

An Investigation into the Characteristics of DISI Injector Deposits Using Advanced Analytical Methods

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ABSTRACT

There is an increasing recognition of injector deposit (ID) formation in fuel injection equipment as direct injection spark ignition (DISI) engine technologies advance to meet increasingly stringent emission legislation and fuel economy requirements. While it is known that the phenomena of ID in DISI engines can be influenced by changes in fuel composition, including increasing usage of aliphatic alcohols and additive chemistries to enhance fuel performance, there is however still a great deal of uncertainty regarding the physical and chemical structure of these deposits, and the mechanisms of deposit formation. In this study, a mechanical cracking sample preparation technique was developed to assess the deposits across DISI injectors fuelled with gasoline and blends of 85% ethanol (E85). The deposits were analysed with SEM-EDS, FTIR Microscopy, TD-GCMS and an Alicona Infinite Focus 3D micro-coordinate system to assess the chemical composition and topography of the deposits for insights into their formation mechanisms. The location and topography of the deposits in this study indicate that they form in the region of the injector tip, and reduce in size and quantity as distance increases away from the combustion chamber. Elemental analysis results indicate that the dominant deposit compositions are C, O, S and Ca, of which S and Ca decrease but C increases with the locations closer to the combustion chamber. The topography results can be used to develop more sophisticated CFD analysis whilst also leading to a deeper understanding of deposit formation.

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INTRODUCTION

With the rapid development of engine technology and the increasingly stringent environmental legislation and fuel economy targets, great pressure has been placed on vehicle and fuel manufacturers to meet these requirements. The DISI combustion system is considered as a leading technology for achieving higher efficiency in gasoline engines[1].

The fuel economy of an engine using DISI technology will be higher than a similar PFI engine due to reduced pumping losses, the charge air cooling of the combustion chamber, and the air fuel mixture enabling the use of higher compression ratio for a given fuels octane level [2]. The in-cylinder injector is a key component of the DISI system and determines the spray performance of gasoline (e.g. the fuel flow rate, the spray angle, the spray penetration length, etc.) and ultimately influences the overall combustion process [3, 4, 5, 6, 7, 8].

Various investigations into engine performance changes resulting from deposits have been reported [9, 10, 11]. However these studies tend to focus predominately on combustion chamber deposits whereas fewer studies have been conducted to examine the characteristics of deposit formation at the tip of the injector [12]. The characteristics (such as the size and location) of injector tip deposits, such as those within the injector nozzle, can have an influence on injector performance.

The chemical characteristics and formation mechanisms of diesel injector deposits are well defined [13, 14, 15, 16, 17, 18]. The sources of deposit have been identified and reduction strategies have been suggested. There are few studies on the chemical characteristics of gasoline injector deposits [7]. Moreover, most of the previous studies have employed techniques such as EDM to section the injector to access the internal deposits due to its precise controllability [19]. However, the high localised temperatures and the working fluids for EDM can significantly alter quality and quantity of deposits. In this study, a mechanical cracking method was developed to section the gasoline injectors. From this, a systematic approach was taken to analyse tip deposits using a combination of SEM-EDS, FTIR Microscopy, TD-GCMS and an Alicona Infinite Focus 3D micro-coordinate system to assess the chemical composition and topography of deposits leading to insights into their formation mechanisms.

The test methodologies developed and applied during the course of the study are an important step for building a comprehensive understanding of the composition and location of the external and internal injector deposits. Ultimately, a detailed understanding of the formation mechanisms will lead to mitigation and solution options from the perspective of engine hardware design and fuel blending.

MATERIALS AND METHODS

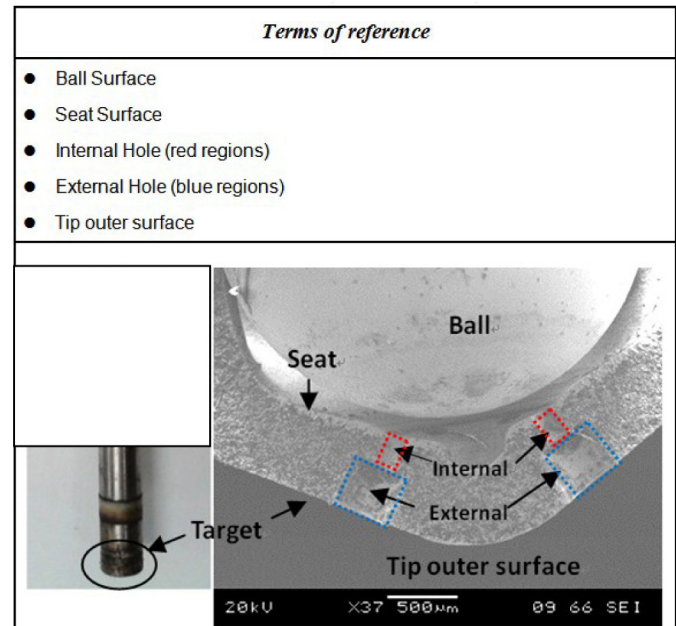
Candidate Injector - Fuel and Engine Tests

The candidate injector set analysed in this work was randomly taken from a dynamometer engine that underwent a severe operating condition test not developed as fouling test cycle. The test fuel chosen was a fuel adhering to an E85 fuel specification. It was not designed specifically as a deposit forming fuel¹. Future papers will give more insights on fuels and test cycles ensuring a closed loop to the deposit formed during test runs.

Injector sectioning

Table 1 gives details of the terms of reference for the injector model used in this study. Analysis of the deposits formed on the injector tip in these areas was performed, encompassing five different locations.

Table 1. Terms of Reference for Injector Geometry



To access the injector tip deposits several methods were used. EDM with a positional accuracy of $\pm 1\mu\text{m}$ was firstly employed to section a candidate injector (as shown in Table 1) and to expose the details of the internal structure of the injector tip. However, on post-process inspection, EDM was shown to have removed significant amounts of deposits from most internal surfaces. A method of mechanically cracking the injector was therefore developed and employed.

The method (shown in table 2) works by aligning the holes of the injector that need to be analysed with the direction of a clamping force. As the load is increased the stresses increase through the injector tip until a crack forms at the stress concentrations (i.e. injector flow apertures). The crack then propagates through the injector tip. The method can be difficult to control however with a quick force application and good alignment (across the centres of two opposite holes), accuracy can be improved. The mechanical cracking method has been shown to minimise deposit disruption. Crack propagation can be further controlled by etching the surface of the injector tip.

Physical and Chemical Analysis Techniques

The analytical procedures employed to determine the characteristics of the injector tip deposits are shown in Table 3.

A JEOL 6060 SEM and an Alicona Infinite Focus 3D micro-coordinate system were used to analyse the physical characteristics of the tip deposits. An Inca 300 EDS system was employed to obtain the elemental compositions.

1. The fuel used in this research was not provided by Shell

Table 2. Procedure for accessing injector tip deposits

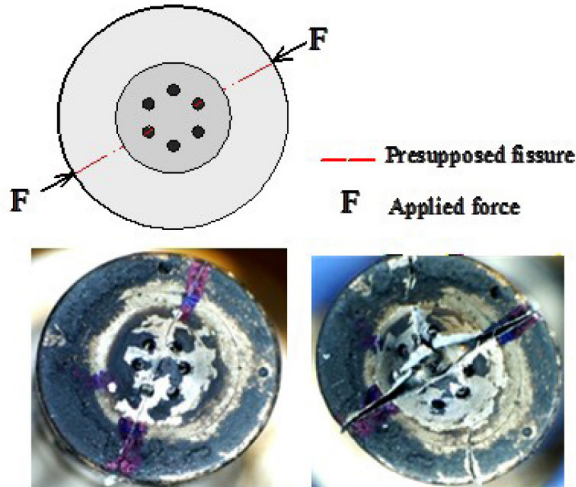
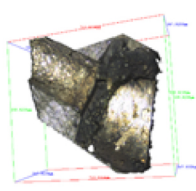
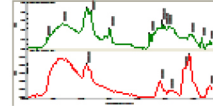
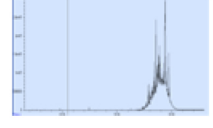
Mechanical Cracking Procedure	
Step 1	
Load applied, inducing stress concentration and failure through injector nozzle — cracks propagate across injector holes	
 F Presupposed fissure F Applied force	
Step 2	
Sectioned Nozzle Tip	
	

Table 3. Analysis procedures for the tip deposits

 Cracked Injector	Physical properties	SEM (Observation)	
		Alicona 3D (Topography)	
	Chemical composition	EDS (Elemental)	 Analysed elements C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Cr, Mn, Fe, Cu, Zn, Pb
		FTIR (Chemical)	
		TD-GCMS (Chemical)	

Different high boiling compounds were assessed to understand if these compounds in the deposits could be successfully analysed in a solid state. Various test mixtures were used to test out the viability of the method of analysis, these included diesel fuel, gasoline T90, E85 gum and an Eicosane/ benzophenone mix in carbon.

Analysis Procedure

The systematic approach taken to analyse the tip deposits was as follows:

Step 1- Deposits were accessed using the mechanical cracking technique outlined in [table 2](#).

Step 2 - SEM-EDS - The deposit form, location and elemental composition was observed using a JOEL 6060SEM -EDS at 20 kV and a probe current of 100 mA.

FT-IR was used to provide a chemical map of the internal surfaces of the injector, in particular the ball and seat. The FT-IR microscope used was a Thermo Fisher iN10 mx in reflectance mode with a fast mapping feature. The chemical structure of deposits was established using TD-GCMS. During analysis a solid sample was introduced directly using a Markes Ultra Thermal desorber onto an Agilent 6890 GC coupled to an Agilent 7777 MS.

Step 3 - Alicona 3D Topography measurement - Deposit topography was observed and measured using a x20 objective lens. The vertical resolution was 10nm with focus variation measured according to EN ISO standard 25178. The measurements strategy was to create a 16 point grid across the interrogated surface and then compare against a clean baseline surface.

Step 4 - Chemical compounds in the deposits were identified using FT-IR microscopy. The polished metal surface of the ball was mapped using the microscope in Reflectance mode. The ball was mounted on the motorised stage of the microscope and an optical mosaic image (i.e. made up of multi images of the surface) was produced. The Microscope aperture was set at 50µm with 50 µm increments, and a dwell time for each spectra of 1 sec. In fast mode (dwell time 0.1 s), this took approximately 20 minutes to complete an Infra-Red map of the surface of the ball. A 1s map was completed in approximately 3 to 4 hours. It should be noted that the longer the dwell time, the better quality of the spectra map produced.

Step 5 - Chemical compounds were characterised using TD-GC-MS. After completion of the other techniques, the ball and other solid samples were loaded into an empty thermal desorption tube and the surface deposit was thermally desorbed on the GC-MS. A test mixture was used to test the method, encompassing high boiling organics, eicosane and benzophenone. These were successfully eluted from the GC column and detected by the MS. The details of the analysis was: TD (280°C for 5 minutes) → Cold trap (-10°C for 5 minutes) → Heat cold trap (300°C for 3 minutes) → transfer line to GC (150°C) → MS (260°C).

It should be noted that the objective of Step 5, the TD-GCMS analysis, was to establish whether solid samples could be analysed following the FT-IR analysis, especially if 'high-boiling' organic compounds could be successfully desorbed, captured and analysed by GCMS.

RESULTS AND DISCUSSION

Physical Characteristics of Tip Deposits

Figure 1 shows the SEM images of the injector tip deposits at seven identified regions. High levels of deposit are shown in all samples. Specific observations are:

Regions 1, 2 and 3: On the needle ball and seat, film-like deposits with a crystalline structure were observed (**figure 1a** & **b**).

Regions 4, 5, 6 and 7: Extensive deposits were observed in both internal seat and external injector holes (shown in **figure 1c**). The external-hole deposits were radially distributed. The

internal aperture deposits were axially distributed and tended to increase in density along one side of the hole. On the outer tip surface, two kinds of deposits were seen with both a rough and smooth topography, seen in region 6 and 7, respectively (**figure 1d**).

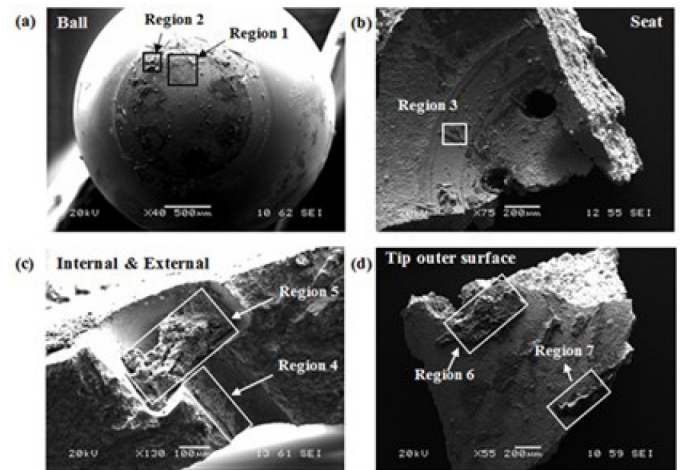


Figure 1. SEM images of the injector tip deposits at various locations characteristics

Deposit Topography

Table 4 shows the surface topography and profile measurements of the internal and external deposits. The scanning directions for the vertical routes (i.e. A, B, C, D, E, F for Internal-hole deposits and E, F, G for External-hole deposits) are from top to bottom and for the horizontal routes (i.e. G, H, I for Internal-hole deposits and A, B, C, D for External-hole deposits) from left to right.

The height of the internal-hole deposits indicate that peaks appear at the beginning of interrogation routes A, B, C, D, E, F and along G. This indicates that most of the internal hole deposits are located in this area. As for the external hole deposits heights, the peaks appear at the extremities of the section with high levels of deposit located within the shoulder. These are shown in **figure 1** region 5. The mean heights of the internal and external deposits are approximately 19.2µm and 79.1µm, respectively. This indicates that deposits are more concentrated within the external hole compared with those in the internal hole. These results correlate well with the SEM observations shown in **figure 1**. Specifically, higher levels of deposits can be observed in Regions 4, 5, 6 and 7 which are closer to the combustion chamber, while lower levels of deposits are observed in Regions 1, 2 and 3 which are shielded from the combustion chamber and further along the axis of the injector.