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**HEAT TREATMENT OF 6A1-4V TITANIUM
FORGINGS TO OBTAIN HIGH YIELD STRENGTH**

Technological Spinoff Report

March 1973

Bendix Corporation
Kansas City, Missouri

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FORGINGS TO OBTAIN HIGH YIELD
STRENGTH

March 1973

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HEAT TREATMENT OF 6A1-4V TITANIUM FORGINGS TO OBTAIN HIGH YIELD STRENGTH

Prepared by J. H. Kuehnle

Rough machined parts made from hand forged titanium alloy stock 6A1-4V were successfully heat treated to meet an unusually high minimum yield strength requirement of 160,000 psi (11 MN/m²). The equipment and operating procedures used and the results obtained are described.

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SUMMARY

Parts machined from titanium alloy 6Al-4V were heat treated to meet a 160,000 psi (1100 MN/m²) minimum yield strength requirement. This high yield strength was obtained by using a high solution heat treatment temperature of approximately 1780°F (971°C), a short solution heat treatment time of 1 hour, and a cold [36° to 40°F (2 to 4°C)] agitated water quench produced by a submerged jet fixture. A high aging temperature of 1100°F (593°C) for 6 hours was used to partially relieve quenching stress. Forty-five cylinders were treated. Eighteen cylinders had one open end and 27 were shorter and open on both ends. Extensive hardness testing of these parts showed good process uniformity (RC 41.8 ±2.1). One part of each type was tested. Both parts had acceptable yield strength.

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DISCUSSION

SCOPE AND PURPOSE

The specified minimum yield strength for a 6Al-4V titanium alloy machined part was 160,000 psi (1100 MN/m²). Material in the form of annealed 6.5-inch (160 mm) diameter by 12.5-inch (317 mm) long, hand-forged solid billets was readily available. Conventional heat treatment of the billet material after machining to 1-inch (25 mm) or less section thicknesses normally would assure a minimum yield strength of 140,000 psi (965 MN/m²) or less.¹ This report covers the work done to establish a heat treatment process for rough machined parts made from this material and to assess the results of this process for a small quantity of parts.

PRIOR WORK

Bendix Kansas City has not previously produced this part. Two other production agencies have fabricated this part, or one very similar, from the same type of raw material. Difficulties were encountered by both agencies in their efforts to meet a 160,000 psi (1100 MN/m²) minimum yield strength requirement. References to reports, if any, covering this work are not available at this time. In addition, discussion with the forging supplier, although resulting in several suggestions, offered no assurance that the requirement could be met.

ACTIVITY

Planning Considerations

The following considerations were significant in planning this work.

1. The number of forged stock pieces available was limited and not more than one could be allocated to destructive tests for proving out the heat treatment process.
2. The diameter of the available forged stock was very close to that required for the rough machined part; as a result, the heat-treated parts needed to be as stress free and as nearly round as possible. It was necessary to demonstrate dimensional stability by heat-treating a whole part to

conserve the limited quantity of available raw material and to avoid manufacturing delays. This prevented dividing the part allocated to destructive testing into segments that could be heat treated under a variety of conditions so that an optimum set of conditions could be developed.

3. The critical strength area of the part is outlined by the dotted area of Figure 1. Tensile yield strength was the only requirement and lower than conventional tensile ductility would be acceptable.
4. The closed end configuration of the part (Figure 1), despite the small slots and hole present, required a method of rapid water circulation both inside and outside the part if a rapid quenching rate was to be achieved. Expulsion of heated water from the open end of the part was essential.
5. The beta transformation temperature reported for the lot of forging stock available was 1830°F (1000°C). It has been reported² that, for an aging temperature of 1100°F (590°C) and time of 8 hours, a peak yield strength of about 162,000 psi (1100 MN/m²) can be obtained by solution treatment at a temperature 40°F (22°C) below the transformation temperature. As a result, 1790°F (977°C) was selected as the nominal temperature to be used. The 1100°F (599°C) aging temperature also reduces previously induced quenching stresses. Subsequent thermal stress relief during final machining might be required, thus a shorter (approximately 6 hours) aging time was chosen. The shorter time would permit up to 2 hours of stress relief with minimum risk of degrading mechanical properties.

Equipment and Operation

A non-circulating, electrically-heated, air-atmosphere furnace with a power operated grating hearth was used for solution heat treatment. Work zone calibration data for this furnace showed it to be capable of maintaining an atmosphere temperature range of ±4°F (±2°C) at operating temperatures in the vicinity of 1800°F (980°C). This furnace had been used in earlier titanium alloy solution heat treatment work and had produced parts free of loose scale. An independent load thermocouple installed in the nose end of the first few heat-treated parts was used to establish a set point for the permanent furnace control instruments.

The furnace work zone height would not permit vertical positioning of the parts on the hearth. The first part was blocked in place horizontally on the hearth, but had marginal roundness after heat treatment. All subsequent parts were supported on the hearth by a welded stainless steel sled having

NOTE: 1 IN = 25.4 MM

Figure 1. Heat-Treated Part

two longitudinal part supports. Roundness of all subsequent parts was satisfactory. Except for the lifting ring (Figure 2), the parts were quenched and aged without fixtures.

A large water quench tank was used and located a few feet from the hearth roll-out area of the furnace. To provide maximum cooling rate for quenching the part, a submerged water jet assembly (Figure 2) was installed in the tank and fed from a 2-inch cold water supply line connected to the plant water distribution system. The work covered by this report was done during January and February, during which time this system yielded quench water temperatures of between 36° and 40°F (2° and 4°C) after a short period of operation at maximum water flow. Under full flow conditions, the fixture produced strong water turbulence throughout the quench fixture area without causing spray or jets to project above the quench bath surface.

With the arrangement described, the furnace operator was able to lift the part from the furnace hearth with a long hook and in one continuous motion, pivot approximately 180 degrees and insert it into the agitated water quench assembly. The typical time from emergence of the part from the furnace to full immersion in the quench bath was 6 to 8 seconds.

A large, electrically-heated, forced air circulation oven was used to age the parts. The aging heat treatment was initiated within 2 hours after quenching.

Process and Product Data

Table 1 shows the conditions used for the first closed-end heat-treated cylinder. The load thermocouple showed that the temperature of this part increased from 1760° to 1772°F (960° to 967°C) during the last 17 minutes of the 58 minute solution heat treatment period. A conservative furnace set point of 1787°F (975°C) was used during the first 40 minutes of the 58 minute period. Although two set point increases of 5°F (2.8°C) each were made during the latter part of the period, part temperature was lower than the 1790°F (977°C) goal. For the remaining 17 parts subsequently heat treated, a higher furnace set point was used and improved load thermocouple readings of 1783° to 1785°F (973° to 974°C) were obtained during the final 15 minutes of the heating period. Table 4 includes a summary of the conditions used for the 17 parts.

Table 2 and 3 show the mechanical property and hardness test data obtained for the first part heat treated. Hardness values shown in Table 3 and 4 are for locations approximately 5 inches away from the tensile test locations (Figure 1). For correlation purposes, hardness tests were also made on a segment of material from between two adjacent tensile test locations. The hardness values (Rc) for the inner and outer surfaces of this segment were

Figure 2. Quenching Fixture

taken from the closed end of the parts. The hardness values (Rc) for the inner and outer surfaces of this segment were within the range shown in Table 3. Hardness values along the centerline of the segment ranged from 39.2 to 40.8 in the thickest portion of the material to 40.4 to 40.8 in the thinner portion.

Table 1. Heat Treatment, Cylinder 1

Category	Results
Solution Heat Treatment (Furnace Chart Data)	
Total soak time	58 minutes
Recovery time to 1750°F (954°C)	9 minutes
Peak temperature	1797°F (980°C)
Final Time at 1792 ±6°F (978 ±3°C)	42 minutes
Quench temperature	39°F (56°C)
Aging time at 1100°F (593°C)	2 hours

Table 2. Mechanical Properties, Cylinder 1

Location Number	Ultimate Strength		Yield Strength (0.2% Offset)		Percent Elongation	Percent Reduction in Area
	kpsi	(MN/m ²)	kpsi	(MN/m ²)		
1	170	(1170)	165	(1140)	8.5	43.5
2	174	(1200)	167	(1150)	12.5	40.6
3	174	(1200)	165	(1140)	12.5	41.6
4	171	(1180)	163	(1120)	12.5	37.5
5	174	(1200)	167	(1150)	12.5	42.8
6	174	(1200)	165	(1140)	12.5	38.7
7	173	(1190)	162	(1020)	8.5	38.7
8	170	(1170)	158	(1090)	9.8	41.8
Required Minimum	-	-	160	(1160)	-	-

Table 3. Hardness, Cylinder 1

Location Number	Hardness on Outer Surface* (Rockwell C; Locations per Figure 1)
1	41.9, 41.6, 41.5
2	41.8, 43.0, 43.0
3	42.0, 42.4, 42.5
4	41.8, 42.0, 41.3
5	41.9, 41.1, 42.2
6	42.7, 42.0, 41.8
7	42.4, 42.0, 41.4
8	41.1, 42.2, 42.1, 41.8
Summary	42.0 +1.0, -0.9

*Surfaces had a dull, brassy-olive color and were free from evidence of loose or heavy scale. At each station, the readings shown were spaced apart in an area of approximately 0.38 inch (9.7 mm) diameter.

Table 4. Final Process Results, Cylinders

Category	Results
Solution Heat Treatment (Furnace Chart Data)	
Total soak time	60 ±3 minutes
Recovery time to 1750°F (954°C)	6 +4 -3 minutes
Peak temperature	1805 +5° -8°F (985 +3° -4°C)
Final time at 1795 ±3°F (979 ±2°C)	39 +5 -7 minutes
Quench Water Temperature	36 to 39°F (54° to 56°C)
Aging Cycle Specified at 1100°F (593°C)	5.7 to 6.0 hours
Rockwell C Hardness (Figure 1)	
Number of readings (18 parts)	471
Mean value	41.8
Standard deviation	0.672
90 percent confidence limits (99 percent conformance)	41.8 ±1.8

* The process previously described was also used to heat treat 27 rough-machined rings made from 6Al-4V titanium alloy mandrel forged rings. The mandrel forgings were made from a pierced forged biscuit and as a result would be expected to have a grain flow in a circumferential direction, rather than parallel to their cylindrical axis as was the case with the closed-end cylinders. The as-forged thickness for these rings was much less than that of the billets used for the cylinders. The ring forgings had nominal dimensions of 6.5 inch (162 mm) outer diameter and 5.0 inches (112 mm) length. The rings were rough machined to approximately the same diameter and wall thickness shown in Figure 1 for the open end portion of the cylinder. Results obtained for these parts are shown in Table 5.

Table 5. Test Results, Rings

Axial* Location Number	Ultimate Strength		Yield Strength (0.2% Offset)		Percent Elongation	Percent Reduction in Area
	kpsi	(MN/m ²)	kpsi	(MN/m ²)		
1	167	(1150)	160	(1100)	12.5	31.7
2	170	(1170)	163	(1120)	12.5	44.2
3	169	(1160)	166	(1140)	12.5	38.8
4	170	(1170)	163	(1120)	9.4	32.3
Rockwell C Hardness**						
No. of readings (27 parts):					658	
Mean value:					41.8	
Standard deviation:					0.785	
90% Confidence limits (99% conformance):					41.8 ±2.1	
*Axial tensile specimens, type R4, 90° apart						
**Eight hardness test locations, 45° apart, minimum of 3 readings at each location						

ACCOMPLISHMENTS

The mechanical properties and hardness data for the first heat-treated cylinder were reviewed with design laboratory personnel and process approval was obtained. During similar reviews of the data obtained for the 17 additional cylinders and 27 rings heat treated, it appeared that there was general agreement that the project goals had been achieved. Further use of the quenching equipment is anticipated.

FUTURE WORK

Die forgings have become available for fabrication of the closed end cylinder and no further use of solid billets for this purpose is anticipated. The 27 ring forgings machined and heat treated to date complete present obligations.

A major titanium producer has recommended that, for reliable quantity production of 6A-14V parts guaranteed to meet 160,000 psi (1100 MN/m²), specially selected or produced forging stock having more restrictive than normal controls would be required. Aluminum, oxygen, and nitrogen content would need to be high and fine-grain microstructure would be necessary. In addition, the forging supplier should be required to demonstrate lot capability to meet the required yield strength by a specified heat treatment process applicable after rough machining.

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REFERENCES

¹"Basic Design Facts about Titanium. " Reactive Metals, Incorporated, Niles, Ohio, 1965, p 31.

²J. A. Burger and D. K. Hanink, "Heat Treating Titanium and its Alloys. " Metal Progress, June 1967 pp 70-75.