4. MATERIALS FOR AIR HANDLING, HOT SECTION, AND STRUCTURAL COMPONENTS

A. High-Temperature Advanced Materials for Lightweight Valve Train Components

Mark J. Andrews and Jesus Chapa-Cabrera
Caterpillar Inc.
Tech Center 854-80 TC-E
14009 Old Galena Rd.
Mossville, IL, 61552
(309) 578-3896; fax: (309) 578-2953; e-mail: andrews_mark_j@cat.com

DOE Technology Development Area Specialist: Dr. Sidney Diamond
(202) 586-8032; fax: (202) 586-2476; e-mail: sid.diamond@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

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Objectives

- Design and fabricate prototype engine valves from silicon nitride and titanium aluminide materials that are 30% lighter than steel valves and provide a 200% increase in service lifetime and a 10% increase in fuel efficiency.

Approach

- Select titanium aluminide (γ-TiAl) and silicon nitride materials for this project because of their high corrosion resistance and their ability to maintain superior strength at elevated temperatures.
- Base engine valve designs on using an optimization routine in conjunction with a probabilistic design approach instead of the traditional deterministic method.
- Develop welding techniques to join TiAl to a titanium alloy in the fabrication of TiAl valves.

Accomplishments

- By optimizing the probabilistic valve designs, showed ways to modify the valve geometry in order to reduce the high operating stresses that are likely to contribute to valve failure.
- Conducted welding trials that showed success in joining TiAl to a titanium alloy, Ti-6V-4Al.
- Developed bench tests to examine the impact and wear resistance of TiAl and silicon nitride materials compared with currently used valve seat insert materials.

Future Direction

- Machine 50 silicon nitride valve blanks to final print specifications and bench- test them for impact resistance, strength, and durability.
- Join TiAl valve heads to titanium alloy valve stems and then machine and bench-test them for strength and durability.
- Schedule silicon nitride and TiAl engine valves for natural gas and diesel engine laboratory tests after completing bench tests.
- Schedule silicon nitride valves and TiAl for field engine tests after completing laboratory engine tests.

Introduction

Valves that are presently made from steel alloys and used in heavy-duty natural gas and diesel engines are reaching material performance limits because of increases in temperature and pressure loads. Advanced materials such as silicon nitride and TiAl, known for exceptional corrosion resistance and for maintaining high strength at elevated temperatures, are the focus of this project. The successful demonstration of engine valves fabricated from silicon nitride and TiAl materials is anticipated to extend the component service lifetimes by as much as 200% over current valve materials. In addition, these lightweight materials will enable the future design of a camless engine that will permit greater control over the combustion process, improving engine performance while reducing emissions.

Approach

Premature engine valve failures are caused by several synergistic factors, one of which is the corrosive environment in which valves must function. A variety of conventional engine component alloys and candidate advanced materials were evaluated for corrosion resistance using an oil-ash test. Test specimens were submerged in engine oil that is heated and burned, simulating the breakdown of engine oils. The residue or oil-ash left behind on the test specimens contained concentrations of corrosive elements such as calcium, sulfur, and phosphorus in the form of oxides. After a series of oil-ash coatings, the test specimens were placed in a furnace at engine combustion temperatures for an extended time period. Measuring the penetration depth after the furnace exposure using optical and scanning electron microscopy (SEM) is one way to assess the corrosion resistance. Figure 1 illustrates the penetration depth measured for silicon nitride and TiAl compared with Nimonic 80 A and Nimonic 90 alloys currently used for engine valves. The silicon nitride and TiAl materials show smaller penetrations from corrosion compared with the current valve alloy materials. The results from these tests indicate that silicon nitride and TiAl

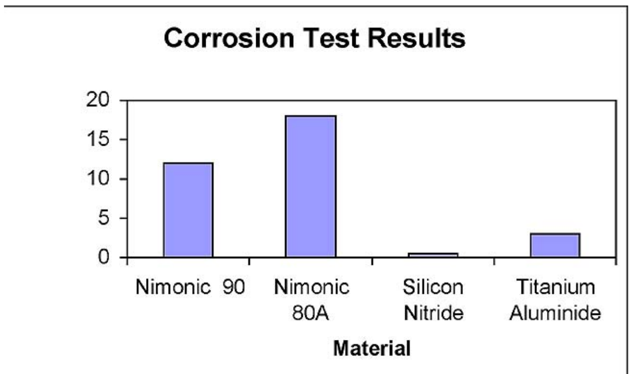


Figure 1. Corrosion test results illustrated as the depth of penetration into material. The silicon nitride and TiAl show excellent resistance to corrosion when compared to the Nimonic 80A and 90, current valve materials.

materials exhibit excellent corrosion resistance when subjected to an engine environment, one of the main reasons for investigating these materials for this engine component.

The design of engine valves made from steel alloys typically follows a deterministic approach in that the strength of test specimens can easily be scaled to different sizes with reliable accuracy. Silicon nitride and TiAl are inelastic materials compared with most alloys and are known to fail in a brittle manner. The brittle nature of these advanced materials necessitates using a probabilistic approach instead of the deterministic approach for component design. The key elements in a probabilistic design approach are illustrated in Figure 2. ASTM standards for test specimens and procedures are followed, using a variety of test conditions such as temperature and loading rate that emulate the operating conditions of the design component. The strength of test specimens is represented using a Weibull distribution function. Finite element models of the design component are created and used to estimate the critical stresses from specified temperature and mechanical load boundary conditions. The combination of the finite element modeling with the test specimen strength data is used as input into a specialized computer program that estimates the service lifetime of the design component.

Two materials are actually used in the fabrication of TiAl engine valves, since reliable casting of TiAl for the entire engine valve has not been successfully demonstrated by casting vendors. The valve head portion is cast using TiAl, while the valve stem is made from the cylindrical stock of a titanium alloy (Ti-6V-4Al), as illustrated in Figure 3. Valve fabrication consists of friction welding TiAl to the titanium alloy, followed by final dimensional machining.

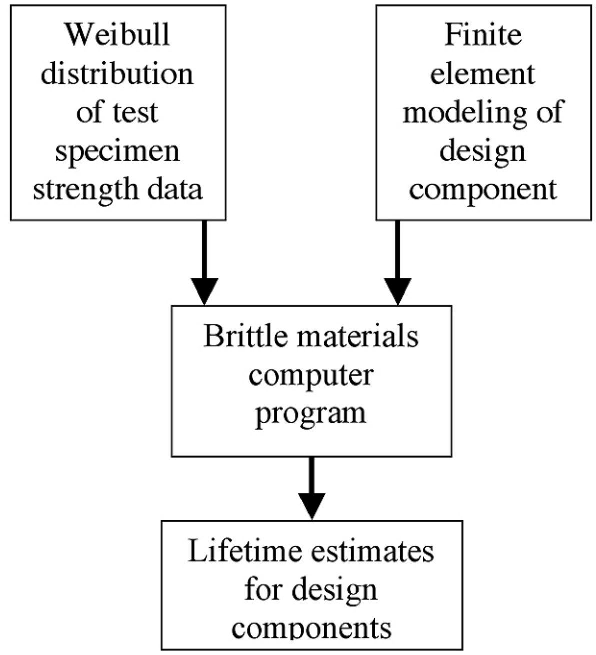
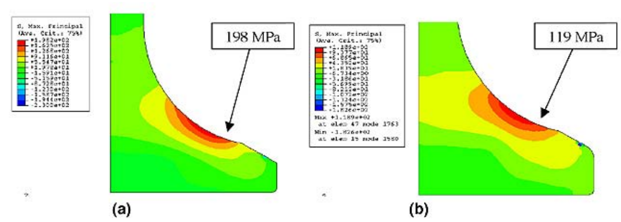


Figure 2. Flowchart of probabilistic design approach used to estimate service lifetimes for engine valves made from silicon nitride and TiAl.



(a) (b)

Figure 3. Maximum tensile stress comparison between the baseline metallic valve design (a) and proposed silicon nitride valve design using the probabilistic approach (b). There is an approximately 60% reduction in tensile stress from the probabilistic valve design as a result of dimensional changes.

Results

The maximum principal tensile stresses in the finite element valve model were reduced by combining an optimization routine with the probabilistic design approach. Changes in the valve geometry resulted in stress reductions of approximately

60%, as illustrated in Figure 4. The importance of this stress reduction will be realized in significantly improving the probability of survival of an engine valve made from these materials, resulting in increased service lifetimes.

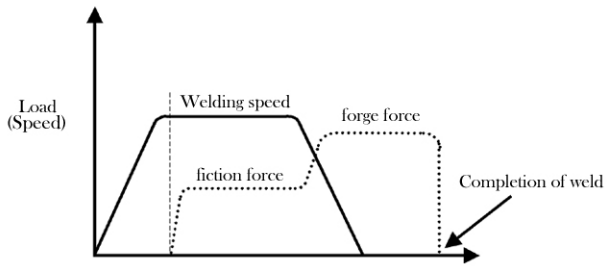


Figure 4. Schematic of joining TiAl valve head to TiAl valve stem by friction welding.

Initial friction weld trials have shown that the strength of the weld increases as the forging force increases and the friction force decreases. Figure 5 illustrates the typical stages in performing a friction weld of TiAl to the titanium alloy, Ti-6V-4Al.

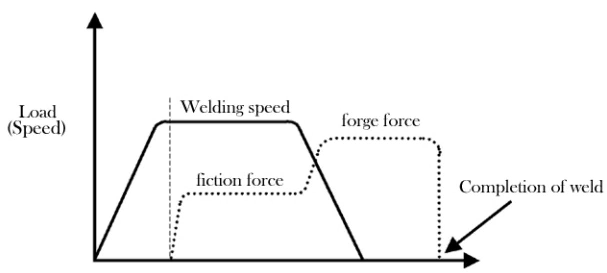


Figure 5. The relationship of friction weld parameters examined in this study.

A cost-effective friction welding process has been developed that demonstrates the successful joining of TiAl to titanium alloy materials. Tensile tests conducted on welded test specimens have shown that the TiAl-titanium alloy weld strength is equivalent to the parent TiAl strength. Additional welding trials are planned to optimize the process for implementing into prototype production.

Conclusions

The optimized probabilistic design approach has shown ways to reduce stress in the valve from geometry changes under service load conditions. Incorporating these geometry changes in the valve design suggest that the service lifetimes of silicon nitride and TiAl engine valves will likely be significantly longer as a result of the noteworthy reduction of tensile stresses in the valve model. Future bench tests and engine tests using the silicon nitride and TiAl valves will help validate the design approach used, and verify the anticipated longer service lifetimes.

The development of a successful friction welding process that joins a TiAl valve head to a titanium alloy (Ti-6V-4Al) valve stem identifies a well-known and cost-effective fabrication process for manufacturing engine valves for these materials. In addition, it orchestrates the high-strength TiAl valve head in the high-temperature region and the more wear-resistant TiAl material in the sliding region of the valve guide.