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 aluminate 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 solidification 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, Volvo, Ford Motor Company, and Nissan Motor Company have all reported successful engine tests of TiAl components. While 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. Blended elemental powder methods were explored in Japan and Europe, but eliminating microstructural segregation has proven difficult. Although gas-atomized powder products have demonstrated good forgeability and microstructural uniformity, 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.

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 and Nissan.

CASTING PROCESS EVALUATIONS

The General Electric alloy Ti-4Al-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...
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. 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. 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 2. A schematic of the permanent-mold process for casting automotive TiAl valves.

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

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.