Properties of Low Cost TiAl Automotive Valves Produced by Cold Wall Induction Melting and Permanent Mold Centrifugal Casting

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ANNOTATION

Initiated by ALD Vacuum Technologies GmbH a new manufacturing process for an economical mass production of TiAl valves has been developed by a joint research project which is financially supported by the Federal Ministry for Education and Research of Germany.

The new process enables the production of TiAl valves in high annual volumes and at cost comparable to conventional steel exhaust valves. The expected price is feasible through the very high level of process integration. Melting, alloying, purification and casting are integrated in single step. The two main features of the manufacturing process are the use of a modified induction cold crucible and a heatable metallic permanent mold in an evacuable centrifugal casting unit.

Based on the results of numerical process simulation as well as casting experiments a pilot plant has been built. In order to minimize the effort for the optimization of melting and casting parameters, regarding the mechanical properties of the valve, an experimental programme based on modern DoE-technique was performed. The development of the process and the results of this programme will be presented.

Key words: Automobile valves, Titaniumaluminide, Cold Wall Induction Furnace, Permanent Mold, Centrifugal Casting, Control of Solidification, Primary Structure, Segregation, Tensile Properties

1. INTRODUCTION

Due to its approx. 50 % less density and higher elevated temperature strength than steel titanium aluminide alloys are excellent candidates for automotive valves of new generation combustion engines with higher exhaust gas temperature. In a number of published reports the excellent behaviour of titanium aluminide exhaust valves has been demonstrated in vehicle tests under severe operation conditions 1, 2, 3. The main barrier to implementation of titanium aluminide valves is the non-availability of a high volume cost effective production method. All valves used in the above mentioned vehicle tests were investment cast or injection cast in a steel mold using vacuum arc remelted feed stock material 4 with subsequent isostatically pressing (HIP). These processes are neither suitable for mass production nor economical.

In a joint research programme initiated by ALD Vacuum Technologies GmbH with seven other partners a new process has been developed. The process includes
- ceramic-free melting and alloying using cheaper individual elements like titanium, aluminium, niobium, chromium etc. avoiding the use of vacuum arc remelted feedstock
- centrifugal casting in a permanent mold with a multiple of valves
- control of solidification of the melt by a thermal gradient in such a way that no macroscopic shrinkage cavities appear in the valve body and the micro-porosities are predominantly on the central axis of the valve so that hot isostatic pressing can be eliminated
2. MELTING, ALLOYING AND CASTING

For melting and alloying the cold wall induction furnace has been selected. In order to avoid any accidental skull formation the furnace has been designed after mathematical modelling of the electric and hardware configuration. It is now possible to control the chemistry even by using individual elements as feedstock. For this present work two TiAl-based alloys, TiAl₄₇Cr₂Nb₂ and TiAl₄₆₆Cr₁Si₀₂, were selected. Table 1 shows the reproducibility of the chemical composition of several melts of the alloy TiAl₄₇Cr₂Nb₂.

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<th>Al (AT-%)</th>
<th>Cr (AT-%)</th>
<th>Nb (AT-%)</th>
<th>H (ppm)</th>
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Tab. 1: Reproducibility of the Chemical Composition

Similar results have also been achieved with the alloy TiAl₄₆₆Cr₁Si₀₂. The equipment for melting, alloying and centrifugal casting, as shown in Fig. 1 schematically, has been described in detail in earlier report.

Fig. 1: Schematic Sketch of the Equipment

For a high volume production of titanium aluminide automotive valves the centrifugal casting of a multiple of valves in a permanent metallic mold is the most economical technology. In order to avoid shrinkage cavities in the valve plate as well as in the first third of the valve stem and to minimize it in the upper stem. For this purpose the mold must be preheated prior to casting up to a temperature of approx. 1000 °C. A niobium alloy has therefore been selected for mold material.
It is not mandatory that the centrifugal casting mold consists entirely of niobium alloy. It is sufficient to use inserts of niobium alloy into the mold body as shown in Fig. 2.

The casting mold consists of 5 layers of mold cavities containing 12 valves in each layer. For the present series of tests only 3 layers have mold inserts. Fig. 3 shows a cluster of 36 valves attached to the remaining skull.
3. QUALITY ACCESSMENT OF THE VALVES

One of the major aims of the present work is to produce titanium aluminide automotive valve which can be used in as-cast condition without any HIP-ing and heat treatment. Accordingly the as-cast structure is the most important factor influencing the quality of the valves. In order to determine the optimum melting and casting parameter a large number of tests was carried out and evaluated with the help of a DoE (Design of Experiment) -programme.

The valves were investigated as follows:
- Primary and Secondary Structure
- Segregation
- Porosity and Position of the Pores
- Mechanical Properties
- Engine Test

4. STRUCTURE AND SEGREGATION

The primary structure of the valves consists of a thin layer of equiaxed zone - so-called chill-zone - with a subsequent columnar crystallization with a length of approx. 1,5 mm to 2 mm (Fig. 4).

![Fig. 4: Primary Structure of the Valves](image)

The center of the valve head and of the stem shows again an equiaxed crystallization. On the center line of the lower part of the stem microscopic shrinkage porosity has been observed. Fig. 5 shows the grain size and lamellae spacing in an as-cast valve without any heat treatment.
The average grain size in the disc and in the center area of the stem is 250 µm and 75 µm respectively. For mechanical properties of titanium aluminide along with finer grain size the α₂-lamellae spacing and their orientation are of special importance. The α₂-lamellae spacing of as-cast valve in a metallic mold with 210 nm in the disc and 140 nm in the stem is very small compared to literature data\(^9\). The orientation of the α₂-lamellae is almost parallel to the valve axis. This extra fine structure is due to the fast solidification rate of the melt during centrifugal casting in a niobium mold.

Along with the structural characteristic such grain size and the geometry of the α₂-lamellar the distribution of the different alloying elements is another factor influencing the mechanical properties of the TiAl-valves. The concentration of different alloying elements, e.g. Ti, Al, Nb and Cr, along the cross section of a valve have been determined with an electron probe micro analyser (EPMA). It is evident from Fig. 6 that no macroscopic segregation has been observed.

Also the scatter range of micro-segregation in the interdentritic area is very narrow. An additional heat treatment for homogenisation is therefore not necessary.
5. POROSITY

As evident in Fig. 7 the valves exhibit micro-porosity around the axis of the lower part of the stem.

Fig. 7: Measurement of Porosity

Shrinkage cavities depending on size and their distribution in the cross section of the valves may have detrimental influence on the mechanical properties, especially on the ductility of the valves. A large number of valves cast with different parameters were sectioned longitudinally and the pores found were measured with an automatic image analysis system. The longitudinal section was divided into 26 windows (Fig. 7) with an area of 2 mm x 4.6 mm (9.2 sq. mm). The measurement of the area of the pores in each window was carried out along three tracks - middle, right, and left. This measurement gives information of the pores' position. The result of this measurement is shown in Fig. 7 as an example. All investigated valves show a similar picture. It is evident that the pores appear essentially on the centre line in the lower half of the valve stem. It is also evident that one third of the valve length from the disc is completely free from any measurable pores.
6. MECHANICAL PROPERTIES

The mechanical properties of the valves were determined in as-cast condition without any heat treatment. Fig. 8 shows the tensile and the yield strength at room temperature as a function of aluminium-content of the alloy TiAl47Cr2Nb2.

Contrary to literature data the aluminium-content in the given range between 46 At% and 47.75 At% has no influence on the tensile properties. The yield strength of the valves also shows much higher values than those in the published literature. In spite of relatively high strength the plastic elongation of the valves is in the usual range (0.5 % to 1.8 % - Fig. 9).

Fig. 8: Tensile and Yield Strength Depending on Aluminium Content

Fig. 9: Plastic Elongation Depending on Aluminium Content
The fracture toughness ($K_{IC}$) of the valves is shown in Fig. 10 as a function of aluminium-content.

![Fracture Toughness Depending on Aluminium Content](image)

Fig. 10: Fracture Toughness Depending on Aluminium Content

The $K_{IC}$-values in average 25 Mpa$\sqrt{m}$ are constant over the whole aluminium range. These higher tensile and toughness properties of the valves are due to the very fine grain solidification during centrifugal casting in a niobi-um mold.

7. ENGINE PERFORMANCE TEST

The engine test was carried out with a 4 cylinder/16 valve BMW-engine. All exhaust valves were replaced by TiAl-valves. The valves were fitted with hardcaps. A chromium-nitride surface coating was applied for the valve stem. The engine was run partly with a stoichiometric air/fuel ratio and thus exposing the valve to higher exhaust fume temperatures of approx. 970 °C. Duration of this engine test was 500 hours. This corresponds to the lifetime cycle of the engine under normal operations/driving conditions. All of the valves completed the test successfully. There was no visible wear on the stems or on the seats. Fig. 11 shows valves in different manufacturing steps and after the engine test.

![Valves in different manufacturing steps and after the engine test](image)

Fig. 11: Valves in different manufacturing steps and after the engine test
8. CONCLUSION

For high volume low cost production of titanium aluminide automotive valves a new process including the necessary equipment has been developed. The process consists of melting of the alloy in a cold wall induction furnace using individual alloying elements as feedstock and casting of a multiple of valves centrifugally in metallic permanent molds of niobium. Due to a controlled solidification in the metallic mold starting from the rear end to the head the primary structure of the valves is free from any macroscopic shrinkage cavities. The micro-porosity observed in the lower half of the stem are all on the central axis. The secondary structure is characterized by a fine grain size and a very fine lamellae spacing resulting in high tensile properties without reducing the ductility. The 500 hrs. engine test with as-cast valves has been completed successfully with a stoichiometric air/fuel ratio. The process for mass production of automotive valves is now available for commercial use.

9. ACKNOWLEDGEMENT

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10. REFERENCES


