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LASER ENGRAVING MODELLING – COMPARISON OF METHODS FOR THE HEAT-AFFECTED AREA DETECTION

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Abstract. The paper deals with the topic of laser engraving modelling. More concretely it describes methods for the automatic detection of the heat-affected area on the real samples and aims at their comparison. Real samples are used as the main input for the modelling process and the detection should be provided several times during data pre-processing. The paper outlines the format of processed data and the way of its acquisition. The main part of the paper is dedicated to three methods designed for the automatic detection of the heat-affected area and their comparison.

Key words. laser engraving, comparison, modelling, data processing, high map, detection

Mathematics Subject Classification: 68U20, 68Q68.

1 Introduction

The work described in this paper is a part of a larger project that deals with laser engraving control and modelling of laser engraving results. We are interested mainly in the real data exploration, comparison and modelling. We are working on finding the way how to get the optimal laser setting description to be able to model the engraving process result without providing the practical engraving. The reason is quite simple, the real experiments are expensive, time consuming and the result depends a lot on the engraving parameters and used material.

During the data pre-processing we need to detect the area modified during the engraving process by the laser beam. This detection should be used several times, e.g. during the sample parameterization or in the phase of the modelling verification and data comparison. That is why the designed method should give optimal results for different processed samples, should be quick and reliable enough. During our research we have designed several methods. Some of them were not suitable, but three of them seem to be possible to use. To choose the best one, we have decided to compare them from different points of view. This comparison was made also as a part of [5]. Compared methods used for the automatic detection are shortly described in Section 2 and their results are compared in Section 3.

But before the detection design itself, we have to analyze the real engraved samples to learn about the structure of samples and we also have to understand the physical background of the laser engraving process. The format of data is described in Section 1.1 whereas Section 1.2 focuses on the physical fundamentals of the engraving process.

1.1 Data Acquisition and Description

For the modelling process, we use real data as an input. Data originates from the real samples engraved by a laser into the material surface. All samples are prepared under the same conditions, only the description of the experiment changes to get a larger data set. All engraved samples are measured by a confocal microscope. During the measurement, for each engraved experiment the close surroundings of the engraved area is chosen, scanned and saved in the form of a high map. This height map is formed by a matrix of real numbers, which express the heights in a uniform rectangular grid (as can be seen in Fig. 1a). The basics of data acquisition process are described in detail in [2]. The dimension of samples reaches approximately several hundreds of micrometers.

We use the special testing data set consisting of samples engraved by the laser into a single point in the material. Such testing data should prevent potential faults caused by the external influences in a maximal possible way. The number of pulses goes in sequence, e.g. from 1 to 100. Each sample differs from the others even if the same experiment description has been engraved under the same conditions and with the same laser settings. This is the reason, why each experiment is repeated several times and so the input set should be representative enough.

To get a better imagination about the appearance of a real sample, see Fig. 1b, where the sample with 50 laser pulses engraved into one point of steel is shown in a 3D view.

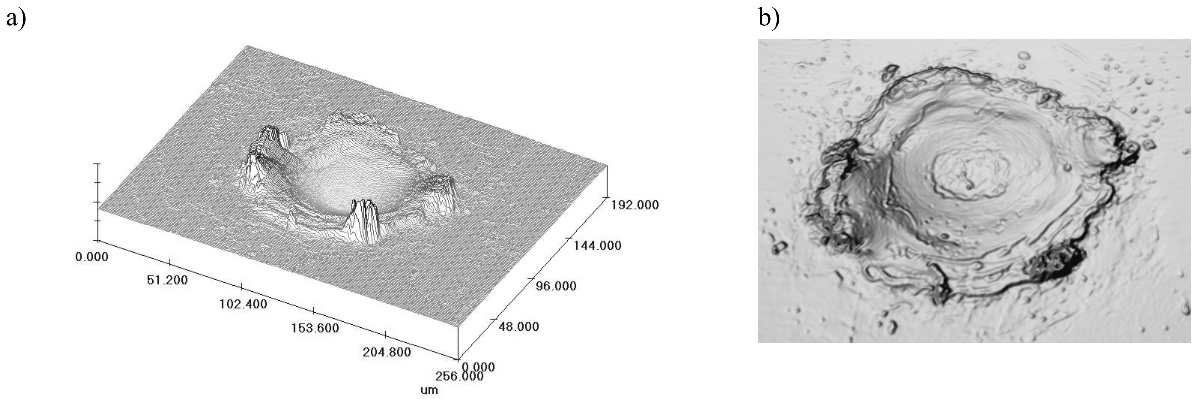


Fig. 1: High map of the sample with 50 pulses engraved into steel: a) 3D view from the confocal microscope; b) 3D view from different angle generated by our SW.

1.2 Engraving Process

Engraving is the process during which the laser beam, which is an electromagnetic radiation, affects the surface of the material. When the laser radiation strikes the material, some radiation is reflected, some absorbed and some transmitted. In our case, the most important is the absorption of the radiation, because it causes changes directly on the surface of the material. Although the physical reason depends on the type of the used material (metal, insulator or semiconductor), the effect is the same – it generates heat on the material surface. The heat generated at the surface directly affected by the laser beam is further conducted into the material.

If the laser intensity is high enough, the incident material heats, melts and if it reaches the boiling point, it starts to vaporize. These three described phases can be seen from the cross-section view in Fig. 2a-c. The solid arrows signal the laser beam direction, dashed arrows show the heat conduction in the material and the melted and vaporized material is highlighted with the gray colour. The vapour interacts with the laser, it ionizes and creates plasma. Vaporized particles, which are not affected by the laser beam, move away from the surface of the material, loose their energy and approximately 18% of them condense back to the surface. This process causes the increase of the sample surface roughness (especially in the heat-affected area closest surroundings). Moreover, the evolving vapor from the surface exerts a recoil pressure on the surface, which causes a melt expulsion, which is schematically shown in Fig. 2d. The whole process and the details related to the plasma phase are described in [1] or [2].

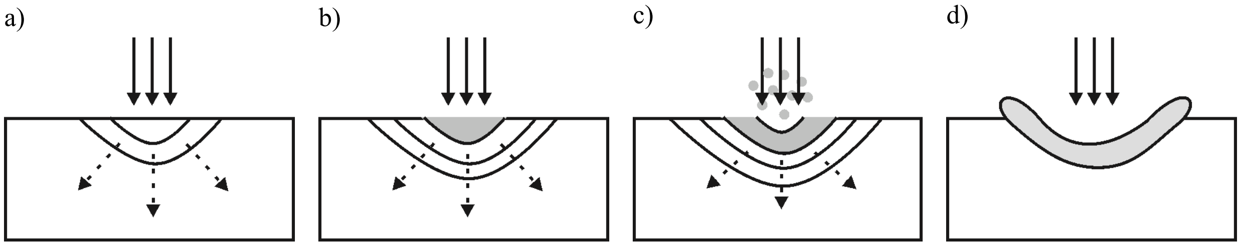


Fig. 2: Phases of interaction of laser and material: a) heating; b) melting; c) vaporization.
d) Schematic representation of melt expulsion process.

After the engraving process a pit with a transition ring around it is left behind at the exposure site. An idealized described cross-section relief is shown in Fig. 3a, the cross-section of real samples can be seen for two examples in Fig. 3b.

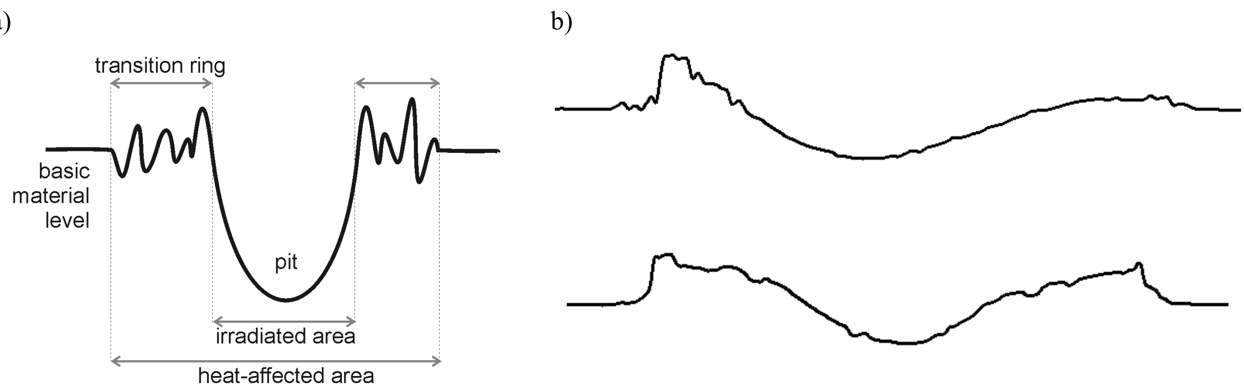


Fig. 3: a) Idealized cross-section relief of a sample and its description; b) cross-section reliefs of two different real samples.

2 Methods for the Automatic Heat-Affected Area Detection

The main task of the heat-affected area detection is to define the area of the material surface, which was affected by the laser beam during the engraving process, as exactly as possible. The required algorithm should detect the area automatically and accurately so that it can be used as a part of the data pre-processing.

In the idealized case, the detection of the heat-affected area would be simple, but for the real samples many problems appears. These problems (such as local defects, material surface roughness and other inaccuracies) can be seen Fig. 4. In Fig. 4a, the sample burned into the smooth surface of steel is shown in the 3D view. The detection of the heat-affected area in this case is even in despite of several local defects less problematical than in the case of the sample burned into cermet (Fig. 4b), where the roughness of the basic material complicates the detection a lot.

The most exact and reliable way of the heat-affected area detection is the manual way. But if we want to use it as a part of the whole data pre-processing, the manual usage slows the computation down and prevents its automation. The detection should be used several times during the process of the laser engraving modelling, e.g. during the parameterization of the sample or if we want to compare two samples. Hence, in order to speed up and simplify the whole pre-processing, the system has to be maximal self-contained. But the precision and accuracy should be preserved in a maximal possible way. While the user is able to distinguish roughness or defects on the material during the manual pulse detection well, for an automatic method it is difficult to differentiate inaccuracies on the sample surface from the outer border of the pulse.

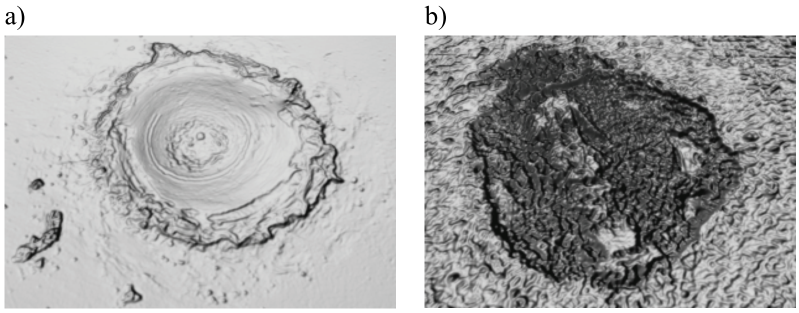


Fig. 4: a) Surface of steel with relatively smooth surface, but several local defects on the surface; b) cermet sample with globally higher roughness of the material surface.

We have designed several methods, which are described in detail especially in [2] and [3]. In the following explanation each algorithm will be shortly outlined and the main focus will be given on their comparison (in Section 3).

2.1 Clipping Method

This detection algorithm goes from unmodified sample surface. At the beginning we need a starting point, which should be determined as the point placed preferably in the middle of the heat-affected area. The starting point for automatic pulse detection is computed as the position of centre of mass in the sample. The standard procedure of the centre of mass computation has to be adapted for the sample representation and so equation (1) for the sample centre of mass computation has been derived. Value $f_i = f[x, y]$ represents the single point of the sample and *materialLevel* represents the height of the basic material. This method returns the starting position which is placed in the area of engraved pulse and is affected by local material defects in a minimal way.

$$x_c = \frac{\sum m_i . x_i}{\sum m_i}, \text{ where } m_i = \left(f_i - materialLevel\right)^4 \quad (1)$$

From the starting position, columns of the height map to the left and to the right side are inspected and the height difference of points in each single column (it means the difference between the maximal and minimal value in the column) is computed. If the value does not exceed given height limit, an inspection in the direction is finished and columns behind these left and right borders are clipped. After clipping the columns on the left and right side of the heat affected area, the same process of border searching is started for rows. Horizontal borders are appointed, the other rows are clipped. The procedure is in a simplified way shown in Fig. 5a.

There is a question, how to gain the value of a difference height limit. If we do not want to set the constant manually, because we explore the sample automatically, we can compute the value as the minimal height difference of several border columns or rows. This approach works for the majority of samples, because the borders of the sample are not modified during the laser engraving and so, they represent the original material surface.

2.2 Spiral Method

All particular steps of spiral method are shown in Fig. 5b. Also this method goes also from unmodified sample surface and uses the starting point that is computed as the centre of mass of the sample. If we put through the starting point two lines parallel with axis x and y (in Fig. 5b see two solid lines), we can get two cross-sections of the sample along these lines similar to those shown in Fig. 3b – the vertical and the horizontal one. On each curve we can determine two points, where the heat-affected area finishes and to define borders there. By this approach we get left and right border of the pulse from the horizontal cross-section curve and the top and bottom border from the vertical cross-section curve.

From this starting bordering rectangle (in Fig. 5b highlighted with dotted rectangle) we have to continue the final border searching. The final borders are searched in a spiral way. All borders are periodically tested if it is possible to move them for one row or one column further from the starting point. In each step for each single border (left, bottom, right and top), the height difference between the minimal and the maximal value in the shifted position is computed and compared with the difference limit (computed in the same way as in the case of the clipping method) for the processed sample. The sequence of borders is preserved through the whole computation (it means borders are rotating during the algorithm). If any border can not be moved further, it is skipped in the next rotation. The final bordering rectangle is in Fig. 5b marked with the dashed line.

a) b)

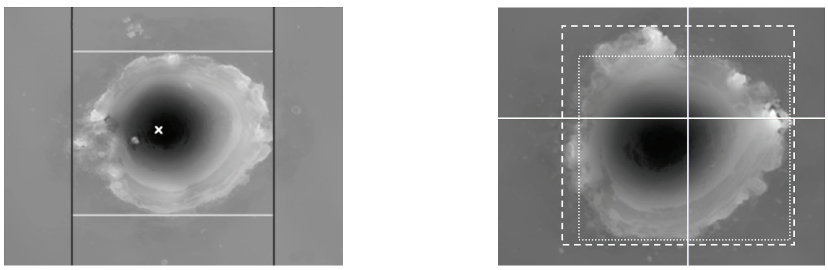


Fig. 5: a) Borders determined during the clipping method (white cross represents the starting point). b) Spiral method detection process – cross-section positions (solid lines), starting rectangle (dotted rectangle), final borders (dashed rectangle).

2.3 Statistical Method

Statistical method works on a completely different principle than methods described in Sections 2.1 and 2.2. The whole sample height map is divided into the regular rectangular grid and for each cell of the grid, a representing value (as a difference of the minimal and maximal height in the cell) is computed. Part of such sample with computed values can be seen in Fig. 6a. In this way we reach simplification of the sample and for its further processing we use the statistical approach. To get optimal results, it is very important to determine size of the statistical grid cell, because we need to simplify it enough, but not too much. Our experiments show that the grid size depends especially on the used material and so, the optimal value is determined experimentally for each tested data set.

To distinguish the values of the heat-affected area from the rest of the sample, we can use thresholding. After doing this, cells representing the basic material are labelled with zero value; the others are indicated by the value of 1 and further processed. In Fig. 6b such cells are highlighted (the dashed rectangle borders the area zoomed in Fig. 6a). To remove the small areas of the local defect, we need to find the largest labelled area and so we use the binary image segmentation, more concretely the connected component labelling, described in [4] or [5]. Finally, we get the largest area which represents the heat-affected area (see Fig. 6c).

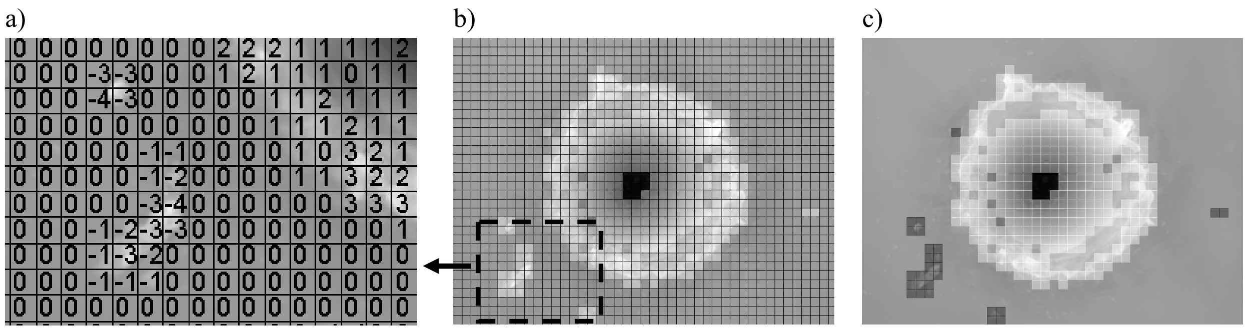


Fig. 6: a) Part of the sample with computed values for the statistical grid (bottom left corner of the sample); b) the grid after the thresholding; c) the largest thresholded area determined.

3 Methods Results and Comparison

All three described methods were tested on the set of real samples. To test all methods properly, we have used samples engraved in two different materials – steel and cermet. For each material several samples with various defects and other problematic parts were chosen. Methods are compared from two points of view – their universality and accuracy. Speed of all methods is comparable, because it depends especially on the sample dimension (on an average 300ms is needed for one detection; Intel Core 2Duo CPU 3GHz, 3.25GB RAM, Windows 7, Java 1.6).

3.1 Accuracy

The accuracy means, how precisely the method is able to set bounds to the heat-affected area. In Fig. 7 and Fig. 8, several testing samples and results of the heat-affected area detection are shown. In all figures, results of the clipping method are bordered with dashed line, for results of the spiral method dash-dotted rectangle was used and the statistical method is visualized by dotted line. The numbers of laser pulses engraved into the material are described directly in the figure labels.

For samples burned into cermet, more often the clipping method was successful. The reason is the higher roughness of the material surface which complicates thresholding phase in the statistical methods. On the other hand, the difference between the original surface and the heat-affected are is higher and so, the clipping method is able to distinguish them well.

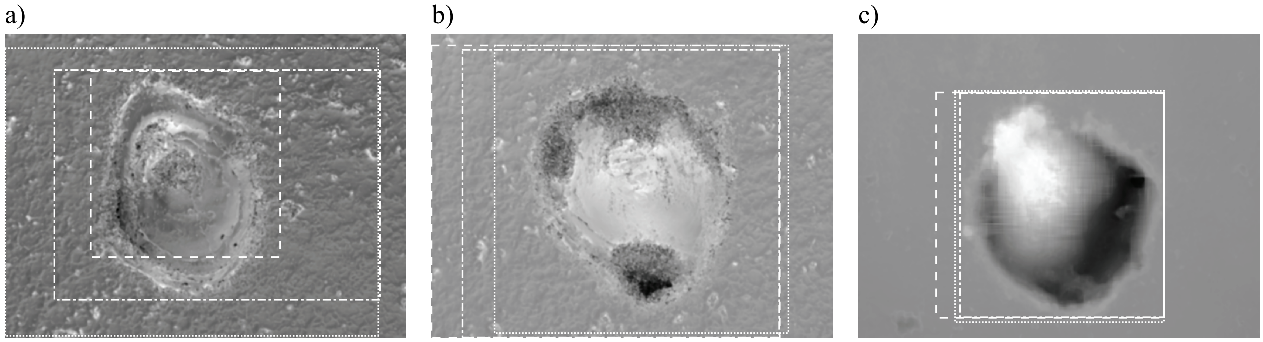
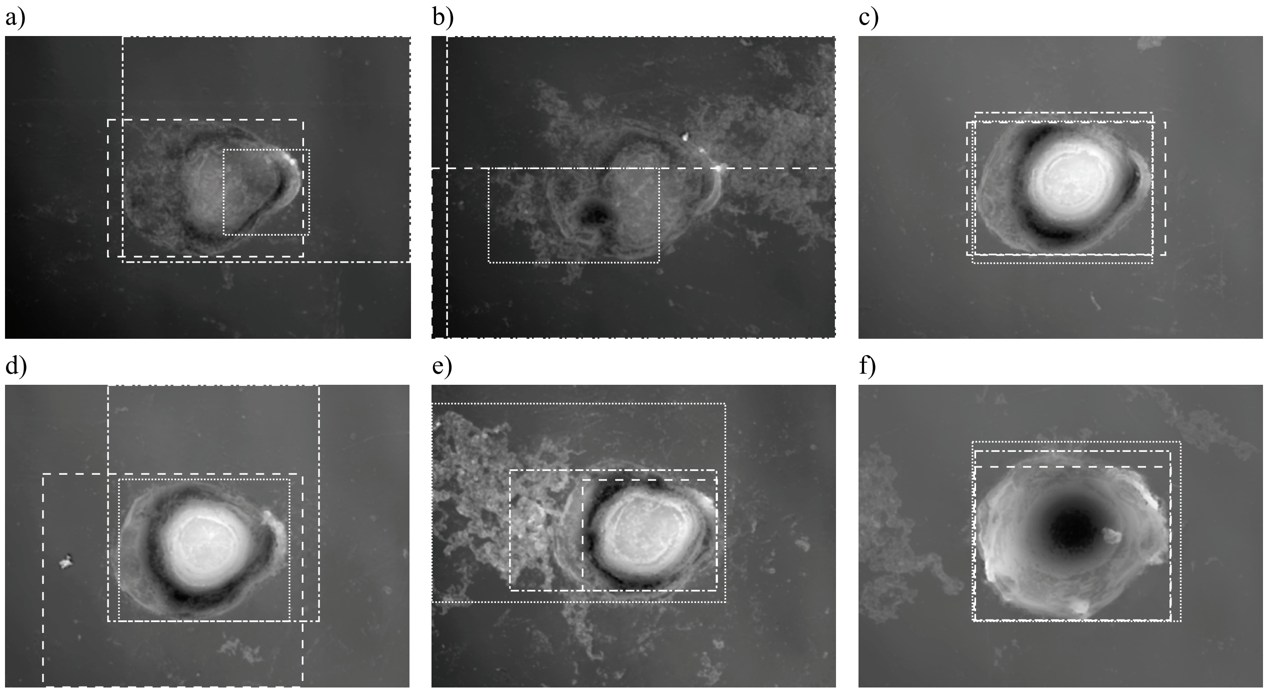


Fig. 7: Samples engraved into cermet with various numbers of laser pulses: a) 2; b) 50; c) 90.

As can be seen especially in Fig. 8a-b, for steel the detection is complicated especially for the small number of laser pulses, because there is only slight difference between the changes of the material caused by the engraving process and the irregularities of the original surface.

Majority of samples were detected well with the statistical method, while the others are more influenced by various defects and surface irregularities. Its main disadvantage lies in the manual experimental setting of the statistical grid cell size. Fortunately, for all samples engraved into the same material it has to be set only once, because this value depends especially on the used material. Clipping and spiral methods work fully automatically.



g) h) i)

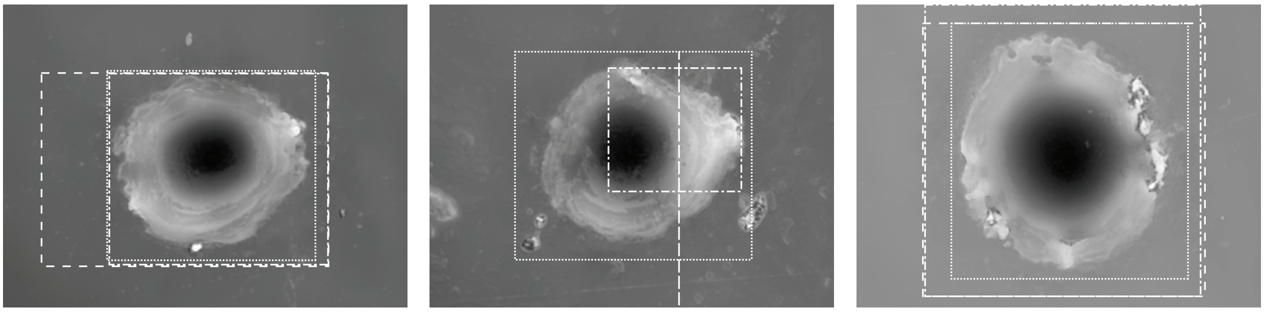


Fig. 8: Samples engraved into steel with different numbers of laser pulses: a-b) 1; c-e) 2; g) 10; h) 20; h) 40; i) 90.

3.2 Universality of Usage

The testing of methods universality was also provided for both materials. For each tested sample all three methods were used and gained results were analyzed. If the heat-affected area was detected well (as e.g. in Fig. 8c), the analyzed method gained a point. If the result of automatic detection was tolerable (e.g. spiral and clipping methods in Fig. 8g or clipping method in Fig. 8i), but not optimal, only half of a point was counted. For all similar samples (i.e. samples engraved into the same material with the same laser pulse number), the results were averaged. Results for cermet can be seen in Fig. 9a, results for steel in Fig. 9b.

Unfortunately our data set for cermet is not as large as in the case of steel and so for cermet only one experiment for each number of pulses engraved into the sample surface was tested. Nevertheless it seems, for cermet the clipping method (and partly also the spiral one) give better results than the statistical detection. On the other hand, for samples engraved into steel (where for each number of laser pulses five similar samples were analyzed), the best results were given by the statistical method, especially for samples with 10 and more laser pulses engraved into one point.

a) b)

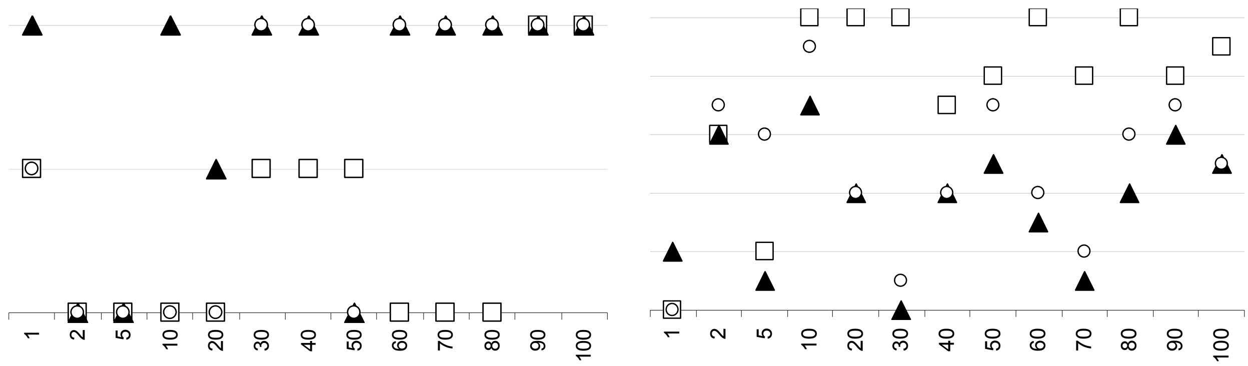


Fig. 9: Comparison of the successful heat-affected area detection for all three methods and samples engraved into: a) cermet; b) steel (☐ statistical, ▲clipping, o spiral method).

4 Conclusion

Our results show, that for different material (especially if they differ in the basic material surface roughness), different approaches are applicable. Another aspect influencing the usable method is the high difference between the basic material level and extremes of the heat-affected area. Tested methods give promising results, hence we will continue in their development and also testing on various materials and samples, so that they could be integrated into the real data pre-processing as the foolproof, exact and self-contained processing step.

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