



Article Practical Use of Hot-Forged-Type Ti-42Al-5Mn and Various Recent Improvements

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Abstract: The use of a hot-forged TiAl alloy enables the fabrication of large parts that are difficult to manufacture by casting or isothermal forging. Ti-42Al-5Mn (at%) is the world's first TiAl alloy in this category and has been used to manufacture practical large-scale structural defense components since around 2010. This paper discusses the developmental status and practical applications of this alloy. In addition, recent developments in process stabilization and improvements in material properties, which have been issues for the practical use of this TiAl alloy in the past, are also discussed.

Keywords: TiAl alloy; hot-forging; beta phase; structural component; ceramic crucible melting; hot-press; forming

1. Introduction

The need for lightweight heat-resistant materials that are usable at high temperatures has increased in recent years for various transportation-equipment and power-generation-equipment applications driven by the need to conserve energy resources and prevent global warming by reducing CO_2 emissions. The TiAl alloy is a new metal-based material developed to meet this requirement in which multiple intermetallic compound phases that exist in the Ti-Al binary system are compounded. The main constituent elements are Ti and Al, and various elements are added to differing degrees; its specific gravity is approximately four, which is approximately half that of a Ni-based superalloy. The phases that constitute the TiAl alloy are not easily deformed because they are intermetallic compound phases that are very strong at high temperatures. Owing to the above characteristics, TiAl is suitable for use in rotating parts and aerospace structural components that require excellent specific strengths (strength/specific gravity) at high temperatures (600 °C or higher), which is difficult to apply with conventional lightweight Ti alloys. However, compared with conventional metal materials, the TiAl alloy is brittle, this may result in the destruction of parts in use.

The market use of TiAl alloys began with the small cast parts in a turbocharger for a gasoline engine passenger car [1]. The turbine wheel in this product was cast TiAl alloy, which was manufactured by precision casting and joined to a low-alloy steel shaft to form the turbine rotor. Even in recent research on the practical application of TiAl alloys, small blades [2,3] and engine valves [4] manufactured by casting, isothermal forging, and extrusion are targeted, and there are no development examples of parts weighing 0.5 kg or more. The TiAl alloy is currently mostly used in the low-pressure turbine blades of jet engines [5] Parts manufactured by precision casting were initially used for practical applications; however, because the TiAl alloy is poorly castable, casting a near-net into a blade shape was difficult, with very large surplus materials required, leading to large amounts of machining that effectively negated the merits of precision casting. As a result, blades are currently manufactured by machining large prismatic ingots.

Because a casting-manufacturable TiAl alloy part is limited in size, hot-forging is required to manufacture large parts in the same manner as an ordinary metal material. In this case, large ingot is first manufactured. After increasing its temperature in a heating



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Copyright: © 2021 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). furnace, the ingot is removed from the furnace and compressed at high-speed using a hydraulic press while atmospherically cooled. Normally, this heating, removal, and pressing process is repeated to bring the product closer to the required shape.

While this hot-forging method is easily applied to ordinary metal materials, it is less applicable to TiAl alloys because these alloys are poorly ductile and badly workable, even at high temperatures. Therefore, the author developed the world's first hot-forgeable TiAl alloy. The author was also significantly involved in the development of large structural parts intended for defense-product applications using this alloy. These structural parts are currently being produced on the large scale, with public disclosure such as displays at international exhibitions being gradual released as well.

This paper first discusses the developmental history of this world-first hot-forged TiAl alloy and its practical applications, after which recent research results focusing on the development of new manufacturing processes and new hot-forged TiAl alloys applicable to high-temperature applications are discussed.

2. Developmental History of the Hot-Forged TiAl Alloy

Because conventional TiAl alloys are difficult to hot-forge, an isothermal forging method is used when a forged material is required. Isothermal forging is a method in which upper and lower dies are used in the forming process; the product materials and dies are held together at high temperature in an inert atmosphere, and the upper die is lowered at an extremely low rate for compression processing. Problems associated with this process include high cost and the inability to manufacture large parts. However, it is an effective method for fabricating high-value-added small parts. While the practical use of an isothermally forged TNM alloy [6] product developed in Germany was announced for use in the low-pressure turbine blades of jet engines [7], the reason is not disclosed in public documents, but the commercialization has been discontinued.

On the other hand, the conventional TiAl alloy is an intermetallic compound with poor deformability against high-speed deformation even at high temperatures, so hot-forging processes required to manufacture larger parts is completely inapplicable. Figure 1a shows the appearance of a normal TiAl alloy composed of the γ and α_2 phases after hot-forging; the alloy was heated to 1350 °C, removed from the furnace, and forged with a hydraulic press. Clearly, the hot-forging method is very difficult to apply, as evidenced by significant cracking. In view of this situation, the author examined ways of improving the hightemperature deformability of the TiAl alloy and found that the incorporation of a (third) β phase was beneficial. The β phase does not exist in ordinary TiAl alloys, but is stabilized by the addition of β -stabilizing elements, such as Cr, Mn, and V. This β phase is a bcc-based phase, which transforms into intermetallic compound B2 at low temperatures, but changes into a metallic phase with excellent deformability at high temperatures. Therefore, hotforging with high-speed deformation becomes possible if a certain amount of the β phase is present at the forging temperature. The author's papers [8,9] and patents [10] relating to this discovery are both global firsts. Ti-42Al-5Mn (at%) is the world's first TiAl alloy capable of being hot-forged using this principle.



Figure 1. Appearance after hot-forging: (a) ordinary TiAl alloy and (b) Ti-42Al-5Mn.

Figure 1b shows the appearance of the Ti-42Al-5Mn material after heating to 1300 °C, removal from the furnace, and forging with a hydraulic press. No cracks are visible, and the effect of the β phase on improving forgeability is clear. Hot-forging, which was not possible with TiAl alloys in the past, is possible when this β phase is incorporated, which paves the way for the fabrication of large parts using TiAl alloys. Figure 2 shows the appearance of a hot-forged Ti-42Al-5Mn product (70 kg) alongside precision cast and isothermally forged products (less than 0.2 kg) fabricated using the TiAl alloy to date; clearly, hot-forging enables significantly larger parts to be manufactured, which was not possible previously.



Hot-forging

Figure 2. Comparing the actual size of products produced by various methods.

3. Application History of the Hot-Forged TiAl Alloy

The Ti-42Al-5Mn hot-forged material developed by the author has been produced on the large scale since around 2010 for large structural components for defense applications. Figure 3 shows some images of the manufacturing process of this component. A large ingot is first manufactured. The ingot is then extended into a stepped flat plate by subjecting it to repeated hot-forging. The surplus metal is trimmed from the flat plate by water-jet cutting. The material is then hot-forged using a hydraulic press which installed the lower die on the bed below and the upper die to a slide (up/down-moving). The plate material removed from the heating furnace is then sandwiched between the dies, and the upper die is gradually lowered to form. Heating, removal, and pressing are repeated many times during this forming process, leading to the fabrication of the large structural member shown in Figure 2, which was subsequently machined and coated to provide the final finished product.



Figure 3. Photographic images showing some of the process used to fabricate a commercial product. (a) Upset forging, (b) width-adjustment forging, (c) plate material after forging, (d) trimming by water-jet cutting, (e) forming by hot-forging, and (f) machining.

Due to the sensitive nature of this product, its details have not been released to date; however, public disclosure such as displays at international exhibitions is gradually being released. Figure 4 shows a large structural component fabricated from Ti-42Al-5Mn as exhibited at the Japanese Ministry of Defense booth at the Japan International Aerospace Exhibition 2018 Tokyo (JA2018 Tokyo). While this product is currently being fabricated on the large scale, details, including the production volume, have not been released.



Figure 4. Large structural Ti-42Al-5Mn components exhibited at the Japan International Aerospace Exhibition 2018 Tokyo (JA2018 Tokyo).

4. Problems with Early Hot-Forged TiAl Alloys

As mentioned above, hot-forged Ti-42Al-5Mn has already been put to practical use, but it has been limited to defense products with short usage times due to very high costs and particularly low high-temperature strengths. These high costs were due to difficulties associated with manufacturing large uniform ingots for components at that time. The lack of compositional stabilization led to the fabrication of many ingots with higher Al and lower Mn contents than specified. As the amount of β phase formed during forging was lower in these cases, decrease in deformability for high-speed deformation was sometimes observed, which led to cracking during forging.

In addition, other problems arose, especially during the forming process. Temperature often dropped rapidly during deformation due to the thinness of the plate and heat was absorbed from the upper and lower dies, resulting in cracking. Because welding (or similar processes) cannot be used to repair cracks in the TiAl alloy, all of the large material was discarded when cracks formed. Moreover, poor shape accuracy, due to the presence of thick oxide layers and positioning inaccuracies was also caused production problems which required large amounts of surplus metal to overcome, resulting in higher material and machining costs.

On the other hand, the large amount of β phase, which was required at the time of forging but remained even after heat treatment, was a problem that affected the material properties of the final product. Figure 5 shows the microstructure (BSE(Backscattered Electron Image)) of the forged Ti-42Al-5Mn material after heat treatment. The heat treatment conditions were cooling at 10 °C/min after holding at 1250 °C for 2 h. This condition was selected so that the amount of β phase was minimized in this alloy composition, but as shown in Figure 5, a large amount of β phase still remains. Because the β phase is soft at high temperatures, it is a natural factor that lowers the high-temperature strength of the material. Figure 6 shows the tensile properties of Ti-42Al-5Mn heat-treated under the above conditions after hot-forging; the strength drops significantly above 700 °C, which indicates that it is unsuitable for high-temperature or long-term applications.



Figure 5. BSE image showing the microstructure of hot-forged Ti-42Al-5Mn after heat treatment.



Figure 6. Tensile strength of hot-forged Ti-42Al-5Mn after heat treatment as a function of temperature.

5. Subsequent Process Improvements

As mentioned above, compositional homogenization of ingot and stabilization in the forming process were issues for products intended for practical use; consequently, new manufacturing processes were developed to address these two problems. At that time, ingots were manufactured by induction skull melting using a water-cooled copper crucible; however, the inability to prepare uniform compositions was problematic due to the low superheated temperature of the molten metal. Therefore, melting in a ceramic crucible that facilitated a higher superheated temperature was examined. Ceramic crucible melting is a method that is not normally used for TiAl alloys because it increases the amount of oxygen. However, examining various crucible materials revealed that yttria crucible melting resulted in only a small increase in oxygen content that hardly affected the mechanical properties of the material [11,12]; hence, an yttria crucible melting was chosen.

Figure 7 shows the ceramic crucible used to melt a large ingot. To reduce the cost of the yttria raw material, a two-layer crucible with an outer alumina layer and an inner yttria layer was prepared. Problems, such as interfacial peeling, are avoided because the linear expansion coefficients of alumina and yttria are almost the same [13]. A large cylindrical ingot was manufactured by melting raw materials in this crucible using an induction melting furnace with a 300 kg iron capacity, and then cast into a cast-iron cylindrical mold. The appearance of the ingot is shown in Figure 8; it is 260 mm in diameter, 650 mm high, and weighs 140 kg. Some shrinkage cavities were formed inside the ingot; however, they were all eliminated by performing HIP (hot isostatic pressing) treatment of $1250 \,^{\circ}C / 142 \, MPa/2 \, h$.

Table 1 lists the compositions (wt%) of a conventional Ti-42Al-5Mn ingot manufactured by skull melting and the Ti-42Al-5Mn ingot melted using the abovementioned ceramic crucible. The composition of the former was far from the target composition. On the other hand, while the oxygen concentration was slightly higher in the latter, the concentrations of Al and Mn were very close to the target values regardless of position in the ingot, highlighting significantly improved component homogeneity. This effect facilitates stable hot-work process quality.







Figure 8. Appearance of the large Ti-42Al-5Mn ingot.

Table 1. Compositions of Ti-42Al-5Mn ingots produced by Y_2O_3 crucible melting and skull melting in wt%.

	Analyzed Position	Chemical Composition (wt%)						
		Al	Mn	С	0	Ν	Fe	Н
Y ₂ O ₃ crucible melting	Тор	28.6	7.03	0.005	0.12	0.012	0.01	0.0016
	Bottom	28.5	6.83	0.004	0.12	0.012	0.01	0.0016
Skull melting	-	28.1	7.63	0.007	0.048	0.008	0.004	0.0013
Target	-	28.7	7.0	-	-	-	-	-

A new method that uses dies was next developed for the forming process. As mentioned above, the temperature of the thin plate material dropped rapidly and cracks occasionally formed during hot-forge forming, which are problems associated with conventional methods. In addition, dimensional accuracy was hard to maintain due to the presence of a thick oxide layer or similar. Therefore, a method was developed in which the material is deformed at a low rate while held at high temperature in an inert gas. While this can be achieved by isothermal forging, the use of this method is unrealistic because the extremely large material size requires equipment that is also very large. Therefore, a process that uses a hot-press with a small pressing capacity but with a large chamber that allows a push rod to descend at a low rate was developed. A test part was formed using this process, as described below.

A disk was first manufactured from a cylindrical Ti-42Al-5Mn ingot by repeated upset-forging. The disk was machined and processed into a 50 mm-thick, 500 mm-diameter test sample; the test forming procedure using a hot-press is shown in Figure 9, with a cone as the target shape. The upper and lower dies were made of carbon, and the test disk was placed between the dies and heated to 1200 °C in an inert gas. The push rod of the hot-press was then lowered at a low rate while maintaining this temperature, resulting in the upper die being pushed into the center of the material to form a cone. This forming process was performed in one operation, and required approximately 10 h to complete. Figure 10 shows the appearance of the formed Ti-42Al-5Mn product after hot-press forming. The tip of the cone was cut for examination. It reveals no problems, including cracking, and that forming along the upper and lower dies proceeded without the formation of gaps. Because this method is not unstable, unlike forming by hot-forging, quality consistency is obtained even after repeated production.



Figure 9. Forming test procedure and jig with hot-press. (**a**) Cross-sectional view and (**b**) appearance prior to forming.



Figure 10. Formed simulated product after hot-pressing (top cut).

A practical component with the same shape as the product was formed by hot-pressing in the same manner; Figure 11 shows the appearance of this component. No particular problems were encountered, and the shape of the component was clearly formed into the predetermined shape.



Figure 11. A member with the same shape as the product formed by hot-pressing.

6. The Development of New Alloys

Hot-forged Ti-42Al-5Mn, which has been practically used in defense products, has a low high-temperature strength because of the large amount of β phase remaining at the end of the fabrication process, which is problematic. Therefore, a new alloy [14] was developed in which the β phase exists at a temperature of approximately 1300 °C at the time of forging, but disappears by subsequent heat treatment at a lower temperature.

Figure 12 [14] shows the appearance of the material after test hot-forging conducted with a small ingot with a diameter of 30 mm and a length of 100 mm, along with microstructural features before and after heat treatment. The heat treatment conditions were cooling at 10 °C/min after holding at 1280 °C for 2 h. While forgeability was good (there are no cracks that always occur in hot-forging of ordinary TiAl alloys), the β phase was almost eliminated by heat treatment, with the microstructure changing into a fine lamellar structure that effectively improves the high-temperature strength. Figure 13 compares the tensile strengths of the new alloy with that of Ti-42Al-5Mn and Mar-M247DS, a directionally solidified Ni-based superalloy [15]. In this case, specific strengths (strength/specific gravity) required for the rotating bodies are compared. The tensile specific strength of the new alloy is significantly higher than those of Mar-M247DS and Ti-42Al-5Mn. In other

words, high-temperature strength, which was a problem for the previous hot-forged TiAl alloy, has been improved. In addition, recent study on hot-forged TiAl alloy [16] has reported a decrease in the amount of β phase due to heat treatment after hot-forging, but the degree of decrease is insufficient and the mechanical properties are not described.



Figure 12. Hot-forging test results and microstructures before and after heat treatment of the newly developed alloy. (a) Appearance of the hot-forged material, (b) As-forged microstructure, and (c) Microstructure after heat treatment.



Figure 13. Tensile specific strengths of the new alloy and comparative materials.

7. Conclusion and Future Prospects

Ti-42Al-5Mn (at%) is the world's first TiAl alloy capable of being hot-forged. This alloy has enabled the manufacture of large structural parts for the first time in the history of TiAl alloys. Ti-42Al-5Mn has already been used on the large scale to fabricate a large structural defense-product component for which public disclosure such as displays at international exhibitions is being gradually released. This paper first discussed the developmental process and practical applications of this alloy.

Next, manufacturing stabilization and improving high-temperature strength, which were issues originally associated with the practical use of TiAl alloys, were discussed. A method for producing a large ingot with high compositional homogeneity was developed as well as a stable forming process involving hot-pressing. Focusing on high-temperature strength, a new alloy was developed in which the β phase exists during hot-forging but disappears by subsequent heat treatment, which significantly improves the high-temperature strength of the material. These new processes and alloys are expected to be applied to large parts for high-temperature applications, such as low-pressure turbine blades for power generation gas turbine.

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