Ink-jet printing for patterning engineering surfaces

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Abstract

This work explored the use of industrial drop-on-demand inkjet printing for masking steel surfaces on engineering components, followed by chemical etching, to produce patterned surfaces. A solvent-based ink was printed on to mild steel samples and the influences of substrate topography and substrate temperature were investigated. Contact angle measurements were used to assess wettability. Regular patterns of circular spots (~60 μm diameter) and more complex mask patterns were printed. Variation of the substrate temperature had negligible effect on the final size of the printed drops or on the resolution achieved. Colored optical interference fringes were observed on the dried ink deposits and correlated with film thickness measurements by white-light interferometry.

Introduction

Surface texturing is the controlled change of surface micro-topography to enhance its performance, and is especially useful in tribological applications [1, 2]. Important industrial sectors where surface texturing can be applied to engineering components, usually metallic, include the automobile industry [3], sliding bearings [4], aerospace [5], metalworking [6], biomedical [7] and microelectronics [8].

Although laser texturing is commonly used to form localized pits in steel components it has several limitations, such as the formation of raised features around the pits which originate from the ejected molten metal, a slow process speed because pits are normally formed sequentially, and the fact that only approximately circular or elliptical features can be produced [9]. Many other methods have therefore been proposed.

Within the semiconductor industry micro- and nano-scale manufacturing methods are routine [10] but they are mostly specific to a particular class of materials, involve very high initial investment, and have been optimized for smaller features sizes than those of engineering interest (which are typically 50 to 500 μm in extent and 1 to 20 μm deep). Alternative manufacturing technologies for surface texturing are needed to overcome the challenges of volume production, and need to be cheap and flexible.

In laboratory studies of the effects of surface textures on engineering components, photochemical texturing has been widely used because it allows complex patterns to be generated. This involves masking a surface with a photoresist which is then exposed and developed; the component is then chemically etched to produce the pattern [10]. This is the standard process for the production of electronic printed circuit boards (PCBs). However, it is relatively inflexible, involves a large number of process steps and is difficult to apply to non-planar surfaces.

In principle, ink-jet printing should provide a method to deposit mask material rapidly under digital control, which can then be followed by etching and mask removal. As a non-contact flexible printing process, it would be applicable to non-planar surfaces and would be as suitable for one-off prototypes as for long production runs. Although there is considerable current interest in the use of direct ink-jet printing of masks for PCB production, very little previous work on the wider application of ink-jet mask printing to the texturing of engineering surfaces has been published. In early work Muhl and Alder [11] used a continuous ink-jet printhead with a solvent-based ink to deposit masks on to steel rolls; the deposited drop diameter was ~150 μm. This process, which could readily be extended to other engineering components, was patented [12]. More recently, James [13] discussed the advantages and disadvantages of several ink types for such masking applications, and reported the printing of 120-150 μm features on metallic substrates with a UV-cured ink.

This paper reports an investigation of the use of ink-jet printing as a masking technique for the surface texturing of steel surfaces, using a drop-on-demand printer and a solvent-based ink.

Experimental Methods and Materials

AISI 1010 steel coupons with dimensions of 60 × 20 × 1.5 mm were used as substrates, and printing was performed with a Dimatix Materials Printer (DMP-2800) with a nominal 10 picoliter drop size. The standoff distance (nozzle-substrate) was 1 mm and the drop impact velocity was 7 m/s. Most tests were performed at room temperature but the heated platen also allowed the substrate temperature to be controlled at up to 60 °C. The ink was a commercial lactate solvent-based black ink (dye-based, JetStream PCS 7561, Sun Chemical) with a viscosity of 12.1 mPa s at 25^{o}C and a surface tension of 31.5 mN m^{-1}.

Two series of experiments were performed. The first explored the whole texturing process, including the etching behavior and methods for stripping the resist. The influence of substrate surface finish on printing and wettability was also studied for highly polished steel surfaces as well as surfaces ground with silicon carbide paper with three different grit sizes (800, 320 and 120 mesh). After grinding, the surfaces were rinsed with acetone and dried in air. Wettability for each surface condition was assessed in terms of contact angles measured by the sessile drop technique with both the solvent-based ink and deionized water. The surface finishing step was performed immediately before the contact angle measurements.

After printing, the masked samples were etched with aqueous nitric acid at concentrations of 1%, 5% or 10% at a temperature of 25 °C for different periods of time. After etching, the ink deposits were stripped by immersion in acetone with ultrasonic agitation at 25 °C for 4 minutes. The samples were examined by optical microscopy before etching, after etching and after stripping. The surface topography of the textured samples was assessed by laser interferometry.

In the second test series, more complex patterns were printed on polished steel samples, to determine the minimum size of complex features that could be printed with this system. The printed samples were assessed by optical microscopy, and laser interferometry was also used to measure the thickness of the ink deposits. For those measurements, a thin film of evaporated gold was applied to improve the surface reflectivity of the ink deposits.

Results and Discussion

Figure 1 shows the contact angle measurements for samples after grinding with the different abrasive sizes. Wettability with the ink was much greater than with water. For water, increasing the surface roughness made the surface slightly more hydrophobic. However, for the ink, increasing the roughness significantly reduced the contact angle, probably due to the spreading of the ink within the surface grooves, which was observed for all the printings on roughened surfaces. This behavior agrees with predictions [14] that surface roughening reduces wettability only if the contact angle for the smooth surface is already large. It was concluded that roughening the surface could not be used to reduce the minimum size of the ink droplets on these metal samples, and indeed that larger deposits might be formed on rougher surfaces.

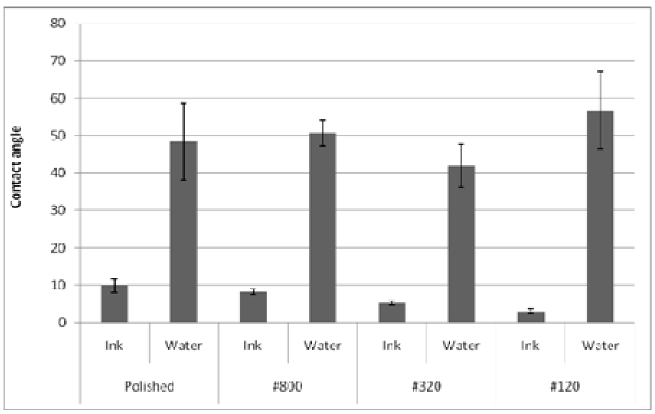


Figure 1. *Contact angle measurements on steel samples with different surface roughness (#800 mesh abrasive gives a smoother surface than #120 mesh).*

Figure 2(a) shows a pattern of circular dots printed on a polished steel sample, representing the smallest features that could be printed in these experiments, with each dot formed by a single droplet. The diameter of the dots was ~60 µm, in comparison with the ejected ink drop diameter of ~27 µm. Interference fringes, discussed in more detail below, show that the dried film thickness was uneven, but the ink film nevertheless provided good protection during etching. Optimal etching behavior was found for a nitric acid concentration of 5%. The ink protected the steel surface during etching and was easily stripped by ultrasonic cleaning in acetone. Figure 2(b) shows the final textured surface, in which a slight undercutting beneath the mask is detected. The diameters of the unetched islands remaining after etching were ~50 µm, suggesting that the extent of the undercutting was ~5 µm per edge.

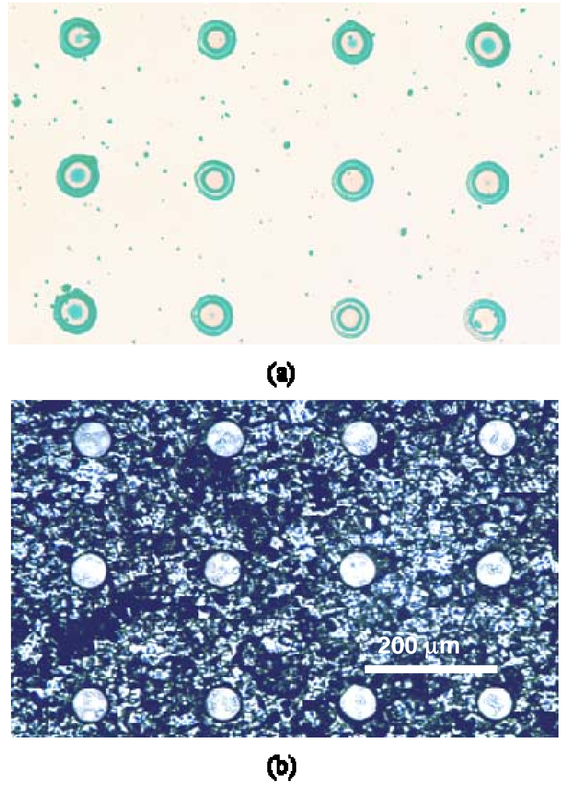


Figure 2. *Individual dots printed on polished steel; (a). after printing; (b). after etching and stripping. Individual printed dot diameters were 60 µm.*

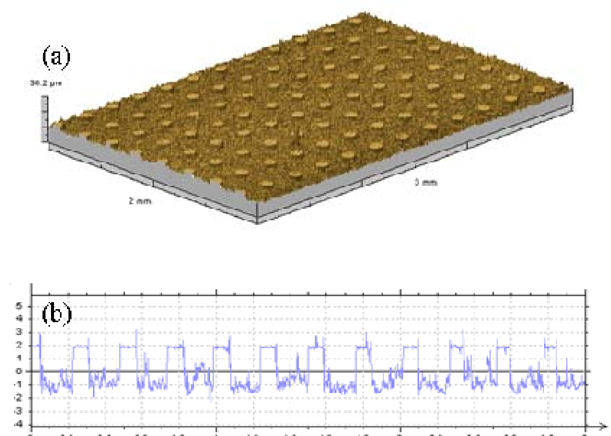


Figure 3. *Surface topography of sample printed with 60 µm dots after etching and mask stripping: (a) 3D map; (b) line profile across line of dots from white-light profilometry.*

Figure 3 shows that for an etching time of 5 minutes in 5% nitric acid the dimensions of the texture were regular, with the depths of the etched features being ~3 µm.

Figure 4 shows the effects of substrate temperature during printing, and of surface roughness, on the size of the printed features. Patterns with dots equally spaced (a and b) and square unprinted gaps equally distributed in a uniformly masked background (c and d) were printed at both room temperature and at

60 °C. The deposits showed negligible differences in overall drop diameter or resolution, although some differences in local film thickness were evident from the interference fringes. It is likely that any potential benefits in terms of smaller deposit size from more rapid solvent evaporation at the higher temperature were offset by a reduction in ink viscosity. Similar behavior was observed for all the patterns printed at different temperatures. Figure 4(e) shows the greater extent of spreading for drops printed on the roughened surfaces, which was consistent with the contact angle measurements.

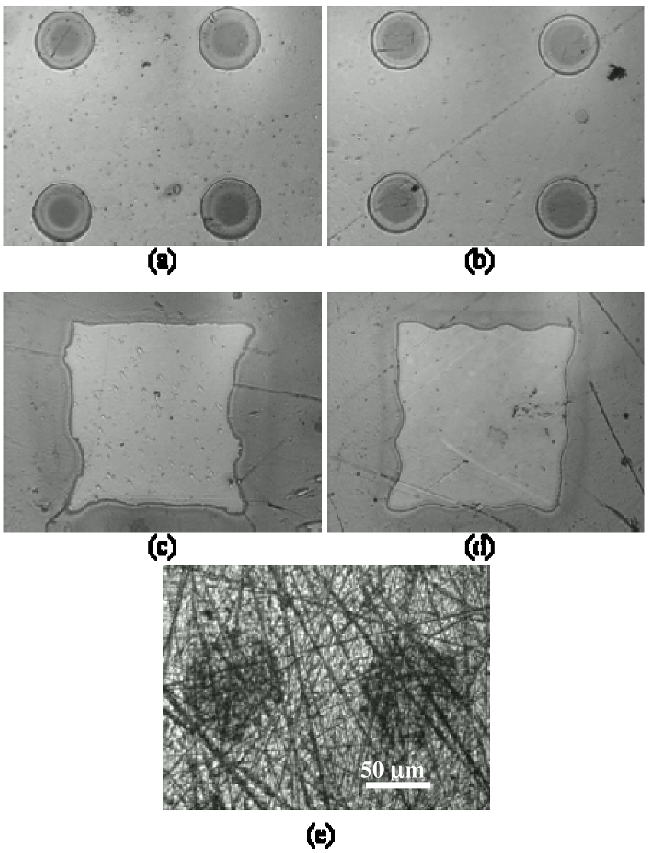
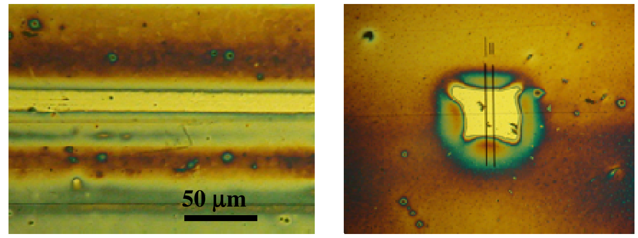


Figure 4. *(a) to (d) Masks printed on polished samples: (a) 60 µm circular dots printed at room temperature; (b) printed at 60°C; (c) square exposed gap in mask printed at room temperature; (d) printed at 60°C; (e) circular dots printed on ground surface, grit size 800, room temperature. All images are at the same scale.*

The printing of more complicated patterns was more difficult to control, because of the complexity of the ink flow on the surface. While individual dots with diameters of 60 µm could be printed, the minimum sizes of gaps of complex shapes distributed in a continuous background was larger.

Parallel linear gaps were easier to achieve and gaps as thin as 20 µm could be obtained, as shown in Figure 5(a).

Attempts to reduce the size of the unprinted gaps further resulted in distorted patterns. For square gaps, the minimum size which could be achieved without gross distortion of the shape was around 40 µm, as seen in Figure 5(b).



(a) (b)

Figure 5. *(a) 20 µm gap between parallel printed lines; (b) 40 µm square gap*

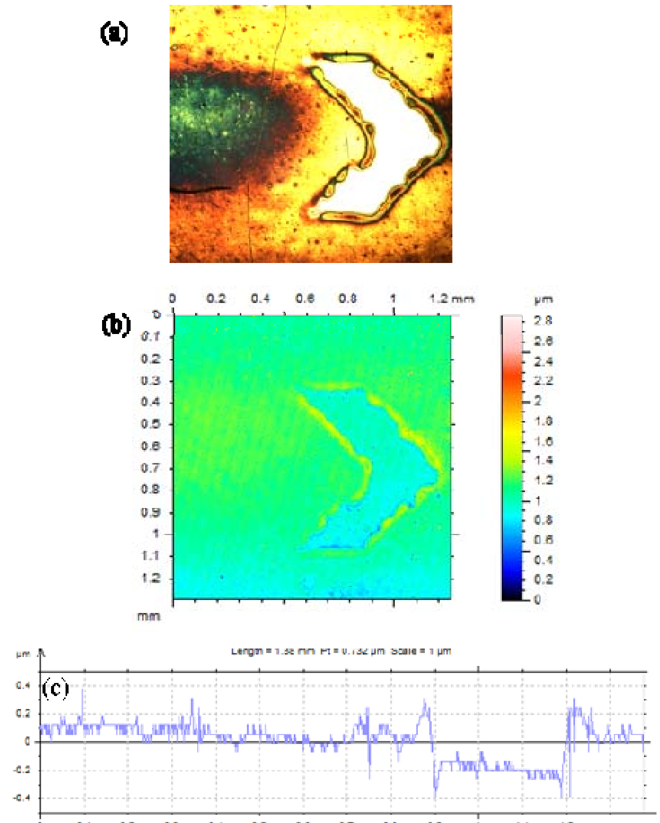


Figure 6. *Color optical micrograph of a chevron-shaped gap in a continuous printed background, showing pronounced interference colors (b) height map generated by laser interferometry; (c) height profile along central horizontal line through the chevron.*

Figure 6 shows an example of a chevron-shaped gap within a continuous printed background. Although a black dye-based ink was used, these thin printed films on a highly reflective steel substrate showed a clear pattern of colored interference fringes.

In order to interpret the interference colors, they were correlated with quantitative surface topography measurements at the same locations by laser interferometry, as shown in Figure 6(b) and (c). The ink film thickness was evaluated from line profiles at different locations, and consistent results were obtained. Other printed patterns, for example consisting of equally spaced unprinted square gaps in a printed background were analyzed in the same way, with similar results. The ink deposit thickness deduced in this way varied between 0.1 and 0.4 µm. The empirical correlation between film thickness and the interference colors is shown in Table 1. After calibration, this provided a simple and reliable method to evaluate dry film thickness.

Table 1. Correlation between ink deposit thickness and color of interference fringes

Interference color	Approximate ink film thickness (μm)
Violet	0.4
Green/blue	0.3
Orange	0.2
Yellow	0.1

Conclusions

Using a solvent-based ink and drop-on-demand ink-jet printing, patterns of circular spots and more complex masking patterns were successfully printed on to steel surfaces with different surface roughnesses, which were then etched to produce textured surfaces. Spot sizes of 60 μm were readily achieved on polished substrates. It was found that:

- With this ink, heating the substrate during printing was not effective to reduce the size of the printed spots.
- Surface roughness increased the wettability of the ink on the steel surface and therefore could not be used to reduce the size of the smallest printable feature; indeed, the highest resolution was obtained with a polished surface.
- Etching caused a slight undercutting beneath the mask, which might be reduced by better choice of etching conditions, although it might also be exploited to reduce the size of features in the etched pattern.
- Printing of complex shapes was more difficult to control due to the flow of the ink on the polished sample. The thinnest parallel gap was ~20 μm and the smallest square gap ~40 μm across.
- Interference colors were formed on the dried deposits of this dye-based ink on reflective metallic substrates and were correlated with thickness measurements by white-light interferometry. Dry film thicknesses were typically in the range from 0.1 to 0.4 μm.

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