

NiTiNb PLUGS FOR SEALING HIGH PRESSURE FUEL PASSAGES IN FUEL INJECTOR APPLICATIONS

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ABSTRACT

A typical heavy-duty diesel fuel injector comprises of a solenoid control valve, a plunger cylinder and a fuel passage linking the first two elements. Through this passage a fuel communication is established where the fuel is delivered into the plunger cylinder via control valve. The plunger pressurizes the fuel in excess of 32,000 psi and the high-pressure fuel is injected through spray nozzle into engine combustion chamber. During manufacturing, this fuel passage is drilled from the outside of injector body, creating an open end that requires sealing at the end of the manufacturing process. Conventional sealing method utilizing a brazed steel plug often fails under prolonged exposure to extreme cyclical pressures. The present paper describes an alternate sealing method utilizing a heat-to-recover NiTiNb plug that offers a more reliable seal and can be installed at much lower temperatures than a brazed steel plug. NiTiNb sealing plug are manufactured from rods that are longitudinally stretched to have a reduced diameter. The stretched rod is then cut and ground to a finished diameter of high precision. During installation, the plug is inserted into the open end of fuel passage and heat is applied to induce shape recovery of the NiTiNb plug. Stress generated from constrained recovery thus creates a tight seal around the cylindrical surface capable of withstanding extreme cyclical pressures.

INTRODUCTION

Fuel injectors are employed in internal combustion engines for delivering a precisely metered amount of fuel to the combustion chamber at pre-selected intervals. In case of compression ignition in diesel fuel engines, the fuel is injected into the combustion chamber at relatively high pressures. Current models of diesel fuel injector are delivering fuel at pressures as high as 32,000 psi. With increasing demands on greater fuel economy and cleaner emission, even higher fuel pressures are anticipated for future generations of diesel fuel injector designs.

Figure 1 illustrates a typical construction of a diesel fuel injector. The injector includes a high-pressure fuel passage linking the solenoid actuated control valve and the plunger cylinder in the injector body. Fuel at relatively low pressure is supplied to the control valve area, which then meters the delivery of fuel at pre-determined quantity through the high-pressure fuel passage to the plunger cylinder. The plunger compresses the fuel to an ultra-high pressure level and then atomizes the fuel through a fuel nozzle.

The high-pressure fuel passage is drilled out from one side of the injector body through the control valve bore and the plunger cylinder. To resist high-pressure fuel leaking, the opening end of the high-pressure passage from drilling must be sealed, conventionally, with a steel plug via a vacuum brazing operation. A photograph in Figure 2a shows the cross-section of an injector body with an installed brazed steel plug. One of the disadvantages with this design is that the braze joint often has sub-surface micro-voids due to solidification or contamination. Since the braze plug and the fuel passage are subjected to cyclical pressures, the alternating stress amplitude along with the small internal braze voids can adversely effect the fatigue life of the injector body and result in early failure through body cracks. As the demand for higher

fuel injector pressure increases, brazed plugs are no longer capable in these high-pressure environments. The photograph in Figure 2b shows the fatigue fracture of a typically failed injector body caused by defective brazing. In 1995, failures due to braze joint fatigue accounted for 89% of total failures and 97% of the total warranty cost within the Diesel Technology Company. In addition, brazed plug requires expensive tools to ream a tapered hole during the manufacturing process. After high temperature brazing and hardening operations, The steel plug extended into the control valve bore must be removed. These processes all impose added cost.

Thus, there is a need to develop an alternate sealing mechanism that is reliable in withstanding high pressures exceeding 32,000 psi. Ideally, the mechanism can be installed at lower than the brazing temperature and can render better fatigue resistance in the extreme cyclical pressure environment. To meet this need, a heat-to-recover NiTiNb shape memory alloy (SMA) sealing plug was developed based on the constraint recovery principle [1].

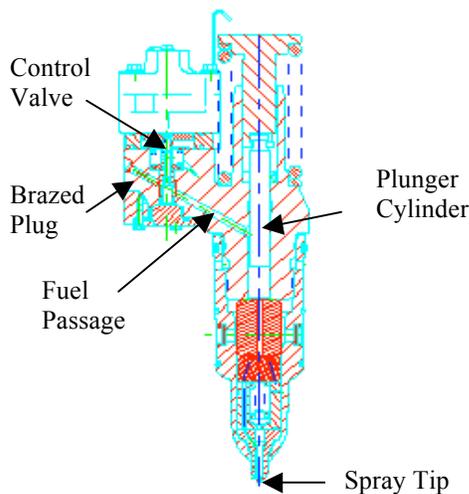


Figure 1. A typical construction of a diesel fuel injector.

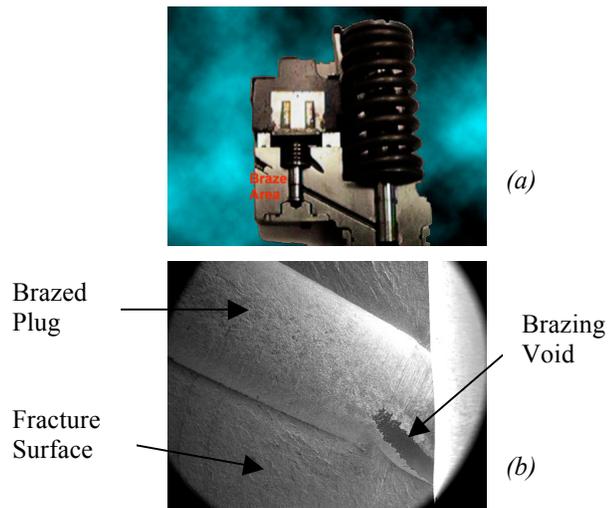


Figure 2. (a) Cross-section of a diesel fuel injector with braze plug, and (b) Fracture surface of a fatigued injector body caused by defective brazing.

DESIGN REQUIREMENTS

A successful mechanism for sealing high-pressure fuel passages in diesel fuel injectors must satisfy following criteria:

1. Withstand cyclical sealing force of 352 lbf (160 Kgf) with a minimum safety factor of 2.5.
2. No leakage or plug migration over the life cycle of the injector (1,000,000 miles).
3. Fully function in the temperature range from -40°C to 150°C .

To meet these design requirements and the feasibility for manufacturing and logistics, the NiTiNb SMA sealing plugs must satisfy following criteria:

1. The shape recovery must fill a clearance between the plug and the sealed bore, up to 1.5% of the plug diameter and provide sufficient constrained expansion to deliver the required sealing force.
2. The shape recovery temperature must be higher than 50°C to avoid pre-mature recovery during manufacturing, transportation and storage.

3. The martensitic transformation temperature must be significantly below -40°C so that the plug maintains sufficient sealing force at cold temperatures in the field.
4. The plug must withstand corrosion and erosion from diesel fuel and its additives.

SMA SEALING PLUG DESIGN

The alloy selected for the application has a nominal chemical composition of Ni-38wt.%Ti-14wt.%Nb. The alloy after annealing at 850°C for 30 minutes has the following transformation temperatures, M_s , M_f , A_s and A_f are -85°C , -105°C , -30°C and -10°C , respectively. Rods of NiTiNb alloy are first drawn to a diameter greater than the inner diameter of the open end, straightened and heat-treated. The heat-treated rods are then pre-conditioned [2-3] by tensile stretching at sub-ambient temperatures to a reduced diameter. The stretched rods were then cut to plugs of 10.8 mm in length and finished by grinding to a final diameter smaller than the inner diameter of the open end. Both cutting and grinding operations were performed in a coolant environment to avoid shape recovery. Imparted by the pre-conditioning process, the finished plug exhibited a one-time expanded transformation hysteresis with reverse transformation temperatures, A_s and A_f , shifted to 58°C and 62°C , respectively, as measured from a differential scanning calorimetry (DSC) curve in Figure 3. The shifted reverse transformation temperatures in this range allow the plugs to be cut and ground to size, transported and stored while avoiding premature shape recovery. The shape recovery measured by monitoring the change in length during heating is plotted in Figure 4. The total recovery corresponds to a 2.5% diametric expansion from 2.930 mm to 3.004 mm, sufficient for filling an installation clearance up to 1.5% of the plug diameter and providing a minimum of 1% unresolved constraint recovery strain for sealing.

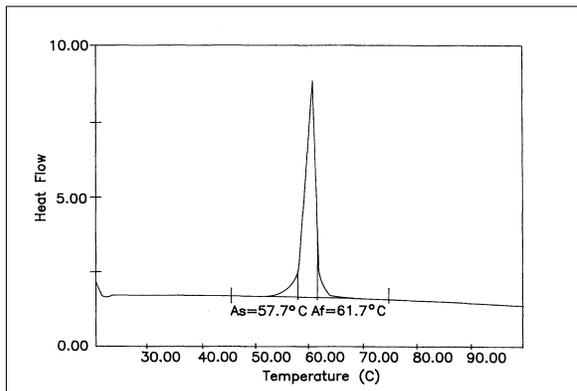


Figure 3. A typical DSC curve measured during heating of a NiTiNb plug sample.

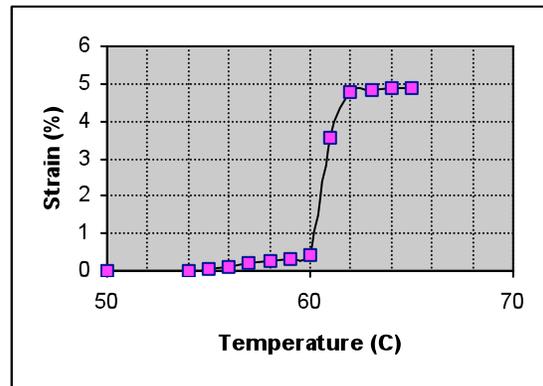


Figure 4. Strain recovery of NiTiNb plug measured along the longitudinal direction.

SMA SEALING PLUG INSTALLATION

The plug installation procedure is illustrated in Figure 5. The finished SMA plug is first pre-sized and categorized. Secondly, to ensure the clearance between the plug and the body open end is less than 30 micron, the diameter of the body open end is measured to match a pre-sized SMA plug. The matched plug is then inserted into the open end of the injector body. Next, the body with the SMA plug assembly is placed on a fixture where a heater is inserted into the valve bore (Figure 5a). The injector body is then heated to a temperature between 150°C and 200°C (Figure 5b) to induce the phase transformation in the SMA plug from martensite to austenite. Accompanying the phase transformation is the shape recovery for the plug to resume a greater diameter against the constraint of the inner diameter of the opening. To ensure

that the recovery is complete, the transformation temperature is monitored by a thermocouple placed on the open end of the SMA plug. Further to ensure that the SMA recovery meets the sealing requirements, a 100% push test under 800 lbf is conducted at the open-end of the SMA plug. Any body with SMA plug moved is rejected.

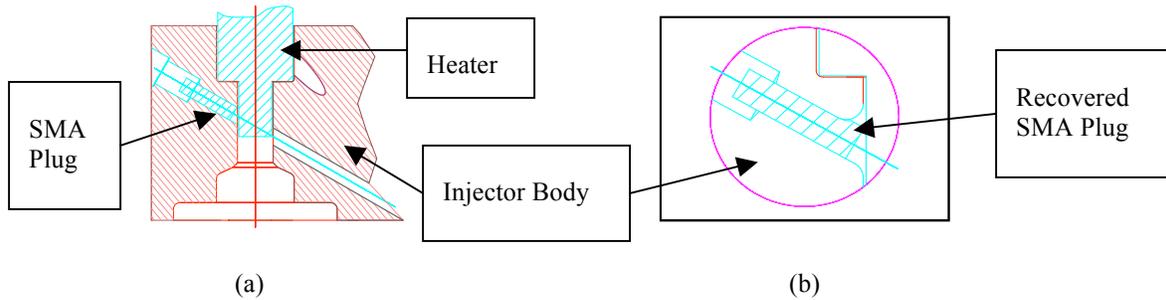


Figure 5. Installation procedure for heat-to-recover NiTiNb Plug.

PERFORMANCE TESTS OF INJECTORS WITH SMA PLUGS

Over-Pressure Validation Tests

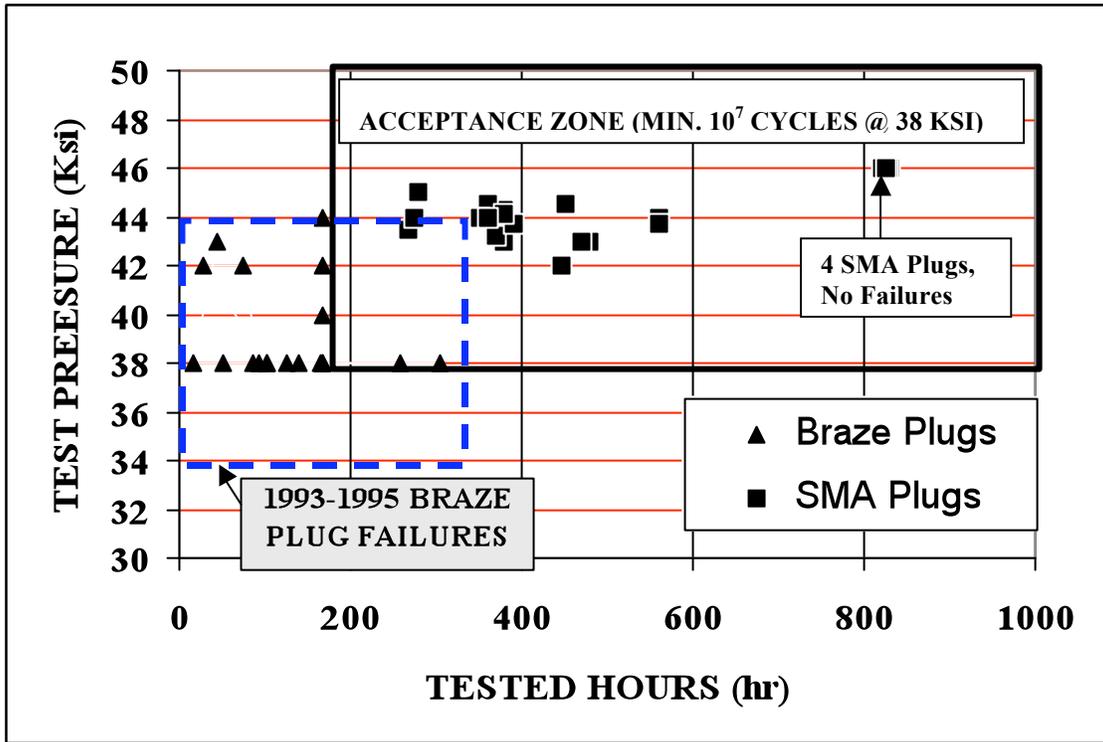
To validate the design with SMA plug, injectors with brazed plugs and SMA plugs were over-pressure tested in multiple engine test stands. The failure pressures vs the numbers of test cycle are plotted in Figure 6. A significant percentage of the brazed plugs failed before reaching the acceptable criterion of 10^7 cycles at 38 Ksi. In contrast to the brazed plugs, all the failures on SMA plugs occur beyond the acceptance criterion. Four injectors with SMA plugs actually survive over 800 hours of testing at an extreme pressure of 46 Ksi. The over-pressure test proves that SMA design is superior to the conventional braze-plug design in cycle life in high-pressure environment.

Field Engine Tests

To evaluate the robustness of SMA plug in actual engine performance, 120 injectors with SMA plug design were installed in 20 field truck engines. The engines were road tested in Colorado during the winter with 22 daily driving hours continuously for six months. These test engines accumulated a total of 4,320,000 miles (216,000 miles/engine). All field test injectors were re-examined after the test and no single SMA failure was found. This test validates the long-run reliability of the SMA design.

Extreme-Temperature Push-out Tests

To ensure the reliability of the SMA plug design under low temperatures, a series of push-out test were conducted at various temperatures ranging from -196°C to $+100^{\circ}\text{C}$. The results are plotted in Figure 7. As expected, the push-out force decreases with decreasing temperature. Nevertheless, the push-out force for SMA plugs as designed consistently exceeds the requirement of 880 lbf (400 Kgf), with a 2.5X safety factor over 352 lbf (160 Kgf) even at a temperature as low as -78°C . This test proves that the SMA design successfully withstands the extreme temperature environments where the diesel fuel ultimately freezes or evaporates.



RESULTS AND DISCUSSION

Upon all three validation tests, the injectors with SMA sealing plugs were released to production. Since the introduction of the SMA plug design, following benefits have been realized:

- Eliminate 200% braze plug quality inspection.
- Eliminate the super cleaning requirement for body and braze plug.
- Completely eliminated brazing related scraps and rework.
- Eliminated the entire vacuum brazing operation.
- Simplified the manufacturing process flow and reduced product sensitivity to process variation.
- Improved the productivity by 10%.
- Reduced warranty cost by 71.6% in 1996 and by 96.8% in 1997 and beyond.
- Achieved zero field failure record.

CONCLUSIONS

1. Heavy-duty diesel fuel injection system has challenged many high-pressure sealing methods. Most of the market-available sealing plugs failed to meet the requirement for ultra-high pressure sealing under cyclic fatigue conditions.
2. Through appropriate design and validation testing, the concept of utilizing NiTiNb SMA for high pressure sealing plug has been proven feasible and cost effective.
3. NiTiNb SMA sealing plug has significantly improved the quality and the productivity of diesel fuel injector since its introduction.
4. NiTiNb SMA sealing plugs are superior to other types of sealing mechanisms, such as brazed or welded plug, mechanical fasteners, heat-shrink fit plug, for ultra-high pressure fluid sealing applications.
5. SMA sealing mechanism opens up a great potential for many future applications in various fluid sealing, in particular for conditions under cyclic pressures, ultra-high pressure, and corrosive environment.

REFERENCES

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3. T.W. Duerig, and K.N. Melton, The Martensitic Transformation in Science and Technology, (E. Hornbogen and N. Jost, ed.), DMG Informationsgesellschaft m.b.H., 1989, p.191.