The Development of Low-Cost TiAl Automotive Valves

M.M. Keller, P.E. Jones, W.J. Porter III, and D. Eylon

This paper presents the results of a project funded by the Edison Materials Technology Center to develop low-cost titanium aluminide automotive valves. In the course of the project, more than 800 valves were produced using several variations of the permanent-mold casting process. Applying pressure during solidifcation improved the casting fill; however, none of the permanent mold casting methods produced pore-free as-cast valves. The as-cast microstructures of the valves were much finer than investment-cast microstructures of similar section sizes. The room-temperature tensile properties of the permanent mold castings were superior to those of investment castings of a comparable section size.

INTRODUCTION

The automotive industry has been studying TiAl intake and exhaust valves since the late 1980s after noting the potential performance, fuel economy, reduced emissions, and lower engine noise benefits that could be realized by replacing 21-2N steel and Inconel 751 valves with TiAl-based alloys. In fact, General Motors,[1] Volvo,[2] Ford Motor Company,[3] and Nissan Motor Company,[4] have all reported successful engine tests of TiAl components. While γ-TiAl alloys show much potential, high cost and difficulty in processing are serious impediments to the marketing of TiAl components, especially in the automotive industry.

While ingot metallurgy processes appear to offer the greatest reliability in producing TiAl components (if uniform microstructures can be produced), they are costly to implement.[5] Blended elemental powder methods were explored in Japan[6] and Europe,[7] but eliminating microstructural segregation has proven difficult. Although gas-atomized powder products have demonstrated good forgeability and microstructural uniformity,[8,9] concerns about processing cost and lack of capacity have limited interest in this process option. Investment casting offers a lower cost alternative to wrought processing, but the cost and cycle times associated with it may not be suitable for an automotive industry concerned with the low-cost production of high-volume components. Permanent-mold casting methods have been used to produce aluminum and steel components, but they have not been widely employed for the production of titanium or TiAl parts.[10]

The Edison Materials Technology Center's (EMTEC's) Automotive Valve Project was established to explore the feasibility of producing lightweight γ-TiAl intake and exhaust valves using permanent-mold casting. Under this project, more than 800 valve blanks were produced using variations in the permanent-mold process. Furthermore, TiAl valves from this project were road-tested in two Chevrolet Corvettes. In both vehicles, the γ-TiAl valves survived more than 24,000 kilometers of testing and exhibited no damage or defects upon completion of the test (Figure 1). Other industrial groups are also investigating permanent-mold processing as a means to produce automotive exhaust valves, including Daimler Benz[11] and Nissan.[4]

CASTING PROCESS EVALUATIONS

The General Electric alloy Ti-47Al-2Nb-1.75Cr was selected as the valve material. Howmet Corporation, which had independently studied the permanent-mold casting of conventional titanium alloys, was the casting source. Figure 2 shows the sequence of melting, die casting, and finishing operations used to produce the valves. All melting was performed using a vacuum arc remelting (VAR) furnace, and the molten alloy was poured into a permanent steel mold. The cast valves and the dies are shown in Figure 3.

Several variations of the permanent-mold process were explored. The baseline process was the static permanent-mold process by which valves were cast via a gravity-feed process. Although the as-cast dimensions of the valve blanks produced using the static side gate process were acceptable, there was considerable dimensional distortion after hot isostatic pressing (HIPing) and heat treatment. This dimensional distortion results from the closure of non-centerline pores, creating subsequent

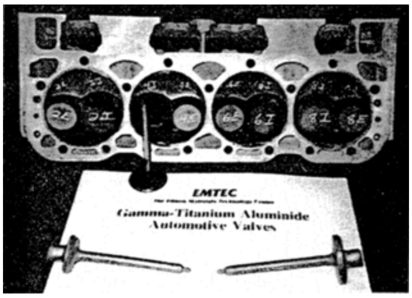

Figure 1. A cylinder head from a road-tested Chevrolet Corvette with the γ-TiAl alloy valves.

Table I. Tensile Properties for Static-, Injection-, and Investment-Cast Processes*

Test Temp.	Cast Process	Condition	0.2 Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
Room	Static	As-Cast–1260 HIP	409	466	1.6
Room	Static	HIP + Heat Treat	429	516	1.4
Room	Injection	As-Cast–1260 HIP	302	411	2.0
Room*	Investment	HIP + Heat Treat	331	465	2.4
760°C	Static	As-Cast–1260 HIP	356	499	3.0
760°C	Static	HIP + Heat Treat	286	428	13.3
760°C	Injection	As-Cast–1260 HIP	302	497	17.8
815°C	Static	As-Cast–1260 HIP	335	469	38.4
815°C	Static	HIP + Heat Treat	368	531	23.3
815°C	Injection	As-Cast–1260 HIP	293	416	23.5

* Average of two data points.

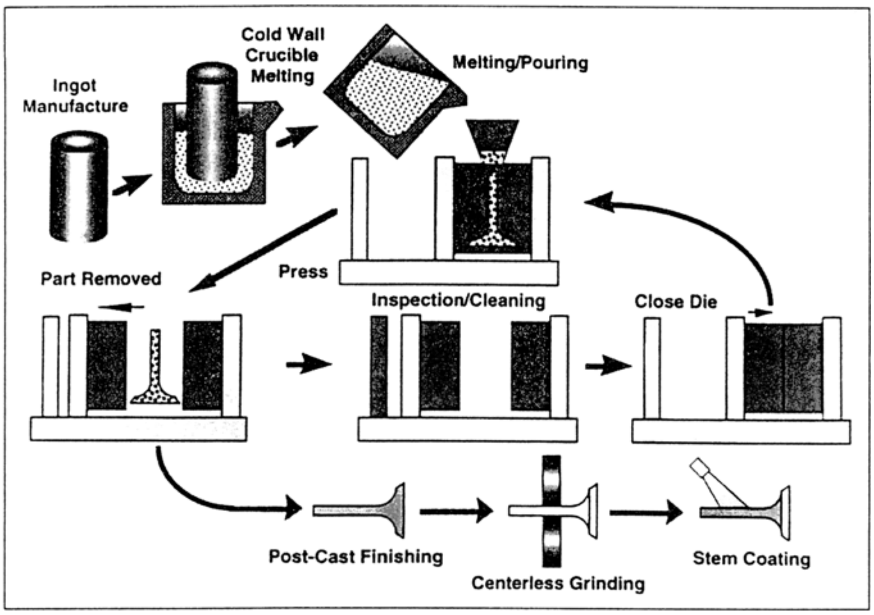

Figure 2. A schematic of the permanent-mold process for casting automotive TiAl valves.

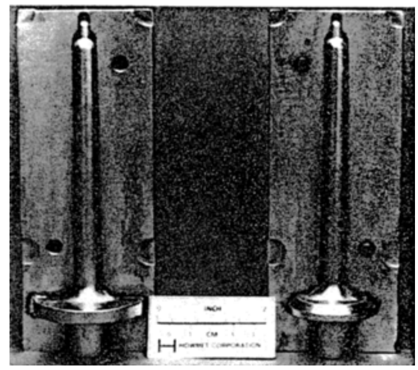

Figure 3. As-cast valves in the steel dies.

machining problems. Present steel valve blanks are forged to a tolerance of less than 1 mm so that they can be centerless ground at a minimum cost.

In an attempt to reduce the shrink to a level that would permit low-cost, as-cast valve production, several methods of applying pressure during solidification were tried: gas boost, centrifugal casting, squeeze pins, and injection. The gas-boost technique entails backfilling the furnace with inert gas just after pouring.[12] The centrifugal casting was performed at 250 rpm, generating a force of approximately 5 g. Such force is lower than typical production values because the casting was performed using laboratory-scale equipment. Squeeze pins are hydraulically actuated plungers that apply pressure to the in-gate (boss) to force liquid metal into the valve head. The injection system was developed by Howmet to adapt die-casting methods to titanium-based alloys. The metal is poured into a shot sleeve and then forced into the die cavity under high pressure.[13] It was found that applying pressure during solidification was beneficial as it could be used to either reduce shrinkage or move the shrinkage closer to the centerline. This is critical since the competitive automotive market may not tolerate the cost of HIPing. Therefore, a mature casting process must produce valves having minimum shrinkage that is reliably located along the centerline of the part.

Fifty-four pours were made using the static permanent-mold process. Inspection of the steel dies revealed no measurable distortion or erosion in any of the valve dies produced. In addition, there was no increase in the dies' surface roughness. However, the surface finish of the as-cast valves was affected by cleaning the dies. After several pours, a metallic-layer buildup on the die surfaces resulted in valves with a poor as-cast surface finish. Therefore, it became necessary to chemically clean the dies after every fifth pour. Although the durability of the steel dies through the 54 pours shows great promise, more extensive trials are needed to determine whether the die life could be suitable for an automotive-quantity production environment. In addition, the cleaning process used in this study may not be suitable for production casting. Hence, another means of reducing the metallic buildup on the dies may be necessary.

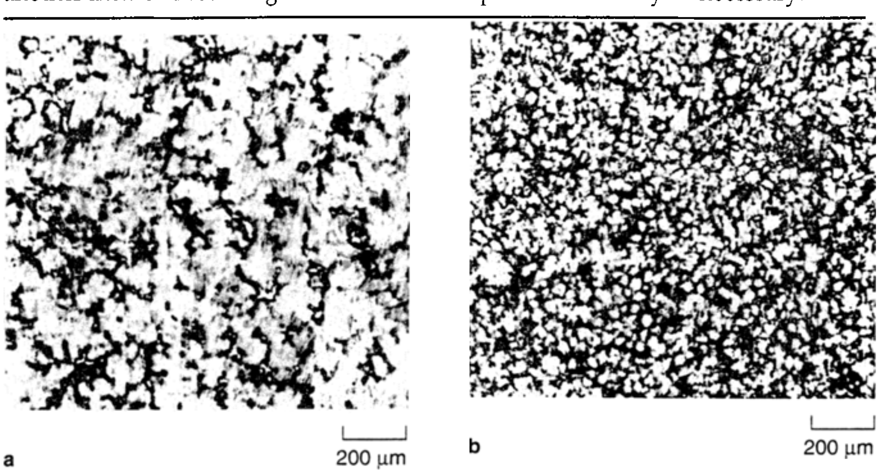

Figure 4. As-cast structures from the (a) static-cast and (b) injection-cast processing.

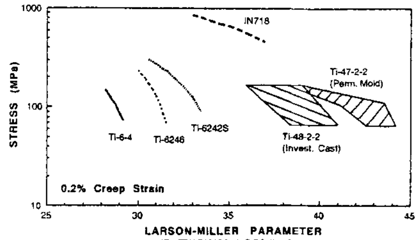

Figure 5. A Larson Miller plot comparing the creep strength of permanent-mold and investment cast Ti-47Al-2Nb-2Cr to other high-temperature alloys.

MICROSTRUCTURAL EVALUATION

The as-cast microstructures for the permanent-mold processes were nearly lamellar and are similar to those found in investment-cast components possessing comparable section sizes and compositions. Static permanent-mold casting produced prior-α grain sizes of 100–250 μm, which is much finer than the prior-α grain sizes of 100–1,000 μm found in investment castings having a similar diameter. The finer grain size was anticipated due to the higher cooling rates associated with permanent steel molds. Figure 4 compares the as-cast microstructures resulting from injection and static castings. The injection-cast microstructure is highly segregated and has a significantly finer prior-α grain size than that of the static-cast structure. The finer as-cast microstructure that results with injection casting may be the result of metal being sprayed into the mold during the injection process or of heat being lost to the shot sleeve. Injection casting produced the finest as-cast microstructure of the permanent mold processes.

MECHANICAL PROPERTIES

Table I compares the tensile properties of static and injection permanent-mold components to counterparts produced by investment casting. At room temperature, the static castings are stronger than the injection castings but have lower ductility. Variation in aluminum content may have contributed to the difference in strength. The first 50 heats of valves exhibited an aluminum variation of 0.5 at.% around the target level of 47 at.%. Previous work on this alloy showed that the room-temperature yield strength decreases ~40 MPa for every 1 at.% increase in aluminum.[15] The room-temperature tensile strength of HIPed and heat-treated static castings is comparable to that of investment castings.[14] The room-temperature strength of permanent-mold castings is greater than that of the investment-cast material. This may be a Hall-Petch effect, reflecting the finer average grain size of the permanent-mold cast material.

Figure 5 is a Larson-Miller diagram comparing time to 0.2% creep strain for investment-cast and permanent-mold-cast Ti-47Al-2Nb-2Cr, other titanium alloys, and cast Inconel 718 having a similar grain size. The TiAl alloys offer improved creep resistance over the conventional titanium alloy. The improved creep resistance of the permanent-mold as opposed to the investment-cast material is most likely the result of a lower aluminum level and different heat-treatment conditions.

CONCLUSIONS AND POTENTIAL APPLICATIONS

Based on the EMTEC project's work with producing more than 800 valves, permanent-mold casting appears to be a viable method for producing small-to-moderate volumes of fine-grained TiAl-based automotive valves. Permanent-mold casting into ferrous dies resulted in minimal mold/metal reaction and minimal tooling erosion, even after 54 pour cycles. The fine grain size and the highly segregated cast structure produced by the injection process offers a better starting point for microstructural refinement during HIP and heat treatment. Applying pressure during solidification improves the casting fill; however, none of the permanent-mold casting methods produced low-porosity as-cast valves.

The amount and location of the shrinkage will influence the market for TiAl valves. Excessive and off-centerline shrinkage results in poor dimensional stability after HIPing and increases machining costs and rejection rates. As it is unlikely that the cost-sensitive automotive market will pay for HIPing to eliminate casting shrink in valves, a minimum shrinkage level during casting (consistently located along the neutral axis of as-cast valves) will be necessary to attract the attention of car makers.

Although the feasibility of the permanent-mold casting process has been established, experience with full-scale production equipment will be necessary to identify the full benefits and economics of permanent-mold casting and to assess the ability of this process to meet the high volume requirements of the automotive market. Cast valve material with subsequent HIPing or heat treatment demonstrated acceptable levels of mechanical properties, provided that shrinkage porosity was not present in critical locations. The dimensional stability of components produced by permanent-mold casting was higher than those manufactured using investment casting.

Permanent-mold casting is also applicable for producing other lightweight automotive parts, including rocker arms, turbocharger impellers, and suspension components.

ACKNOWLEDGEMENTS

The support of EMTEC, the EMTEC Valve Team, the National Science Foundation, and Wright Laboratory at Wright-Patterson Air Force Base made this work possible. Their contributions are greatly appreciated.

References

1. S. Hartfield-Wunsch et al., "Titanium Aluminide Automotive Engine Valves," *Gamma Titanium Aluminides*, ed. Y-W. Kim, R. Wagner, and M. Yamaguchi (Warrendale, PA: TMS, 1995), pp. 41–52.
2. D.E. Larsen, Jr., and D.A. Wheeler, "Investment Cast Gamma and XD™ Gamma Titanium Aluminide Components for Aerospace and Automotive Applications," *Investment Casting Institute: 42nd Annual Technical Meeting* (Investment Casting Institute, 1994).
3. W.E. Dowling, Jr., et al., "TiAl-Based Alloys for Exhaust Valve Applications," SAE paper 930630 (Warrendale, PA: SAE, 1993).
4. K. Maki et al., "Development of a High-Performance TiAl Exhaust Valve," SAE paper 960303 (Warrendale, PA: SAE, 1996).
5. Y-W. Kim and D.M. Dimiduk, "Progress in the Understanding of Gamma Titanium Aluminides," *JOM*, 43 (8) (1991), pp. 40–47.
6. D. Eylon, private communication (1993).
7. G.-X. Wang and M. Dahms, "Reactive Powder Processing of Intermetallic Alloys Based on γ-TiAl," *Structural Intermetallics*, ed. R. Darolia et al. (Warrendale, PA: TMS, 1993), pp. 215–222.
8. S.L. Semiatin, G.R. Cornish, and D. Eylon, "Hot-Compression Behavior and Microstructure Evolution of Pre-Alloyed Powder Compacts of a Near-γ Titanium Aluminide Alloy," *Materials Science and Engineering*, A185 (1994), pp. 45–53.
9. G.E. Fuchs, "Powder Metallurgy Processing of Ti-48Al-2Nb-2Cr (at%) Alloys," *MRS Symp. Proc.*, vol. 288 (Pittsburgh, PA: MRS, 1993), pp. 847–852.
10. Y. Mae, "Development of Titanium Die Casting," *Metallurgical Review of MMIJ*, 8 (1) (1991), pp. 113–118.
11. S. Hurta et al., "Valves of Intermetallic γ-TiAl-Based Alloys: Processing and Properties," *Titanium '95, Proceedings of the Eighth World Conference on Titanium*, ed. P.A. Blankinsop, W.J. Evans, and H.M. Flowers (London: Institute of Materials, 1995), pp. 97–104.
12. G. Colvin, U.S. patent 5,287,910.
13. Howmet, patent pending.
14. S.V. Ram and J.R. Barrett, "Investment Casting of Near-Net Shape Gamma Titanium Aluminide Low Pressure Turbine Blades,"*Titanium '95, Proceedings of the Eighth World Conference on Titanium*, ed. P.A. Blankinsop, W.J. Evans, and H.M. Flowers (London: Institute of Materials, 1995), pp. 90.
15. D. Eylon et al., *EMTEC TR94-24 Part 1* (Kettering, OH: EMTEC, 1994), pp. 69–137.

ABOUT THE AUTHORS

M.M. Keller earned her M.Sc. in materials engineering at the University of Dayton in 1993. She is currently a Ph.D. student in materials engineering. She is also a member of TMS.

P.E. Jones earned her M.Sc. in materials at the University of Dayton in 1993. She is currently a Ph.D. student in materials engineering. She is also a member of TMS.

W.J. Porter III earned his M.Sc. in materials engineering at the University of Dayton in 1990. He is currently project engineer at the University of Dayton Research Institute. He is also a member of TMS.

D. Eylon earned his D.Sc. in materials engineering at Technion, Haifa, Israel, in 1972. He is currently a professor of graduate materials engineering at the University of Dayton. He is also a member of TMS.

For more information, contact M.M. Keller, University of Dayton, 300 College Park, Dayton, Ohio 45469-0240; (937) 229-2628; fax (937) 229-3433.