Hemispherical Shells have been processed at temperatures about 50°C below and 100°C above the beta-transus temperature respectively. These components have been evaluated for their microstructures, mechanical properties, fracture toughness and weldability. The microstructure of the rings which have been rolled at 950° C reveals the presence of equiaxed primary alpha in the matrix of transformed beta. On the other hand, the microstructure in the case of hemispherical shells forged at 1100°C, is 100 percent transformed beta. The tensile ductility of the rings is found to be higher than that of the hemispherical shells. However, the fracture toughness of hemispherical shells is much superior to the rings. The samples cut from these components are machined to 12mm thickness and electron beam welded for their comparative property evaluation. It is seen that the welded samples reflect and retain almost the same tensile properties as the parent material except for the impact toughness at the fusion zones.

INTRODUCTION

Pure titanium possesses hexagonal close packed structure (hcp) at room temperature designated as "alpha" phase and it allotropically transforms to body centered cubic structure (bcc) known as "beta" phase at 883°C. On alloying, the elements depending on their solublity in the respective phases, stabilise either alpha or beta. Based on the alloy additions, titanium alloys are classified as alpha, alpha-beta and beta alloys. The relative metallurgical, mechanical and physical properties[1] for these alloy types are shown in Table 1.

TABLE-1 Property variation with alloy types for commercial titanium alloys

ALPHA	ALPHA-BETA	BETA
Ti-5Al-2.5Sn	Ti-6Al-4V	Ti-5Al-2Sn-2Zr-4Mo-4Cr
Ti-5Al-6Sn-2Zr-1Mo-0.2Si	Ti-6Al-6V-2Sn	Ti-10V-2Fe-3Al
Ti-8Al-1Mo-1V	Ti-6Al-2Sn-4Zr-6Mo	Ti-8Mo-8V-2Fe-3Al
[————————	Alpha+Beta/Beta Transus	
[————————	H.T. Flow Stress	
	Formability	————————]
	Strain Rate Sensitivity	————————]
	Heat Treatability	————————]
	Hardenability	————————]
	R. T. Strength/Toughness	————————]
[————————	H. T. Capability	
[————————	Weldability	
[————————	Alpha Stabilization	
	Beta Stabilization	————————]
	Density	————————]
[————————	Modulii	

H.T. = High Temperature ; R.T. = Room Temperature

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As seen from Table 1, alpha-beta type alloys offer a balance of properties viz., mechanical strength, ductility, toughness, formability and weldability. Because of the inherent high specific strength and the above mentioned optimum properties, Ti-6A1-4V is the most extensively utilised alloy for aerospace applications.

The processing temperature of Ti-6A1-4V alloy is important as it can influence the resulting microstructure and hence the properties achievable. The mechanical working below the beta transus temperature (993°c) results in a microstructure containing equiaxed primary alpha in a matrix of transformed beta. Working in the beta phase region results in a microstructure containing completely transformed beta. The beta forms on the alpha/alpha grain boundaries[2] Thus the room temperature microstructure of the alloy is decided by the hot working temperature, which in turn controls the mechanical properties to a great extent. For Ti-6A1-4V alloy, the microstructure-property correlations have been well studies[3,4,5] but only limited data is available on the effect of hot working temperature on the weldability of Ti-6a1-4V alloy. Hence a programme was undertaken to study the effect of hot working temperature on the mechanical properties of the samples welded from the rings rolled at 950°C and the hemispherical shells forged at 1100°C

❒ Experimental

The required Ti-6A1-4V billets for the 650 mm diameter rings and hemispherical shells were procured. The chemical composition and the mechanical properties of the starting billets are given in Tables II & III respectively.

TABLE II. Chemical Composition of the Ti-6A1-4V Billet
(In WT %)

A1	V	Fe	C	O	N	H	Ti
6.28	3.97	0.052	0.008	0.1442	0.0062	0.0049	Bal

TABLE III. Average Mechanical properties of the Ti-6A1-4V Billet

Properties	Longitudinal	Transverse
UTS (MPa)	916.0	921
0.2% YS (MPa)	857.5	882
%Elongation (25mm GL)	16	14
%Reduction in Area	40	40
Impact Strength (Joules)	23	23.5

Ring Rolling

Ti-6A1-4V billets of 300 mm diameter and 225 mm length were used to make proof machined rings of 650 mm outside diameter (OD), 590 mm inside diameter (ID) and 265mm height. The billets were initially forged down to 260 mm diameter and 295 mm length at 950°C. After punching, the stock was transferred to the ringh rolling mill and rolled to the final size in 8 reheats. The reheating was carried out at 950°C for 45 minutes. After the rolling was completed the rings were annealed at 730°C for 2 hours followed by air cooling. The ring rolling operation is shown in **Fig. 1**. **Fig 2** shows the photograph of the ring in the proof machined condition.

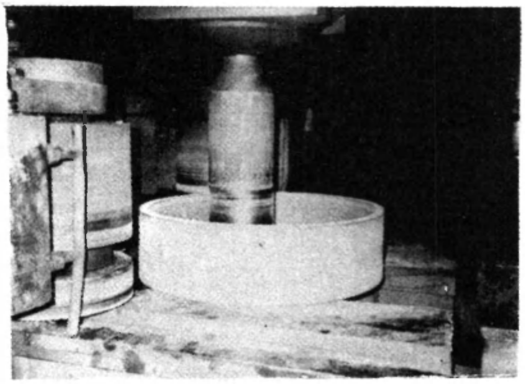

Fig. 1. The Ring Being Rolled in a 80 ton capacity Rolling Mill

Fig. 2. Proof Machined Ring Rolled in the "Alpha + Beta" Field

Hemispherical Shell Forging

Billet of 300 mm diameter and 465 mm lengh was close die forged at 1100°C to a hemisphere of 650 mm outside diameter (OD) and 40 mm thickness in 8 reheats after initial soaking at 1100°C for 3 hours. The subsequent reheating was carried out at the same temperature for 45 minutes. The forged shells were annealed at 730°C for 2 hours and air cooled. **Fig. 3** shows the forging of the hemispherical shell on a 55 meter-tonne hammer. The photograph of the shot blasted hemispherical sheel is shown in **Fig. 4.**

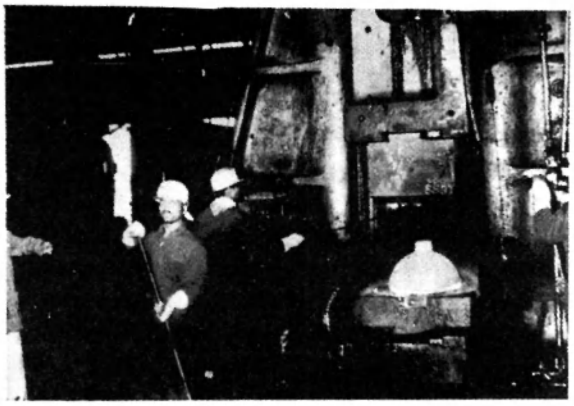

Fig. 3. Hemispherical shell being forged in a 55 meter-ton hammer

Fig. 4. Hemisherical shell forged in the Beta field

Electron Beam Welding

Samples were cut from both the ring and the hemispherical shell in the circumferential direction and machined to strips of 60 X 60 X 12 mm size for electron beam welding (EBW). The EBW parameters were optimised with the help of the data[6] generated over a series of bead-on-plate welds carried out on thick Ti-6A1-4V sections and a few trial welds performed on 12 mm thick strips. The welded joints found acceptable as per ASME Boiler and Pressure Vessel Code7 were selected for evaluating the weld properties. The optimised EBW parameters are given in Table IV.

TABLE IV. Optimised EBW parameters for 12mm thick Ti-6A1-4V Alloy

Accelerating Voltage	150 KV
Beam Current	68 mA
Welding Speed	240 Cms/Min
Beam Focus	25mm below surface
Work Distance	190mm
Vacuum	10^{-4} Torr

Evaluation of the Properties

Standard tensile (25 mm gauge length) and Charpy-V-notch impact specimens were prepared from the ring, the hemispherical shell and the welded samples. In the case of welded samples, tensile samples were made with the weld joint at the centre of the gauge length. For the impact specimens, care was taken to locate the V-notch at the centre of the fusion zone (FZ). The tensile tests were carries out at a strain rate of 4 X 10^{-2}, min^{-1}. The fractured surfaces of the impact specimens were observed in a scanning electron microscope (SEM) for their surface topography. Fracture tougher test were performed on compact tension specimets of 16 mm thickness prepaed as per ASTM E-399-87 standard from the "beta" processed rings. The specimens were pre-cracked and opened out in servo hydraultic machine. A plot of load versus crack opening displacement (COD) obtained from XY plotter was used to calculate the fracture toughness data. Fig.5 shows the sketch of the tensile and impact samples prepared from the welded samples as well as that of the fracture toughness sample prepared from the parent material. Metallographic samples were prepared by adopting standard procedures. Using etchant, microstructures of the parent metal (PM), heat affected zone (HAZ) and the fusion zone (FZ) were observed.

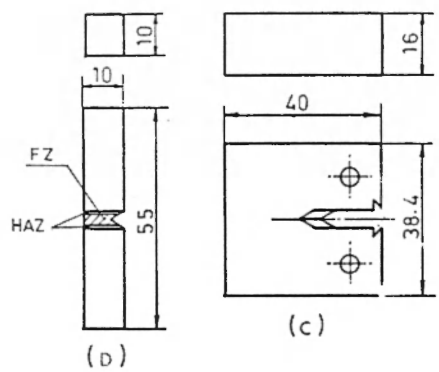

Fig. 5

RESULTS AND DISCUSSIONS

Mechanical Properties

The ultimate tensile strength (UTS), the 0.2% yield strength (YS), the percentage elongation (%EL) and the Chary-V-notch impact values for samples from the ring, the hemispherical shell and the EB welded joints are summarised in Table V.

TABLE V. **Average Mechanical properties of Samples from the Ring, Hemispherical Shell and Welded Joints**

PROPERTIES	RING			HEMISPHERE		
	PARENT METAL		WELDED SAMPLES	PARENT METAL		WELDED. SAMPLES
	RADIAL	HEIGHT		RADIAL	TRANS-VERSE	
UTS (Mpa)	950	955	970	911	941	930
0.2% YS (MPa)	872	867	833	862	862	823
% Elongation (25mm GL)	16.0	16.0	12.5	7.0	6.5	7.0
Impact Strength (Joules)	23.5	23.5	21.8	35.3	39.0	22.5
Fracture Tough-ness (MPa/m)	61.0	60.5	--	85.0*	90.0*	--

*Invalidity due to thickness limitation.

Parent Metal

The UTS and YS of samples from the rings as well as the hemispherical shells remain almost the same. However the samples from the ring exhibit better tensile ductility and lower toughness as compared to those from the hemispherical shell. This difference in their properties comes from the difference in their micros-tructures. The morphology of the alpha phase is influenced by the temperature at which the compo-nents have been processed. The microstructure (**Fig. 6**) of the ring processed in the subtransus temperature range reveals the presence of equiazed primary alpha in a matrix of transformed beta. The microstructure (**Fig. 7**) of the hemispherical shell processed entirely in the beta field reveals colonies of completely transfromed beta (lamellar alpha). While the lamellar alpha promotes toughness, the tensile ductility is seen to be improved by the equiazed alpha. The SEM fractographs (**Figs. 8 & 9**) of the "alpha+beta" and the "beta" processed material show a transgrannular dimpled appearance which indicates that the fracture mecha-

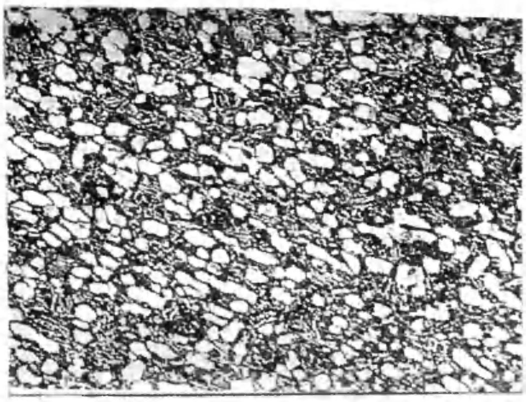

Fig. 6. Microstructure (320X) of "Alpha + Beta" processed ring showing equiaxed primary Alpha in a matrix of transformed Beta

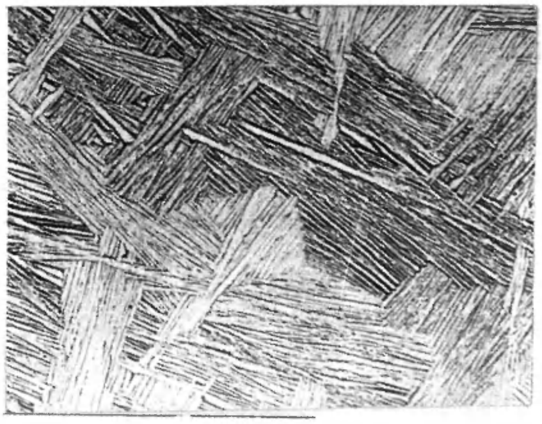

Fig. 7. Microstructure (320X) of "Beta" processed hemispherical shell showing colonies of transformed Beta (Lamellar Alpha)

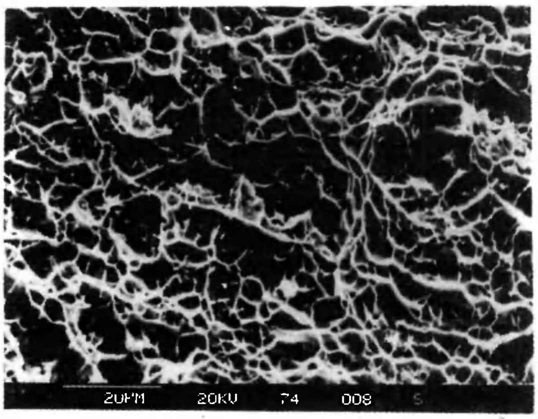

Fig. 8. Sem fractograph of "Alphe + Beta" processed parent metal showing a well defined net work of dimples

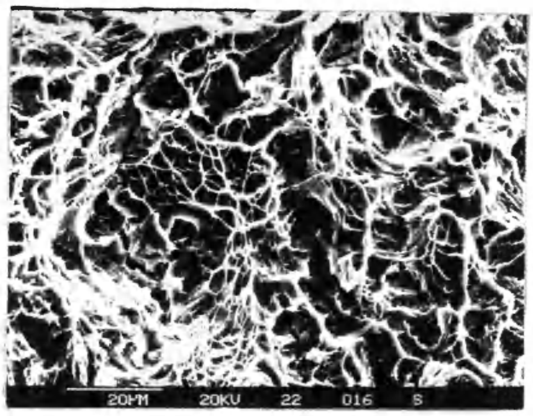

Fig. 9. Sem fractograph of "Beta" processed parent metal showing bifurcation of crack

nism that is operative in both the instances is one of microvoid nucleation and growth. The fracture stress depends on the ease of void nucleation and growth.

According to Monogolin and others[8,9,10] the amount of ductility achievable in a material depends on the rate of void growth. Fracture occurs during tensile straining when a critical-relationship is reached between the void size and the fracture stress. Here the void is considered as crack when it reaches critical size for fracture. The voids reach a critical size by a process involving slip at the void tip and or coalesence with voids encountered as the voids grow by slip. If the void growth rate is fast it reaches a critical size for fracture at a lower strain and hence the ductility is less. It has been shown in the case of Ti-5.2A1-5.5V-0. 9Fe-0.5Cu alloy and Ti-6a1-4V alloy10 that the void growth rate is slower for the equiaxed alpha structure than for the "widmanstaten alpha+grain boundary alpha" structures. The comparatively low ductility of the beta processed sample having almost the same yield strength as the "alpha+beta" processed samples may also be ascribed to the rapid growth rate of voids in the lamellar structures.

The fractograph (fig 8) of the samples from the "alpha +beta" processed ring shows a well defined network of dimples of non-uniform size and this may result from the varying distribution and size of the equiaxed alpha phase. the fractured surface of the beta processed sample looks rougher. It is indicative of a larger fracture surface area which results in a greater fracture energy absorption to achieve failure. Table V shows that the samples from the hemispherical shell have better impact and fracture toughness than the smaples from the ring. The SEM fractograph of the fractured surface of the impact sample prepared from the "beta" processed hemispherical shell shows extensive crack bifurcation. The tortuosity of the fractured path which deviates along the "alpha" colonies and prior beta grain boundaries is responsible for the better fracture toughness of the "beta" processed hemispherical shell. On a micrroscopic level the crack in the lamellar structure of the "beta" processed hemispherical shell may be propagating as it does in an equiaxed structure of the "alpha+beta" processed ring, but it travels a greater distance due to crack branching. The extensive bifurcation of crack gives rise to lower crack growth rates and increased total fracture engergy.[11,12,13]

Welded Samples

Table V shows that the UTS and Ys of the welded samples remain almost the same as those of their respective PM. It is seen during tensile tests that the failure always occurs in the PM region of the welded samples and hence the tensile strengts obtained reflects mainly the strength of the PM. The microstructures of the FZ of both the weldments are identical and reveal the presence of the long martensitic needles.

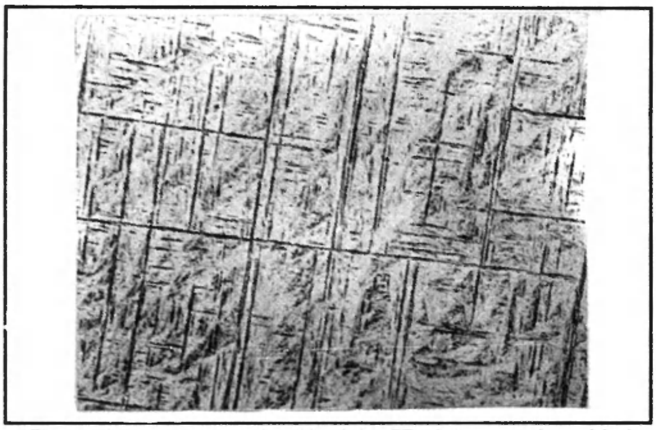

Fig. 10. Microstructure (320X) of the FZ of the sample welded from the "Alphe + Beta" processed ring showing the presence of martensitic needles

(**Fig.10**) Because of the highly localised nature of the heat input and the high cooling rates involved with the EBW process, the FZ microstructures consist predominantly of the long narrow martensitic phase. Presence of coarse martensite is reported[14] even in 51 mm thick EB welded Ti-6A1-4V alloy. The presence of martensite in the FZ does not appreciably alter the ductility of the welded samples. Table IV shows that the samles welded from the "alpha+beta" processed ring retains about 80% of the tensile ductility of the parent material. This relatively small reduction in ductility is due to the fact that the weld-region amounts to only a small portion (10%) of the total gauge length (25 mm). The FZof the samples is also found to retain about 95% of the impact toughness of the "alpha+beta" processed parent material.

The smaples welded from the beta processed hemispherical shell exhibit almost the same ductility (7%) as the "beta" proccessed parent material. This indicates that the actual ductility of the weld-region is around that of the "beta" processed material. However the FZ of these samples is found to retain only about 50% of the impact toughness of the "beta" processed parent matreial and it is almost the same as that of the "alpha+beta" processed parent material. Thus we see that if the tensile ductility of the weldregion corresponds near to that the "beta" processed parent material, its FZ impact toughness corresponds more or less to thatof the "alpha+beta" processed parent material. The fractographs of the fractured surfaces of the impact samples prepared from both the "alpha+beta" processed and the beta processed material with the notch located at the FZ are almost identical and atypical one is shown in **fig.11**. The fractopgraph reveals a dimpled appearence indicating that the fracture mecheanism is again one of microvoid coalesence. The observation of the comparitively high ductile high toughness martensite in the FZ of the welded samples is in agreement with the high energy

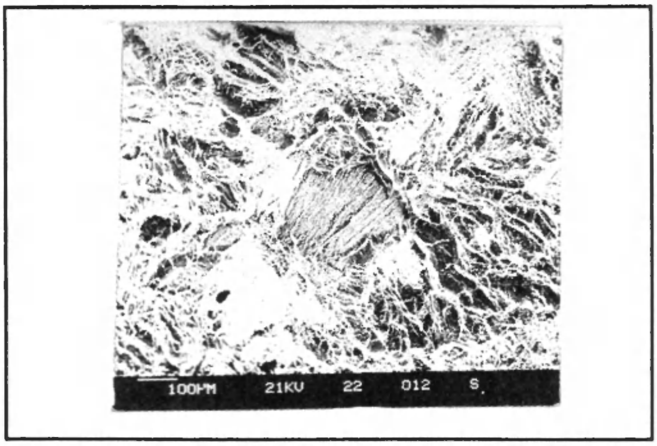

Fig. 11. Sem fractograph of FZ of sample welded from the "Alphe + Beta" processed ring showing dimpled appearance

absorbing characteristics of the as quenched martensite found by Margolin and Mahajan[10].

CONCLUSIONS

- The processing temperature controls the type of microstructure and the properties achievable in Ti-6Al-4V alloy.
- The "alpha+beta" processed ring possesses better ductility and marginally higher tensile strength as compared to the beta processed hemispherical shell.
- The "beta" processed hemispherical shell shows better fracture toughness due to increased tortuosity of the crack path.
- The samples welded from the "alpha+beta" processed ring and the "beta" processed hemispherical shell retain and reflect almost the same properties as those of the respective parent material proprties except the impact toughness at the FZ.
- EB welding does not seem to deterioraate the tensile ductility of the parent material. Infact the welded samples retain almost 100% and about 80% of the tensile ductility of the"beta" processed and the "alpha+beta" processed material respectively.
- The martensite present in the FZ microstructure shows high energy absorbing characteristics.

Acknowledgements

The authors are indebted to Shri M. J. Nair, Head, Materials Processing Division, Dr. K. V. Nagarajan, HEad, Metallurgy and Materials Group and Shri D. Easwardas, Deputy Director, Materials and Mechanical Systems for their suggestions and guidance in completing this work. They are also thanful to Dr.S.C. Gupta, Director, VSSC for according permission to publish the results of this study. The authors also wish to express their gratitude to M/S Echjay Industries, Rajkot for carrying out the ring rolling operation, M/S Bharath Forge, Pune for forging the hemispherical shells and the Gas Turbine Research Establishment, Bangalore for extending help in EB welding.

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