Characteristics of engraving by diamond needle-tip with various tip shapes and engraving parameters

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ABSTRACT

In modern security printing technology, such as in card production there are several micro-machining methods in use. Needle tip engraving is one of them, and in this study we analyzed its effects on AISI 304 steel. The method is basically known but processes and effects in the metals are still subject of investigations.

Engraving with a hard-pointed diamond “needle” on a sheet metal plate produces microscratches in the material. Quality of the structure and accuracy are based on the process parameters. To improve quality and avoid needle-tip breakage, the Tool press load, engraving speed, Tool radius and number of tool passes are the relevant process parameters worth to be studied.

We analyzed the following basic scratch properties: line width, line depth and roughness of the engraved structure. Their relatation to the process parameters was evaluated using a statistical method, the response surface methodology (RSM).

Keywords: AISI 304 stainless steel, Needle-tip tool, Engraving, Groove, RSM

1 THEORY

1.1 Engraving of sheet metals

Engraving is the practice of incising a design onto a hard, usually flat surface, by cutting, scratching or laser ablating grooves into it (Fig. 1). The result may be a decorated object in itself, as when silver, gold, steel, or glass are engraved, or may provide an intaglio printing plate (Fig. 2) of copper or another metal, for printing images on paper as prints or illustrations; these images are also called engravings.

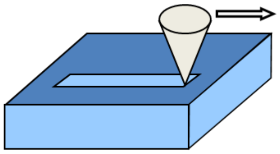
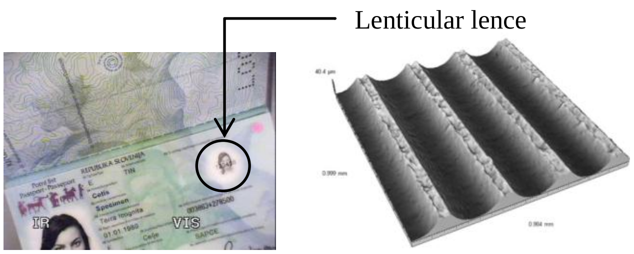


Figure 1: Schematic diagram of needle-tip engraving

Needle-tip engraving has partly been replaced by improved techniques, such us the deep laser engraving method. However, the needle-tip engraving technique is still used for manufacturing details on the lamination press plates. They are used in commercial and security graphic lamination as moulding tools to create optical and tactile security features within the lamination for a huge range of card and passport applications (Fig. 2).



Lenticular lence

a. b.

Figure 2: Passport data page (a.) and (b.) 3D-profile of the engraved security feature on the press lamination plate

1.2 Response surface methodology (RSM)

RSM is a collection of mathematical and statistical techniques that are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimise this response [1]. RSM also quantifies relationships among one or more measured responses and the vital input factors [2].

It was originally developed for the model fitting of physical experiments by Box and Draper [3] and later adopted in other fields. The RSM experiment is designed to allow us to estimate interaction and even quadratic effects, and therefore give us an idea of the (local) shape of the response surface we are investigating. For this reason, they are termed response surface method (RSM) designs. RSM designs are used to:

- Find improved or optimal process settings
- Troubleshoot process problems and weak points

- Make a product or process more robust against external and non-controllable influences. "Robust" means relatively insensitive to these influences.

The primary purpose of the experiment is to select or screen out the few important main effects from the many less important ones. These screening designs are also termed main effects designs.

2 EXPERIMENTAL

The engraving experiments were carried out on an experimental lathe setup using a diamond needle-tip tool for the engraving of the AISI 304 stainless steel in the form of rectangular sheet with 0.85 mm thickness. A Gravograph IS6000XP machine was used in wet engraving conditions in a WD40 oil liquid. The chemical and mechanical properties of the workpiece material are listed in Tables 1 and 2.

C	Cr	Ni	Si	Mn	P	S	N
0.037	18.11	8.02	0.35	1.28	0.031	0.005	0.053

Table 1: Chemical properties of the AISI 304 in wt.%

Tensile strength	520 MPa
Compression Strength	210 MPa
Proof Stress 0,2%	210 MPa
Elongation A5	45 (%)
Hardness Rockwell	92 HRB

Table 2: Mechnical properties of the AISI 304

Experiments were conducted using the engraving parameters given in Table 3, to obtain the engraved surface on the AISI 304 stainless steel. In all experiments the Tool radius, the Tool press load, the Engraving Speed, and the Number of passes were taken as various values in three different levels. They were evaluated at their low–middle–high levels (Table 3).

In this study, three factors were studied: Scratch width, Scratch depth and Surface Roughness at the bottom of the groove.

Engraving Parameters	Notation	Unit	Levels of engraving parameters		
			1	2	3
Tool radius (A)	TD	µm	90	130	150
Tool press load (B)	F	N	38.7	43.2	44.7
Tool speed (C)	V	mm/min	200	400	800
Number of passes (D)	N		1	5	9

Table 3: Engraving parameters and their values

The needle-tip load was measured using the Quartz Force Sensor (208C02), and a data acquisition system. The groove properties (width, depth, roughness) were measured using a stylus profilometer (Taylor Hobson). For each experimental trial, a new needle-tip engraving tool was used. An investigation of the engraved surface properties on the AISI 304 stainless steel solid plate was performed using the statistical RSM software "Design Expert 8" [4].

A predefined shape of the groove was made for every parameter combination (Fig. 3a). A specific position on the groove was used for all the measurements (detail shown in Fig. 3b).

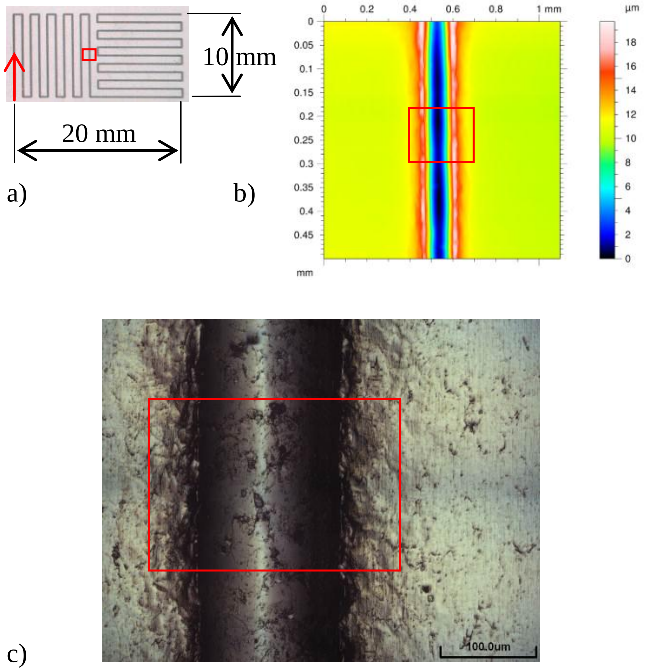


Figure 3: Predefined engraving contour, marked with the engraving direction (a), topography of the place of measurement (b) and optical image of the profile (c)

As we use 4 factors (Tool radius, Tool press load, engraving speed, number of passes) and 3 levels of factors, the most suitable array is L_{27} (3^13) orthogonal array. The number of levels for each parameter is indicated by 3. The total number of factors including the interaction between factors is designated by 13.

In this study, the L_{27} Taguchi standard orthogonal array is adopted as the experimental design. The most suitable array is L_{27}, which needs 27 runs and has 26 degrees of freedom (DOF). To check the DOF in the experimental design, for the three levels test, the four main factors (Tool radius, Tool press load, engraving speed, number of passes) take 6 DOFs (3 × 2) and the remaining DOFs are taken by interactions.

3 RESULTS AND DISCUSSION

3.1 Overview

The results from engraving trials performed as per the experimental plan are shown in Table 5. These results were input into the Design Expert software for further analysis following the steps outlined in Section 3. Without performing any transformation on the response, examination of the fit summary output revealed that the linear model is statistically significant for both responses and therefore it will be used for further analysis.

A profile and schematic dimensions of the groove are shown in the Fig. 4 where depth of the engraved structure is presented by E [µm] and width on level plane by H [µm].

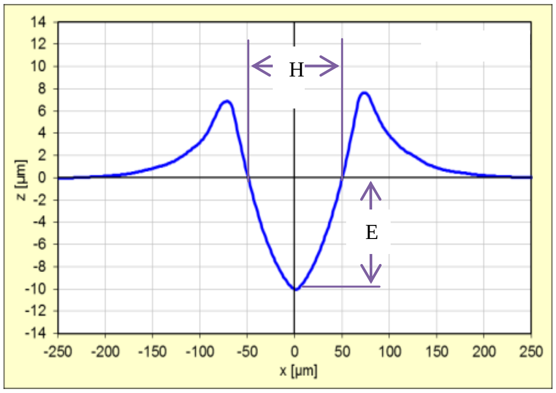


Figure 4: Needle tip engraved profile structure and evaluated dimensions of the groove

It was previously mentioned that a test for significance of the regression model, significance on individual model coefficients and lack-of-fit needs to be performed. One of the methods to analyse data for process optimization is use an analysis of variance (ANOVA) to summarise the tests performed [6]. The experimental parameters used and the corresponding responses are the Tool radius (TR), the Tool press load (F), the Tool speed (V) and the number of tool passes (N). The Scratch width (H), the roughness at groove bottom and Scratch depth (E) measurement results are evaluated by Taylor Hobson profilometer.

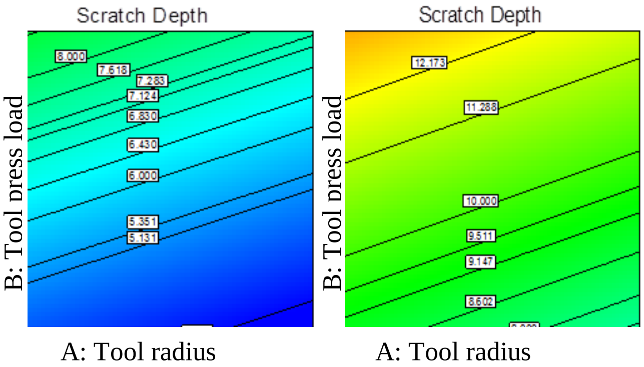
3.2 ANOVA analysis of Scratch depth

F-Value (F distribution) is a probability distribution used to compare variances by examining their ratio. If they are equal then the F value would equals 1. The F value in the ANOVA table is the ratio of model mean square (MS) to the appropriate error mean square. The larger the ratio, the larger the F value and the more likely that the variance contributed by the model is significantly larger than random error. The most significant factor affecting the Scratch depth is Tool press load with the F-value of 33.24. The Tool speed has no influence on the Scratch depth; therefore it was not included in the model and Scratch depth equation as mixed factors. The value of R^2 = 0.753 shows that the model explains 75.3% of the total variations for the Scratch depth.

The linear response surface equation in terms of actual factors for Scratch depth obtained from ANOVA are given as:

$$\text{Scratch depth} = -25.9 - (0.0260 \times \text{Tool radius}) + (0.8067 \times \text{Tool press load}) + (0.5422 \times \text{Number of passes})$$

In Fig. 5, the influence of the factors Tool press load and Tool radius on the Scratch depth is shown. The Scratch depth decreases with the increasing Tool radius for all the values of Tool press load. In order to obtain maximum Scratch depth, maximum Tool press load and minimum Tool radius should be used.



a) Number of tool passes: 1, Tool speed: 800 mm/min

b) Number of tool passes: 9, Tool speed: 800 mm/min

Figure 5: The influence of Tool press load and Tool radius on the Scratch depth

3.3 ANOVA analysis of Scratch width

The value of R^2 = 0.887 for the Scratch width shows that the model explains 88.7% of the total variations.

The most significant factor affecting the Scratch width is Tool press load with the F-value of 87.7 and Number of Passes with F-value of 38.0. Factors which have no influence on the Scratch width were not included in the model and Scratch width equation:

$$\text{Scratch width} = -45.2 + (0.12824 \times \text{Tool radius}) + (2.1780 \times \text{Tool press load}) - (0.5454 \times \text{Tool speed}) + (34.7044 \times \text{Number of passes}) + (0.0125 \times \text{Tool press load} \times \text{Tool speed}) - (0.7131 \times \text{Tool press load} \times \text{Number of passes})$$

The influence of the interaction between Tool press load and Tool speed on the Scratch width is shown in Fig. 6. The graph was plotted at the condition of the Too radius 130 µm and the Number of passes 9. Tool speed decreases the Scratch width at the low values of Tool press load, while the Scratch width increases with the increasing Tool speed at the high values of Tool press load. Regarding to the effect of Tool press load on the Scratch width, its effect changes according to the Tool speed used. At the low Tool speeds the Scratch width decreases with the increasing Press, but vice at the high Tool speeds. The maximum of the Scratch width can be obtained using minimum values of Tool press load and Tool speed. When the high value of the Tool radius (180 μm) is used, the maximum Scratch width can be obtained by maximum Tool press load and maximum Tool speed.

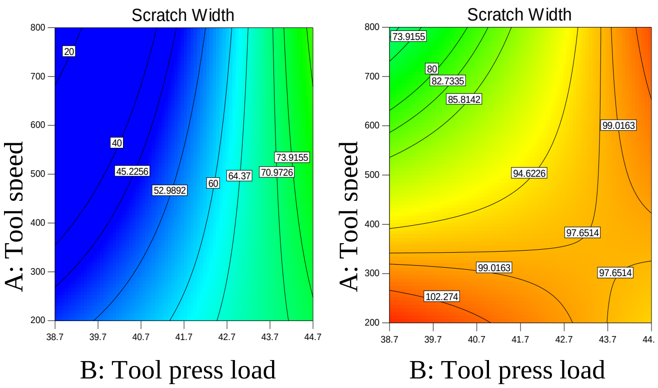


Figure 6: The contour plot of the interaction of Tool press load and Tool speed

3.4 ANOVA analysis of scratch roughness

The backward elimination procedure was selected to automatically reduce the insignificant terms. The value of $R^2 = 0.4199$ for the scratch roughness is quite low and it shows that the model explains only 41.9% of the total variations. The coefficient of variation is also very high (C.V. = 34.30%). Therefore, the model is not good enough to be used. From the ANOVA table, we can understand that used factors are not influential on the roughness as we expected.

4 CONCLUSION

In the experiments the influence of Tool radius, the Tool press load, the engraving speed, and the number of passes to a Scratch depth, Scratch width and Scratch roughness were studied:

- CASE No. 1 - ANOVA analysis of Scratch depth gives a linear model equation. The Tool press load and number of Tool passes are the most significant factors.
- CASE No. 2 - ANOVA analysis of Scratch width gives a non-linear model equation using reduced two-factor interactions. The Tool press load and number of Tool passes are the most significant factors.
- CASE No. 3 - ANOVA analysis of Scratch roughness shows insignificant values of the model factors. For this case no model can be applied.

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