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Shear-force microscopy investigation of roughness and shape of micro-fabricated holes

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ABSTRACT

The paper reports the analysis of roughness and shape of micro-machined workpieces carried out with a specifically conceived scanning probe microscope using the shear-force established between a vibrating tungsten tip and the surface under investigation. Samples, fuel injector nozzles, were prepared by different drilling techniques using either electro-discharge or laser-based machining techniques. Owing to its operation in true non-contact mode and the ability to analyse recessed surfaces, the microscope enables comparing the performance of the drilling processes through the determination of roughness parameters of the hole inner surface and the reconstruction of the shape at its edge. Both finishing and morphological details, expected to be involved in determining the fluid dynamics occurring inside the nozzle, can be captured by the developed diagnostics. The findings reveal that the use of ultrafast laser machining can lead to significantly improve the quality of fuel injector nozzles with respect to the present technology standard.

1. Introduction

In the present technological scenario, there is a continuous demand for the development of new devices able to meet the requirements of evolving standards. Assessment of device and technology performance requires in turn the availability of robust and reliable diagnostic tools. An example is represented by the machining of fuel injector holes in automotive industry. Improving the efficiency of fuel spray atomisation is mandatory to meet the requirements of the EU6 and forthcoming regulations [1]. Amount and quality of exhaust gas emission from direct injection gasoline engines, as well as reduction of fuel consumption, strongly depend on the geometrical properties of the injector nozzles [2]. Fuel injected through the micro-hole, typically featuring 150–200 μm diameter and 250–350 μm thickness, is assumed to form a liquid core which is then broken-up and atomised into fine droplets. The more complete the atomisation, the cleaner and more efficient the engine operation is, since a properly atomised fuel jet is expected to prevent wet parts in the engine. Atomisation of the fuel spray and jet breaking are governed by the fluid dynamics processes occurring inside the hole, affected by the hole geometry (size, taper angle) as well as by microscopic details of the surface finishing. They include the roughness of the inner surface and the sharpness of the corner edge, which depend on many factors related to both material and process parameters.

Tools capable of investigating the machined surface at the sub-micrometre scale must be used in order to measure the relevant quantities. This need is even more urgent when new machining approaches are being introduced into the industrial environment, as in the case of fuel injector micro-holes. At present, micro-Electrical Discharge Machining (μ-EDM) is a well established technique for drilling nozzles in diesel and gasoline injection systems. The flexibility with respect to workpiece geometry and material is a distinctive advantage of this fabrication approach [3]. Despite of the frequent breakage of electrodes occurring when sharp and very small holes are fabricated [4], it remains the method of choice for drilling hard conductive materials with diameters down to 5 μm. Other machining techniques have been proposed and demonstrated to further improve the process performance and workpiece quality. In particular, techniques based on pulsed lasers have been widely explored. Unique advantages are offered

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by the use of laser tools such as, the excellent spatial resolution, a good degree of flexibility, and the inherently true non-contact and no tool wear machining due to the use of an immaterial beam [5]. Application of μs and ns laser pulses in the context of industrial micro-fabrication is concerned by the occurrence of large heat affected zones and recast of material [6], preventing the attainment of the required surface quality. The availability of ultra-short laser pulses, with a duration in the sub-ps range, has recently opened the way to circumvent the above mentioned problems, leading to a surface quality even better than in μ-EDM-machined holes. Owing to the very high transient intensity and small heat affected zone induced [7], ultra-short pulses prevent material melting and the consequent recast.

For those reasons, the use of ultrafast laser sources is gaining a strong momentum also for industrial applications. However, due to the relatively recent introduction of laser methods in the field of micro-hole drilling for automotive components, a careful tuning of the process parameters is needed in order to improve the effectiveness of the technique. In addition, its assessment in terms of quality of the machined workpiece requires the ability to reliably compare the surface and shape properties of the laser-machined micro-holes with those obtained through more conventional techniques. Within this context, the ability to measure roughness and edge sharpness with the required sub-micrometre spatial resolution is a key point to enable the envisioned progresses in process technologies [8]. Unfortunately, access for metrological characterisation is very limited to the inside surface of deep and narrow holes. Highly valuable diagnostics able to measure directly inside the hole have been proposed (see, e.g., [2]). However, despite of its destructive and time wasting nature, sectioning the nozzle along its axis is a commonly used procedure in order to expose a curved and recessed surface to the analysis, as carried out also in the present work.

Scanning Electron Microscopy (SEM) is a precious tool to reconstruct the surface morphology with an extremely large spatial resolution. Shape and size of the holes can be duly analysed by SEM, which, however, is not suited for direct measurement of the surface roughness. Several technical options are available for metrological surface analysis, each approach owning distinctive advantages and disadvantages, whose detailed discussion is out of the scope of the present paper. Conventional stylus profilometers have been around for many years. They have been used to retrieve morphological information also in the context of micro-hole fabrication (see, e.g., [9]), including, for instance, a configuration using a cantilever-type tactile probe sensor able to penetrate into the hole [2]. In stylus profilometers the probe has to be kept in mechanical contact with the investigated surface, that can make probe wear or surface scratching an issue, in particular when corrugated surfaces or soft materials are investigated. Optical profilometry (digital optical microscopy) is a technique developed to avoid the need for contact, while providing a fast two-dimensional morphology reconstruction with an accuracy depending on the actual spatial resolution of the used instrument [12]. According to the experience with the machined parts considered here, the optical approach can be prone to several artifacts, as also reported in the literature (see, e.g., [11]), in particular when surfaces featuring relevant slopes or showing a complicated texture, for instance made of different components, are analysed. In addition, the metrological characterisation of the corner edge and the measurement of its sharpness cannot be achieved with purely optical methods, even though many advancements have been carried out in the field of optical profilometry in the last years, leading to commercial instruments combining different technologies (see, e.g., [10]) for an enhanced versatility.

Scanning probe microscopy (SPM), in particular Atomic Force Microscopy (AFM), represents a valuable diagnostics for surface morphology [13] able to obtain accurate roughness information [12]. While being originally conceived for the investigation of atomistically flat surfaces, where atomic resolution has been demonstrated, AFM has also been used in the context of investigation and assessment of machined surfaces (see, e.g., [14–16]). The performance of AFM has stimulated the development of sophisticated metrological instruments [17], able to determine shape and surface properties with an accuracy exceeding the nanometre level.

According to the experience with the samples considered here, application of conventional AFM to the practical determination of surface finishing in machined workpieces reveals several critical issues. First of all, in the conventional tapping-mode operation of AFM a fast oscillation is applied to the tip along the vertical direction [18], leading to the possibility of intermittent contact between tip and surface and eventually to tip wearing and material scratching issues. Even though such effects can severely affect the measurements only in the case of soft material analysis, or when ultra-sharp tips are used in order to ensure high spatial resolution (below 10 nm), a true non-contact tool is often desirable. Moreover, large travel capabilities are needed when workpieces with complex shapes are analysed, which are not always found in instruments designed for atomic-scale imaging (typical maximum vertical displacement in AFM is around 5 μm [19]). In addition, the optical lever method generally exploited in AFM can be affected by artifacts due to scattering of stray light from the corrugated surface, particularly relevant in the case of rough metal surfaces. The use of non optical methods for detecting the probe motion can suppress such artifacts while ensuring the ease-of-use required for routine analysis, as often needed in the assessment of machined workpieces. Finally, while flat surfaces can be analysed in a straightforward way by using a conventional AFM, the shape and size of the cantilevered probes can pose physical limitations for accessing recessed surfaces, due to possible mechanical interactions between the cantilever and the edges of the machined workpiece.

The main goal of the present paper is to show the metrological results acquired with a specifically conceived SPM tool, namely a SHear Force Microscope (SHFM), on cross-sectioned micro-holes for fuel injectors. In order to elucidate the capabilities of the instrument, samples machined by different drilling techniques are investigated: μ-EDM, water jet guided laser (WJ), short (ps) and ultra-short (fs) pulse laser machining. The inner surface roughness and the sharpness of the generated edges are compared. The measuring procedure is able to identify standardised values of the surface finishing and to evaluate the crucial parameters defining the shape of the corners of the machined micro-holes.

2. Experimental setup

Approaches based on SHFM allow keeping the advantages in terms of resolution and sensitivity of AFM while virtually eliminating the above mentioned limitations. In SPM technology, shear-forces are conventionally used to sense the surface as in Scanning Near-field Optical Microscopy (SNOM) [20]. Their occurrence and behaviour are mostly due to the viscous interaction of the air layers imprisoned between the tip, kept in oscillation parallel to the surface, and the surface itself. Such an interaction is known to produce a strong damping when the tip-to-surface gap decreases at the few nanometres level [21]. Remarkably, in SHFM the tip is forced to oscillate only in the direction parallel to the sample surface. Therefore, any form of contact is avoided, at least if the oscillation amplitude is kept small enough (below 10 nm in the instrument presented here) compared to the typical spacing of surface features. This prevents tip wearing, improving as a consequence repeatability of measurements, a key point when comparison between different machined surfaces is the main

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