

Fabrication and Characterization of Micro-Orifices for Diesel Fuel Injectors

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ABSTRACT

Stringent emission standards are driving the development of diesel-fuel injection concepts to mitigate in-cylinder formation of particulates. While research has demonstrated significant reduction in particulate formation using micro-orifice technology, implementation requires development of industrial processes to fabricate micro-orifices with diameters as low as 50 μm and with large length-to-diameter ratios. This paper reviews the different processes being pursued to fabricate micro-orifices and the advanced techniques applied to characterize the performance of micro-orifices. The latter include the use of phase-contrast x-ray imaging of electroless nickel-plated micro-orifices and laser imaging of fuel sprays at elevated pressures. The experimental results demonstrate an industrially viable process to create small uniform orifices that improve spray formation for fuel injection.

INTRODUCTION

For 2010-model and later heavy-duty diesel engines, the U.S. Environmental Protection Agency (EPA) regulations mandate emission reductions of 0.01 grams particulate matter (PM) per engine horsepower per hour and 0.2 grams nitrogen oxides (NO_x) per engine horsepower per hour. To achieve these levels, various combustion concepts are being developed to limit in-cylinder production of NO_x and particulates as well as to trap and convert tail-pipe pollutants. One approach to limit in-cylinder production of particulates involves the development of diesel fuel injection systems with micro-orifices that improve fuel distribution and atomization.

Pickett and coworkers [1,2] have shown elimination of soot in a test cylinder by reducing the injector orifice diameter to 50 μm , even with high levels of exhaust gas recirculation (EGR) and concomitant reduction in NO_x emissions. These reductions likely arise from increases in fuel atomization efficiency, leading to more complete combustion. Although it is currently possible to economically mass produce injectors with 100- μm -

diameter orifices using electric-discharge machining (EDM), further reductions in hole size are accompanied by unacceptable fabrication error rates at this point.

High fuel injection pressures are an essential element in meeting the 2010 EPA emissions standards for heavy-duty engines. To produce low levels of engine-out NO_x , larger amounts of EGR can be used to lower peak local combustion temperatures, thus reducing the formation of NO_x [3]. The introduction of higher levels of EGR lowers the oxygen concentrations available during the fuel mixing and combustion process, and increases the potential for soot/PM formation. In a stratified charge combustion system, higher injection pressure increases atomization and PM control. These higher pressures require smaller nozzle holes to maintain injection durations and best manage the mixing of the fuel spray with the surrounding air [4]. In contrast, larger nozzle hole sizes portend lower injection pressures at constant injection durations or shorter injection durations at higher pressure. Either of these consequences of larger nozzle holes results in relatively poor air entrainment into the spray core [5]. A higher resulting penetration from larger hole diameters at high pressure also tends to have adjacent spray jets overlapping at bowl impact and, therefore, greater fuel-rich regions resulting in lower PM reduction after its initial formation. Higher fuel injection pressures applied through smaller hole nozzles improves the fuel atomization and the degree of pre-mixing with the charge air prior to the onset of combustion. The intent of the present work is to investigate the fuel spray development of various orifice sizes in a high pressure hydraulically intensified fuel injector in a diesel engine application with high levels of EGR for NO_x control. The practicality of nozzle hole diameters below 100 μm is uncertain in larger displacement engines due to the total fuel delivery requirements per combustion stroke; however, the combination of both larger and smaller holes may be beneficial to mixing with the low levels of oxygen available in a high EGR strategy. For the present study, the fuel penetration rates and atomization of various injection hole sizes were investigated.

maximize the fuel/air mixing in this environment before combustion.

Multiple approaches have been, or are being, pursued to fabricate small (50- μm diameter) orifices for fuel injection applications. For example, Baik et al. [6], reported the application of x-ray lithography (called LIGA, a German acronym for *Lithographie, Galvanoformung und Abformung*) to fabricate single and multiple 40- to 260- μm orifices on planar-orifice injectors. Success has also been reported on the application of lasers to fabricate 50- μm diameter orifices in steel using a helical drilling strategy [7]. Coating of nickel via chemical vapor deposition is also being explored [8].

Another approach, the topic of this article, addresses coating the inside orifices with a suitable material to reduce their size to 50 μm . In this concept, conventional commercial injectors (produced by electric-discharge machining (EDM) and abrasive slurry polishing) are coated by either aqueous or vapor chemical deposition techniques. We discuss development of an electroless nickel (EN) coating process to deposit thick nickel-phosphorus coatings on commercial nozzles, the application of high-resolution x-ray phase contrast imaging to characterize nickel coating uniformity, and high-speed imaging of coated and uncoated commercial injectors.

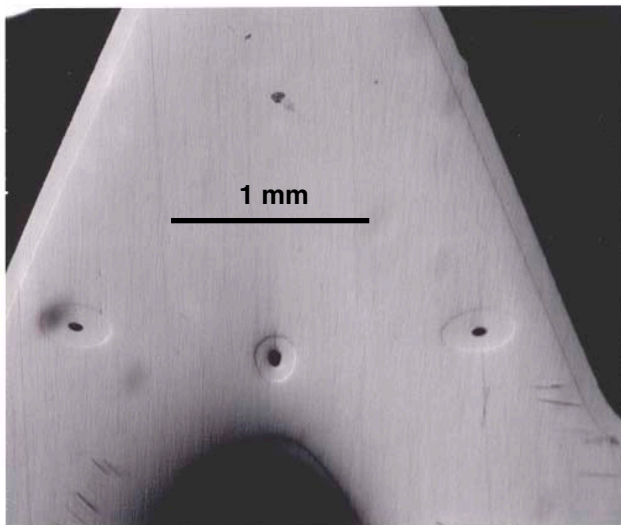


Figure 1: Optical micrograph of sectioned EN plated nozzle.

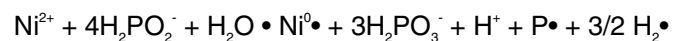
PROCESS DEVELOPMENT AND PROPERTIES

ELECTROLESS NICKEL COATINGS

Several coating approaches were considered [9] before selecting an EN coating method that involves immersion of a substrate in a solution of ions of the material to be deposited, together with a reducing agent. The most

common reducing agents used are sodium hypophosphite, dimethylamine borane, and sodium borohydride. Reduction of the ions takes place in a surface-catalyzed reaction, resulting in the coating deposition. Since the coated surface then acts to catalyze the deposition of the next layer of material, this method is sometimes referred to as “autocatalytic plating”. Electroless coatings generally contain up to 15 wt% of a second element from the reducing agent, either phosphorus or boron. The material most widely deposited by electroless plating is nickel, although a wide range of other metals, including copper, cobalt, and tin, can also be deposited. Electroless plating is a mature, commercialized coating technique used in a wide variety of areas, so cost should not be an issue. With appropriate surface preparation, adhesion can be excellent. As long as the plating solution has reasonably good circulation, electroless plating can be used to uniformly coat complex shapes and internal surfaces, and the deposition rate is on the order of tens of $\mu\text{m}/\text{hour}$.

The mechanistic details of the electroless plating reactions are complex and in dispute [10]. However, the overall reactions are well-established. For example, electroless nickel plating using sodium hypophosphite as the reducing agent proceeds via the overall reduction/oxidation reaction:



That is, Ni and P codeposit, although the actual Ni:P mole ratio is much greater than 1 because of the side reaction:



As can be seen from both reactions, hydrogen gas is evolved during the deposition. Over the course of the deposition pH declines; depending on the bath composition, this change may or may not affect the plating quality. For this reason, most baths contain buffers to stabilize the pH. The evolution of hydrogen during deposition presented significant challenges to the development of the technique not only due to the incorporation of hydrogen in the coating (which requires post-deposition thermal treatment to remove hydrogen), but also to the formation of gaseous hydrogen bubbles that adhered to the internal surface and locally hindered coating formation. These challenges were eventually overcome [9], and the process transferred to an industrial firm.

Once optimized, the EN process provided adherent, uniform Ni-P coatings along the interior of fuel injector nozzles. Figure 1 shows a metallographic cross section of a six-hole heavy-duty diesel nozzle coated with the EN process using agitation to mitigate buildup of hydrogen gas bubbles. The nozzle was fabricated with 180- μm diameter orifices. This nozzle was treated for

approximately 3 hours, producing a coating approximately 75- μm thick (25- $\mu\text{m}/\text{hr}$ deposition rate).

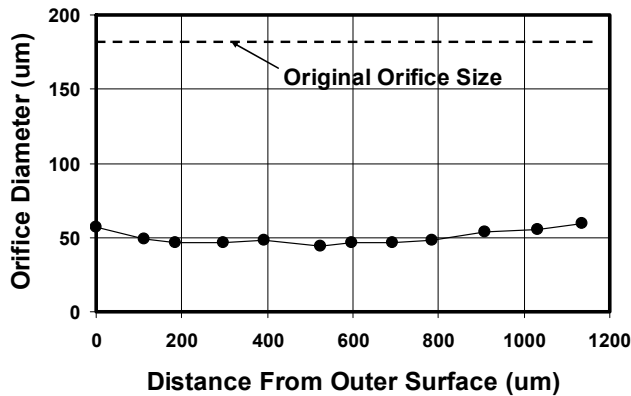


Figure 2: Orifice Diameter as Function of Position along an Orifice.

EN COATING CHARACTERIZATION & PROPERTIES

As seen in Figure 1, the Ni-P coating is uniform circumferentially around the orifice. Sequential polishing and optical examination of cross-sectioned nozzles indicated the coating thickness can be controlled along the length of the orifice to produce straight or tapered orifices. Figure 2 shows the variation of the orifice diameter for a six-hole nozzle that was plated to reduce the orifice diameter to approximately 50 μm .

Adhesion of the coating is a critical issue. Early deposition runs revealed poor adhesion; however, optimization of the coating process resulted in excellent adhesion of both as-deposited EN coatings, and, as-deposited EN coatings that were heat treated at low temperatures. Weil and Parker [11] note that some of the hydrogen produced during the plating process can diffuse into a steel substrate. If not removed, the hydrogen can damage the near-surface region of the substrate, reducing adhesion by creating a brittle underlayer. Baking the plated piece at 200°C for several hours immediately after plating allows the hydrogen to diffuse out of the part before it can cause damage. This process frequently improves adhesion.

Figure 3 shows a scanning electron micrograph of a plated nozzle. It shows a cross section of one of the six orifices at the external surface (exit). The adhesion, as indicated by the lack of gaps between the plating and the injector, is excellent. Semi-quantitative adhesion tests using the Rockwell C indentation technique indicated excellent adhesion for the coatings with no delamination.

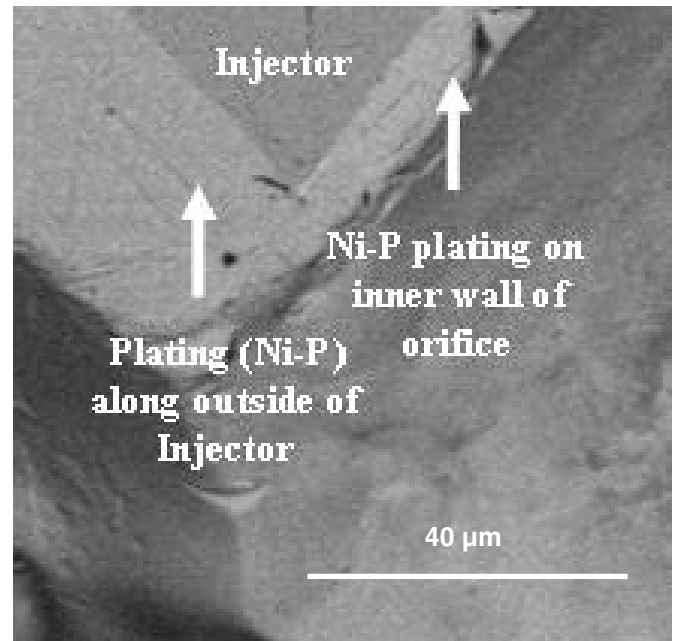


Figure 3: Scanning electron micrograph of EN-plated nozzle.

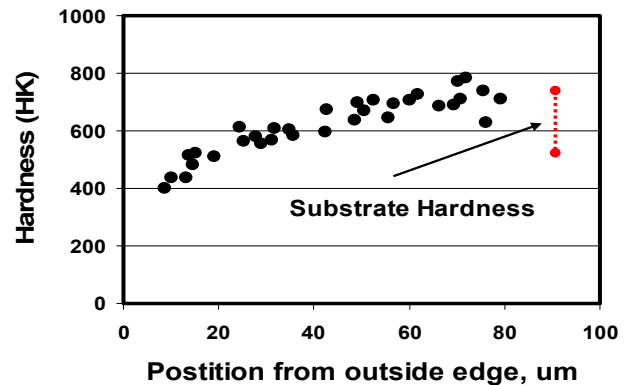


Figure 4: Knoop hardness of EN plating as a function of position.

Another property critical to performance of the coated nozzles is the coating hardness. Figure 4 shows the Knoop hardness as a function of distance from the outer surface of the coating for a nominal 80- μm -thick coating applied to a nozzle. As seen in Figure 4, as the plating process proceeds, the coating grows softer, going from ca 700 H_k adjacent to the underlying substrate to ca 400 H_k at the outer surface. This softening is likely due to chemistry changes as the laboratory-scale bath (approximately 1 to 2 liters) becomes depleted in nickel and the pH decreases, leading to an increase in phosphorus concentration. This hypothesis is consistent with the literature regarding the mechanical properties of EN plating [11]. It is not known what EN hardness would be best for this application, but the differences indicate that some degree of tailoring should be possible.

PREPARATION OF COATED NOZZLES FOR FLOW VISUALIZATION STUDIES

Satisfied that the EN plating concept was capable of depositing Ni-P coatings of suitable uniformity density,  Documents
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