The Application of Isothermal Near Net-shape Forming Technology on Titanium Complicated Load-bearing Structures

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The isothermal near net-shape forming technology is one of feasible approaches for forming titanium alloys and some other difficult deformation materials. Based on the current project researches and achievements, the application of isothermal near net-shape forming process was introduced, and the specific isothermal near net-shape forming technologies for small size, medium size and large size complicated structures were listed. Forgings obtained by isothermal near net-shape forming exhibit good quality, reasonable streamline distribution along the forging, uniform and fine microstructure, and excellent mechanical properties. The size of the forgings was greatly refined, therefore a great precious raw material and machining hours were saved. However, the isothermal near net-shape forming technology still faces further improvements to enlarge the engineering application scale.

Keywords: *Isothermal net-shape forming, titanium alloy, complicated structure, precise forging*

1. Introdution

As the advantages of high specific strength, good heat resistance and corrosion resistance etc., titanium alloys possess great potential applications in aerospace parts and rigorous working conditions. The proportion of titanium alloys in advanced aircrafts and engines reached more than 40% and 30% respectively. The aircraft load-bearing structures, fasteners and key engine components are also manufactured using titanium alloys. The researches of new titanium alloys with high temperature, high strength, high toughness and other high performances become an important trend as the rising performance of titanium alloy in advanced aircraft[1-2)]. However, a series of urgent problems, such as forming, in practice application need to be solved. Some alloys, such as TiAl and Ti_3Al alloy, have excellent elevated temperature property, but the plasticity at low temperature is very poor and the conventional forging technology can not achieve the formings[3)]. In addition, the forming difficulty is more aggravated because of the fairly complicated shape of aircraft structures, such as some narrow and high ribs and thin and wide webs. Isothermal near net-shape forming provides a practical forming process for the complicated structures of the alloys which are difficult to forming.

Isothermal near net-shape forming technology mainly utilize the superplasticity of the alloys to manufacture precise forgings with complicated shape at relatively constant temperature and lower strain rate. Such precise forgings can be assembled only after a small amount of machining, exhibiting high material utilization. The microstructure of forgings is homogeneous and the performance is good. Furthermore, the load of isothermal near net-shape forming technology is only 1/5~1/10 of the general forging. Therefore, the large size forgings can be forged in small press equipments, and the technology provides new methods for the manufactures of the large and whole aviation components. The restriction of large forging press equipment has been got rid of in some certain extent.

2. The Process of Isothermal Near Net-shape Forming

2.1 Equipment

Isothermal near net-shape forming technology can be conducted in general press equipments. The processing parameters of the equipments, such as strain rate, deformation degree, should be controlled accurately by the computer. The speed of beam should be slow and the general strain rates are at the range of $10^{-1}\sim10^{-4}$ s^{-1} to devolp the superplasticity of the materials.

2.2 Dies and Heating Devices

The die materials were selected according to the forging temperatures. Due to the high forging temperature of titanium alloys, the K403 and other superalloys are often selected. Vacuum casting, machining and electric spark were used to the production of the dies. The dies with combined structure were adopted to decrease the difficulties of casting and machining. Then the strength of the dies was tested. The dies can be heated by electric resistance, flame, generally. Meanwhile a uniform heating environment was necessary and the dies were surrounded by thermal insulation material to decrease the temperature drop.

2.3 Preforming

Preforming is a key step for isothermal near net-shape forming technology. The quality and process of forgings were influenced by the design of preforming influences seriously. The shape and size of the preforming can be designed according to physical simulation experiment and computer numerical simulation results to satisfy the need of isothermal near net-shape forming technology.

The material was forged freely and the grains were refined. Therefore, the superplasticity of the material was realized during the net-shape forming.

2.4 Isothermal Near Net-shape Forming

The processing parameters of the isothermal near net-shape forming were determined according to the results of the isothermal compression, superplastic tensile, physical and computer simulation. The workpieces were coated with glass lubricant before isothermal forging, and heated in furnace. The heating temperature was chosen according to the microstructure and properties of the forgings. The die heating temperature is the same as the workpiece, and the heating times were established based on the actual situation. The less heating times, the better performance. The cooling method after forming was selected referring to the general forging process.

2.5 Heat Freatment

The standard heat treatment was used to eliminate the warping deformation and stabilize the performance of the forgings.

3. The application of Isothermal Near Net-shape Forming

3.1 Small Size Complicated Components

The adding allowance for high rib and thin web, small size complicated components to meet the dimensional requirement during the general die forging. Therefore, a low material utilization and serious waste in the general die forging. Isothermal near net-shape forming can greatly improve material utilization, save machine work hours and lower the cost for these complicated components,

Figure 1 shows Ti-1023 alloy aircraft structure with overall dimensions of 350mm forged by isothermal near net-shape forming, which attains the precise forming technical effects of ultra-thin abnormity complicated aircraft structure. The minimum webs thickness, ribs width, fillet radius, draft angle and dimensional tolerance are separately 2.5mm, 2.5mm, 1.5mm, 0° and ± 0.3mm. The surface roughness is Ra0.4 ~ 3.2μm, the machining allowance is 1 ~ 3mm, and the non-machining surface area is above 70%. Compared with the general die forging, the weight of the forgings decreases from 15.5kg to 1.9kg, the material utilization increases from 9.1% to 74.2%, the amount of machining reduces above 90%, and the machining cycle shortens from 45 days to 5 days.

As shown in Figure 2 and Figure 3, the microstructure of this isothermal precise forging are fine and homogeneous equiaxed grains and the flow line distributes logically along the forging shape. The microstructures of web and rib are fine equiaxed α phase. The macrostructure and microstructure of precise forging meet Q/6s 834-90 standard. The mechanical properties fully meet the technical standards (Table 1), and the performance of this precise forging is significantly higher than free forging and general die forging. This technology increases the strength forging and avoid multiple heat treatments of Ti-1023 general forgings.

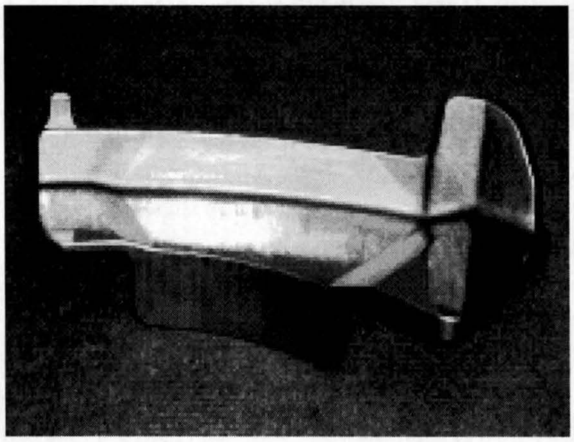

Figure 1. The precise forging of aircraft bulkhead for Ti-1023 alloy

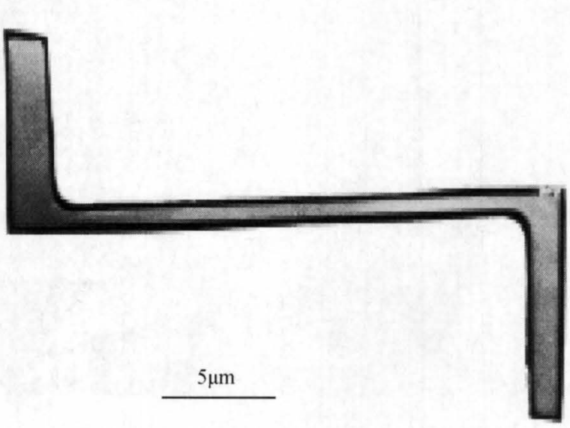

Figure 2. Macrostructure of isothermal precise forging

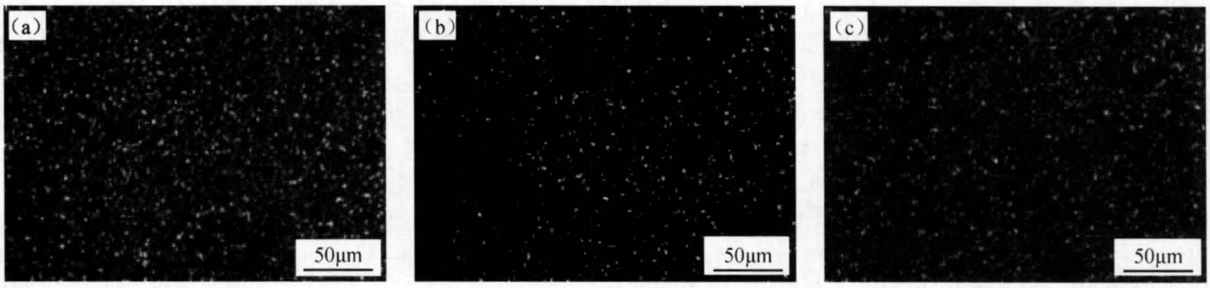

Figure 3. Microstructure of isothermal precise forging: (a) upper rib region (b) web region (c) bottom rib region

Table 1. mechanical properties of Ti-1023 precise forgings at room temperature

Items		σ_b(MPa)	$\sigma_{0.2}$(MPa)	δ(%)	ψ(%)	K_{IC}
Billet	L	1180	1150	12	46	
		1170	1140	11	57	61.8
	T	1160	1120	7.8	31	61
		1210	1160	6.5	31	
Precise forging	L	1220	1150	11	44	
		1230	1160	12	47	—
	T	1230	1180	11	47	
		1230	1170	11	47	
Technical standards	L/T	≥1105	≥1035	8/6	15/10	≥60(T-L)

3.2 Medium Size Complicated Components

Medium size complicated components forged by isothermal near net-shape forming technology are shown in Figure 4. The length of the forging is 730mm, the maximum width is 220mm, the projection area is 1201cm^2, the width of rib are respectively 5, 6, 7 and 17mm, the height of the cross ribs is 20mm, the height of the surrounding ribs is 41-75mm, both side draft angle are 0-3°, and the thickness of web is 8mm. Chemical milling allowance of non-machining surface is 0.3-0.5mm and the allowance of machining surface is 2-4mm. the primary difficulties of the forgings are the high convex lug and rib of the outer profile.

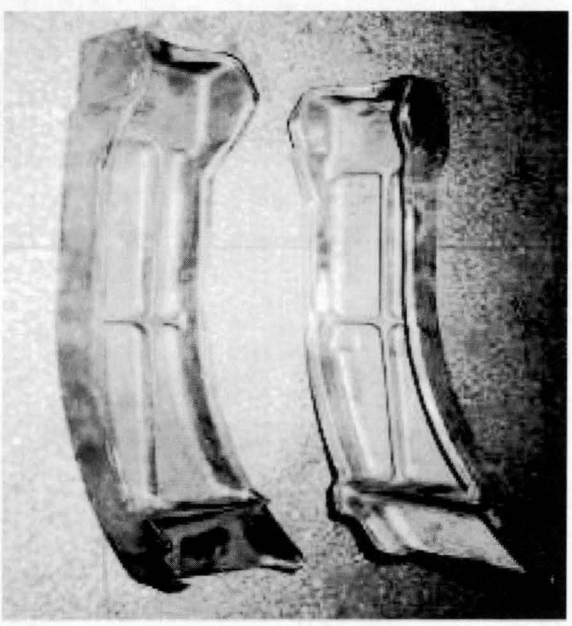

Figure 4. The precise forging of aircraft bulkhead for Ti-1023 alloy (left and right)

The isothermal near net-shape forming for the precise forging avoids fold, reflux and other defects. The forging has good forming quality. Except for a small amount of machining on both sides and back of the forging, the remaining is non-machining surface. The weight of this isothermal precise forging is 13.5kg, and the weight of the component is 5.1kg, which improves material utilization and decreases the machining work hours. The heat treatment specification after isothermal precise forging was 760℃/2h, AC + 525℃/8h, AC. The forgings passed the ultrasonic inspection successfully, the content of H is 0.0014%, and α brittle layer was not observed after chemical milling on the surface. Observed from the macrograph (Figure 5) and micrograph (Figure 6), the macrostructure of the forging was fine and homogeneous equiaxed fuzzy grain, and the metal flow lines distributed along the forging shape. Fine and homogeneous equiaxed α phase was obtained at each part of the forging, except for a spot of α phase with long strip shape at the head of webs. The macrostructure and microstructure of the forgings meet the Q/6S 834-90 standard completely.

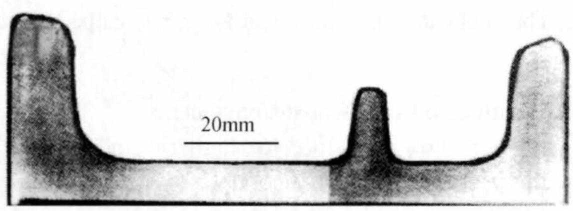

Figure 5. Macrostructure of isothermal precise forging

The mechanical properties of every part of forging at room temperature are listed in Table 2. It is concluded that the mechanical properties of the head, web and rib have a good consistency and meet the requirements of the standard Q/6S 834-90.

3.3 Large Size Complicated Structure

Large size TA15 titanium alloy isothermal whole aircraft bulkhead forging was successfully forged by isothermal near net-shape technology, shown in Figure 7. The inclusive area of the forging is 1.25m^2, the physical projected area is 0.45m^2, the maximum outline is 1300mm, and single side machining allowance is just 3~4mm. In addition to these, the forging also exhibits thin web, high rib, complicated shape, and great size. In particular, the difference of local height of forging part is more than 3 times. All of these factors brought great difficulties in billet shaping and die forging.

Compared with general die forging, the weight of isothermal precise forging decreases about 100kg and the periodicity of machining shortens more than 50%. After annealing, the macrostructure of the forging is homogeneous and fine equiaxed fuzzy grain structure, and the flow lines along the forging shape are homogeneous and reasonably distribute (Figure 7). Microstructure of each part of forging are shown in Figure 8, which exhibit fine and homogeneous equiaxed α phase and β transformed structure, and the content of equiaxed α phase is 25%~35%. The macrostructure and microstructure meet the technical standards.

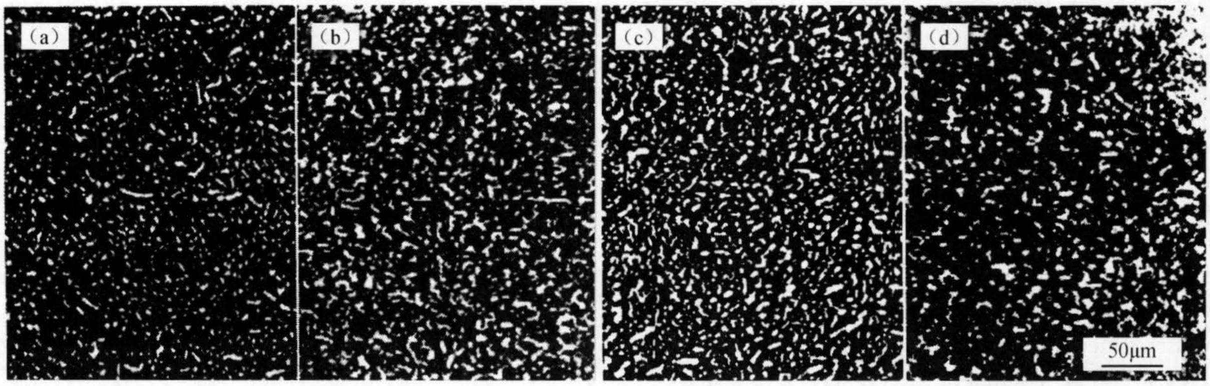

Figure 6. Microstructure of isothermal precise forging (a) web of region I; (b) web of region II; (c) rib of region II; (d) web of region III

Table 2. Mechanical properties of Ti-1023 precise forging at room temperature

Position	Direction	σ_b(MPa)	$\sigma_{0.2}$(MPa)	δ(%)	Ψ(%)	K_{IC}
I	T	1250	1190	10	52	
		1230	1160	11	64	
	T-L					62.0
						60.1
II Web	L	1210	1150	13	51	
		1230	1160	12	49	
	T	1190	1130	14	60	
		1210	1150	13	57	
Rib	L	1180	1120	12	55	—
		1190	1130	14	59	
	T	1170	1100	13	60	
		1170	1100	13	64	
Q/6S 834-90	L	≥1105	≥1035	≥8	≥15	≥60(T-L)
	T	≥1105	≥1035	≥6	≥10	

Figure 7. Photograph of isothermal forging of large and whole bulkhead of TA15 alloy (top right corner image is macrostructure of the forging)

Near α titanium alloy TA15 with high aluminum equivalent has medium room temperature, high temperature strength and good thermal stability. Mechanical properties of this forging are shown in Table 3, showing excellent high and low temperature tensile properties, impact properties, endurance performance and fracture toughness, which meet the technical standards.

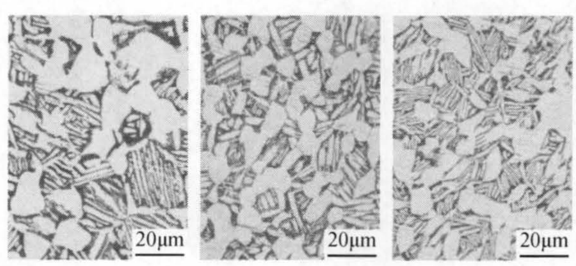

Figure 8. Microstructure of isothermal die forging

4. Conclusions

The application of isothermal near net-shape forming technology in several different sizes of titanium complicated structures indicated that the complicated and key forgings, especially for difficult deformation materials can be formed through this process. However, the die materials used in isothermal near net-shape forming is still expensive, and the cost can be reduced only when the amount of forgings reaches certain quantities. Therefore, the die materials used in isothermal

Table 3. Mechanical properties of isothermal die forging

Sampling direction	Room temperature					500℃		Fracture toughness
	σ_b(MPa)	$\sigma_{0.2}$(MPa)	δ(%)	Ψ(%)	α_k	σ_b(MPa)	τ(h)	K_{IC}(MPa · $m^{1/2}$)
L	1050	960	16	37	53	675	≥51	88.6
	1050	960	14	36	48	715	≥51	89.9
T	1050	945	15	33	55			
	1050	955	14	34	55			
H	975	895	15	40				
	990	905	18	41				
Technical standards	930～1130	≥855	≥10(L) ≥8(T)	≥25(L) ≥20(T)	≥40(L) ≥30(T)	≥635(L)	≥50(L)	

near net-shape forming at high temperature should be developed in future, and also the die life should be improved. To meet the need of application of isothermal forming at a higher temperature on special new materials, the research on isothermal forging under vacuum or protective atmosphere should be carried out. In order to expand the engineering application of isothermal near net-shape forming technology, further research should be carried on the design of superalloy die, die precise casting, machining, lubrication technology, computer simulation and so on.

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