Strain behaviour of aluminum 99.5 in micro-forming conditions of the coining process

Dehnungsverhalten von Aluminium 99.5 unter mikrobildenden Bedingungen des Prägeprozesses

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The coining process can be identified as a shallow die forging. By using this process, it is possible to produce very fine surface geometries. This leads to dimension scaling into micro dimensions and causes the specific material behavior. In the micro area, continuum laws are not strictly followed anymore. The leading role in determining the deformation and strain level is taken by the fine surface geometry dimension and the size of the crystalline grain of the workpiece material. This is known as the size effect and defines all micro-forming processes. In order to provide monitoring of the filling of the smallest die dimensions, additional supporting procedures should be used. In this case, radiography testing procedures for observing the specific points of the workpiece geometry are applied, characterized with very small dimensions (less than 0.5 mm). Testing aluminum samples are formed using two techniques – open and closed die coining, with identical surface geometry. Their crystalline structures are in two-grain sizes of 34 µm and 80 µm. Scanning results show different material behaviour and different surface deformation for the same level of forming force in all four testing cases.

Keywords: Shallow die forging **/** crystalline structure **/** micro-forming **/** die cavity filling **/** digital radiography

Der Prägeprozess kann als flaches Gesenkschmieden identifiziert werden. Mit diesem Verfahren können sehr feine Oberflächengeometrien erzeugt werden. Dies führt zu einer Dimensionsskalierung in den Mikrobereich und verursacht ein sehr spezifisches Materialverhalten. In diesem Mikrobereich gelten Kontinuums-Gesetze nicht mehr absolut. Die Hauptrollen bei der Bestimmung des Verformungs- und Dehnungsgrades spielen das Maß der Feinheit der Oberflächengeometrie und die Größe des kristallinen Korns des zu bearbeitenden Materials. Dies ist als Größeneffekt bekannt und definiert alle Prozesse der Mikroumformung. Um die Füllung der kleinsten Matrizen zu überwachen, sollten zusätzliche unterstützende Verfahren angewendet werden. In diesem Fall werden radiografische Testverfahren zur Beobachtung der spezifischen Punkte die Werkstückgeometrie angewendet, die mit sehr kleinen Abmessungen (kleiner als 0,5 mm) gekennzeichnet sind. Die Aluminiumproben wurden in zwei verschiedene Verfahren - offenes und geschlossenes Prägeverfahren mit identischer Oberflächengeometrie hergestellt. Ihre kristallinen Strukturen liegen in zwei Korngrößen vor, 34 µm und 80 µm. Die Scanergebnisse zeigen in allen

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vier Prüfungen ein unterschiedliches Materialverhalten und eine unterschiedliche Oberflächenverformung bei gleicher Formkraft auf.

Schlüsselwörter: Flaches Gesenkschmieden / kristalline Strukturen / Mikroumformung / Matrizenhohlraumfüllung / digitale Radiographie

1 Introduction

Micro-forming is a micro-manufacturing process that offers a promise for the sustainable production of small-size products, parts, or features. Features smaller than 100 μm can be produced (comparable with the thickness of a human hair) which is the main advantage of the micro-forming process. Reaching these dimensions leads to specific behaviour of a material when it suddenly does not follow continuum laws and its deformation and strain level becomes strictly dependent on the part feature size and crystalline grain size. These phenomena are known as size effects. Size effects might occur when the standard manufacturing process is scaled down until the produced features are below 1 mm in size. They can enable or disable the particular manufacturing process by introducing density, shape, or structure effects.

The coining process (shallow closed die forging) can produce parts with complex geometry and very small features along with the highest quality details. This process can be considered as a micro-forming process [1–4]. The analysis and models of the coining process, as a classical forming process in pioneering work, are better suited the analysis of the classic forging processes [5]. The total material deformation is sometimes completely neglected, and the emphasis is put on the influence of the surface roughness on the friction under the high level of contact pressure. It is shown that surface roughness is unrelated to the part size, hence surface roughness has significantly influence on the real contact surface and the friction coefficient [6]. The causes of the size effects appearance can be categorized as the causes of material structure, density, and part shape [7]. Grain orientation, geometry, dislocations, surface roughness, etc., can be associate with structural size effects. If the dislocations density in material remains unchanged during the part scale down the density size effects will appear as a result of smaller part volume and the reduced number of dislocations within the part material. Since some properties are dependent on the part surface area (number of surface crystalline grains, friction, surface tension, heat, etc.), while other are dependent on the part volume (total number of crystalline grains, thermal capacity, weight, etc.), shape size effects will be caused by the change in the ratio of a part surface and volume in case of unchanged part shape during part scale down. While the material surface topography mainly influences the tribology, grain size and size of die feature influences the material properties. In a conventional forming process grain size defines the proportion of grain boundaries to material volume. Larger grains yield a smaller proportion of grain boundaries and results in lower flow stress, lower forming force, a higher degree of deformation and better die filling. But in micro-forming, when the size of grains become larger than the size of die feature (e.g. channel), the size effect is strongly present resulting in a change of deformation mechanism causing the increase of flow stress and forming force, and a decrease in the degree of deformation and consequently poor die filling [7].

The coining force is also determined in an ideally plastic material, but elasticity and constant yield stress are neglected [8]. Furthermore, hardening of the workpiece material in coining process is examined for the material with strain hardening and without elastic properties [9]. Since elastic properties of the material have significant influence on die filling, this information is mandatory in the research of coining process. The coining process is categorized as the micro-forming process when the coin surface is analyzed by taking into account its micro-geometry with plane state of strain [10]. Several articles have examined the impact of size effects on various micro-forming processes [7, 11–19]. However, there is limited number of researches dealing with real problems in coining regarding elastic deformations, residual stress, and half-filled die cavities, the traces of lubricants and surface imperfections, and development, manufacturing and analysis of tools [1–3, 10, 20–25]. By determining the influence of size effects caused by different crystal grain sizes, the forging force, filling of the die cavity and elastic spring back can be estimated, by which the properties of the final product can be controlled and customized. Therefore, there is the place for a new research which takes into account different stress state schemes caused by different flow possibilities of the material (i.e. open and closed die coining with identical surface geometry).

In this study, experiments were carried out regarding impact of the grain size effects on the die cavity filling in the case of open and closed die coining process. In both cases, the geometry of die was the same, and all coins were forged with the same process parameters. Radiography testing procedures are applied as a supporting method for determination of die filling in specific points of die cavity characterized with very small dimensions, which surely belong to the microforming area. Two samples are the product of open die coining, and two of them are the product of closed die coining processes. Their grain structures are in two sizes. One sample in open and one sample in closed die have a grain size of 34 μm and the other two, one coined in open and one in closed die have a grain size of 80 μm.

2 Experimental procedure

2.1 Tool, machine and measuring equipment

Coining experiments were conducted with a tool, *Figure 1*. Main parts of develop tool are: upper die, lower die, ring, and ring raising and lowering mechanism. Ring raising and lowering mechanism enable the use of the same tool for open and closed die coining process. In the case of open die coining, the ring is in its lower position and radial expansion of the workpiece occurs. In the case of closed die coining, the ring is raised, and radial expansion of the workpiece is prevented. Axial compression of the workpiece is achieved by the upper and lower dies. The force is applied to the upper die which causes its movement forward the lower die and filling of the die cavity. To measure the applied force the load cell HBM KMR 400 was placed between the top of the upper die and the hydraulic press punch. Press used was a modified version of PZM PHM-63a press.

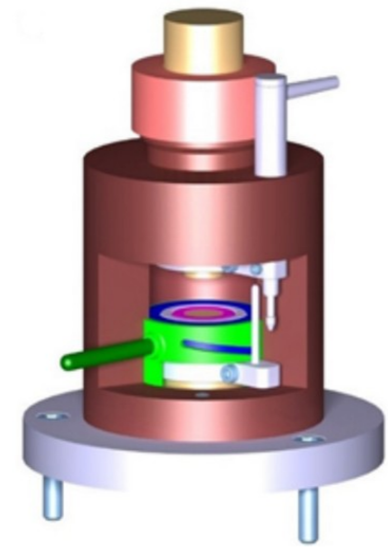

Figure 1. A developed tool used for open and closed die coining experiments: computer-aided design (CAD) model.

The geometry of the die cavity is the negative geometry of the final product. To have a quality product it is necessary to assure that the die cavity is completely filled at the end of the coining process and it is also necessary to provide free separation of the workpiece from the tool cavity after the deformation process is completed. Therefore, to obtain the final product shape, it is necessary to find a compromise between the design and the imposed geometric constraints. The final geometry of the die cavity comes from the experience and the method of attempt and error. For this research, the industrially used geometry of the die cavity is utilized, *Figure 2*. It is a complex geometry die cavity which consists of very fine surface details. The smallest channels are 0.125 mm wide with approximately square cross-section. To reduce the influence of friction between the workpiece and the tool ring, the die cavity was placed only on the upper moving die while the lower fixed die was flat.

2.2 Workpiece material

Aluminum (Al) 99.5 % was chosen as the workpiece material as it has a good formability and it is widely used in industry. Workpieces with dimensions Ø20 mm × 2 mm are made from pre rolled aluminum sheets and the grain structure of workpieces was modified by recrystallization heat

Figure 2. The geometry of the upper die cavity.

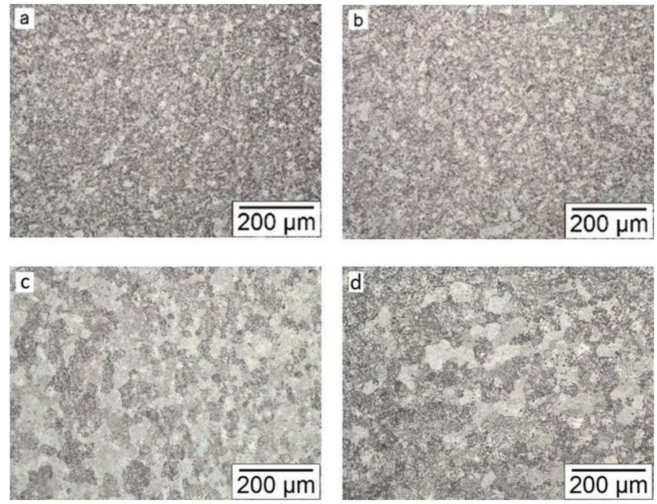

Figure 3. Workpiece microstructures: a) and b) 350 °C, 30 min, 34 µm, c) and d) 450 °C, 120 min, 80 µm; for radial and axial section, respectively.

treatment. Two groups of workpieces were produced. The first group was held for 30 minutes at a temperature of 350 °C while the second group was held for 120 minutes at a temperature of 450 °C. After metallographic sample preparation (cutting, polishing, and etching) the workpiece grain size is determined by an optical microscope (Olympus GX51) and chart comparison methods according to ASTM-E112 standard [26]. The grain size is average grain diameter, and, in this research, it is obtained as the mean value of at least five grain diameter measurements on radial and the axial plane of the workpiece. The initial grain size of the pre-rolled sheet could not be determined due to the small and elongated crystal grains and highly directional structure.

The grain size of the workpiece after recrystallization heat treatment at 350 °C for 30 minutes was 34 µm. Increasing the temperature to 450 °C and duration of 120 minutes increased grain size to 80 µm, *Figure 3*.

To avoid incomplete filling of the die cavity because of lubricant trapped in small parts of the cavity coining is conducted under the dry conditions, i.e. without any lubricant. The forming force was 200 kN all the workpieces were compressed at a punch speed of 0.01 mm/s.

2.3 Computer radiography (CRT) workpiece material

For determination of die filling in specific points of the die cavity the surface of forged coins was scanned by computer radiography (CRT), also known as a technique of digital radiography. Intense development of computer radiography over the last few decades lead to its frequent application in different technical and nontechnical fields. Computer radiography is commonly used in the aerospace industry for testing complex composite materials, for weld and casting inspection to detect any discontinuity, for clinical application in dental practice and medicine as well. Computer radiography has also been applied in the fields of art and archaeology and as an alternative method for some type of application for which it is not primarily intended. By attentive selection of relevant parameters to ensure the quality of digital records, it is possible to reveal some appearance in a material structure such as a watermark or paper structure [27]. Mentioned properties are significant parameters that allow historians and restorers to conclude when a particular paper was produced. There are various researches in the field of building industry where the potential application of computer radiography systems is used for the characterization of materials assessment of production quality and also the digital neutron radiography technique to visualize cracks in concrete and for a larger number of scientific applications [28–32].

Computer radiography is a technique of radiography non-destructive testing method which by using an imaging plate as a detector of x-ray stores the absorbed x-ray exposure in the photostimulable phosphor (PSP) layer, *Figure 4*. Energy deposited in the photostimulable phosphor layer causes local electrons to be elevated from an equilibrium (ground state) energy level to a stable "trap" known as an "F-center". The number of electrons trapped is proportional to the number of x-ray photons and represents the latent image. Trapped electrons in the photostimulable phosphor layer are stimulated by the additional light energy of the proper wavelength by the process of photostimulated luminescence (PSL). A highly focused and intense laser light of low energy (~2 eV) a significant fraction returns to the lowest energy level within the phosphor, with a simultaneous release of photostimulated luminescence of higher energy (~3 eV). The intensity of photostimulated luminescence in a form of light is detected by a photomultiplier tube which converts and amplifies the photostimulated luminescence into a corresponding output voltage and by using an analog-to-digital converter produces a digital picture record pixel by pixel during the scanning process. The latent image is erased with white light and the image plate is reused [33].

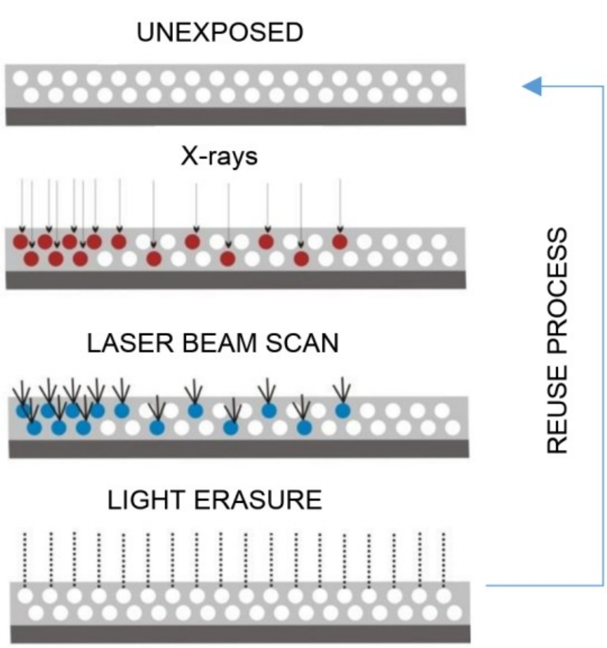

Figure 4. Exposure process and digital images recording [34].

The coins were radiographed with ERESCO 42 MF4, a portable x-ray tube with 200 kV maximum x-ray energy. The radiography images were exposed on Carestream Flex Blue Digital Imaging Plate 5537. For the latent image scanning from the active layer of the imaging plate, it was used the VMI 5100MS scanner which has 16-bit greyscale resolution. The scanners for the industrial computer radiography commonly allow three system parameters to be selected depending on the desired results, *Table 1*. The first one is a scanning resolution which represents the pixel size on the digital radiographic image and is determined by the laser beam size and sampling pitch of the scanner, which is regulated by scanning speed. The second one is laser power which represents the energy of the laser beam, and the last one is a photomultiplier tube gain that represents the amplification of the light signal when transformed in the electrical signal. The amount of amplification is regulated by the voltage on the photomultiplier tube [29].

Optimal exposure parameters for both processes of open and closed die coining and for various grain sizes were obtained after a series of preliminary experimental settings, *Table 2*. X-ray energy and x-ray tube current are varied to obtain the best optimal exposure parameters to achieve the 16-bit grayscale tagged image file format (TIFF) image format for image analysis in the ImageJ image analysis software [34].

The greater amount of x-ray absorbed energy will be on the part of coins with higher height and better die filling. Accordingly, on the image plate mentioned effect will be shown as a pixel with a lower grayscale value (brighter pixel intensity),

Table 1. Selected system parameters of the scanner.

Scanning resolution, µm	50
Laser power, W/m^2	15
Photomultiplier tube, V	5,25

Table 2. Exposure parameters.

X-ray energy, kV	30
X-ray tube current, mA	3
Focus distance, mm	1000
Exposure time, sec	40

Figures 5, 6. Further, imaging analysis by ImageJ software was run using colour coded 16-bit greyscale images, *Figures 7, 8*. Accordingly, in the Interactive 3D Surface Plot, the area of lower coin height and worse die cavity filling will appear in different colors than the area with higher coin height and better die cavity filling.

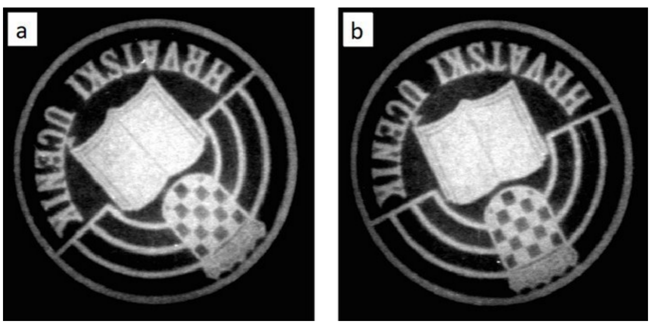

Figure 5. Computer radiography (CRT) digital radiographic image of the coins; a) open die coining process, 34 μm; b) open die coining process, 80 μm.

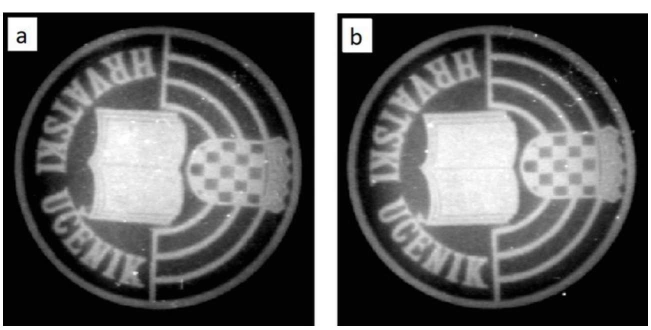

Figure 6. Interactive 3D Surface Plot of the coins; a) open die coining process, 34 μm; b) open die coining process, 80 μm.

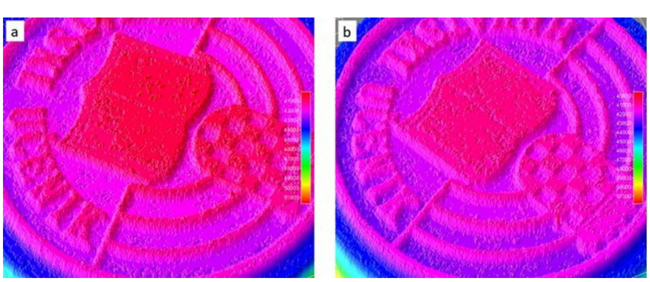

Figure 7. Computer radiography (CRT) digital radiographic image of the coin: a) closed die coining process, 34 μm; b) closed die coining process, 80 μm.

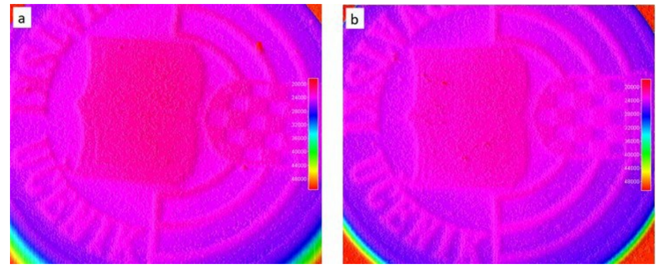

Figure 8. Interactive 3D Surface Plot of the coins: a) closed die coining process, 34 μm; b) closed die coining process, 80 μm.

3 Results and discussion

All data of selected coins after exposure were analyzed in software package ImageJ where 3D display techniques of image data were used, Figures 5, 6. It is important to emphasize that selectable modes for displaying surface plots are set at the same level. For all coins, the exposure was conducted on the same imaging plate to eliminate any systematic parameters affect. Seeing the Interactive 3D Surface Plot of the computer radiography (CRT) digital radiographic for open die coin images, where the luminance of an image is interpreted as height for the plot, it is obvious that the part of coin colored in the red absorbed a higher level of -ray energy and its die cavity filling is better, Figure 7. Hence, better die filling is obtained with smaller grain size. For the case of closed die coining, the Interactive 3D Surface Plot of the computer radiography (CRT) digital radiographic coin images are created, *Figure 8*.

From the comparison of the results it can be seen that better die filling is obtained in case of open die coining, Figures 7, 8. This result can be explained by the fact that in open die coining material can freely flow in radial direction and deformation occurs through whole workpiece while in case of closed die material is confronted by the tool from all sides and deformation occurs mainly at the surface layer of the workpiece. Hence, reduced degree of deformation in closed die coining can be attributed to the reduced number of available slip systems which adversely affects the die filling.

For more detailed analysis of the cavity filling in case of closed die coining, in addition to a visual 2D representation (), pixel values can be related with coin height, Figure 8. For this purpose, a software package Isee! was used where the ROI (Region of Interest) is selected on 16-bit grayscale tagged image file format (TIFF) image format for closed die coining process[35], Figure 6. The selected Region of Interest is a line of pixels named "profiler" as it is presenting pixel grayscale values along the selected line. The grayscale value is located on the graphs ordinate, *Figure 9*a, b. Each pixel along the Region of Interest line is given on the abscissa of the graphs. Graphs indicate the minimum and maximum numerical pixel greyscale values along a selected Region of Interest, also presenting mean and standard deviation value.

From the comparison of the results, it can be noticed that more pixels with a lower pixel grayscale value are obtained on a coin with a grain size of 80 µm which represents a coin area with higher height and better die cavity filling, Figure 9a, b. Meanwhile, on the coin with a grain size of 34 µm, there are more pixels with higher pixel grayscale value which means that the area of coin absorbed less x-ray energy due to the lower height of coin causing worse die cavity filling. It should be also emphasized that the difference between standard deviations of two Region of Interest lines is of the same amount i.e. the difference between mean values is approximately two standard deviations.

4 Conclusion

In this study, the die filling in the coining process was investigated with respect to various workpiece grain sizes (34 µm and 80 µm) and material flow conditions (open die and closed die coining). Since die cavity of complex geometry is used which consists of fine surface details of very small dimensions, this process enters the micro-forming field. This leads to a specific behavior of a material and it is dependent on the part feature size and crystalline grain size. Radiography testing procedures were used for determination of die filling. Results from radiography testing showed that

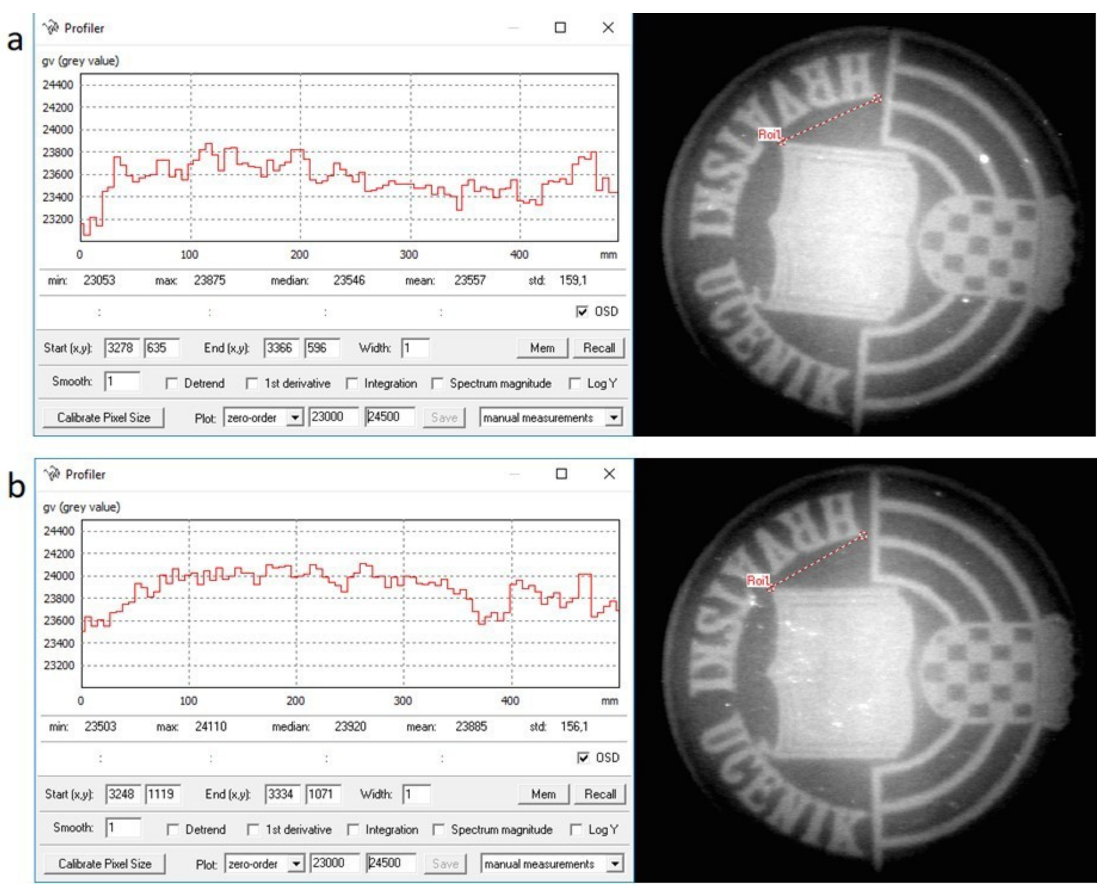

Figure 9. Location of the ROI at the coins with a corresponding display of pixel grayscale values: a) closed die coining process, 34 µm; b) closed die coining process, 80 µm.

in both cases, better die cavity filling is obtained in case of smaller grain size, which is contrary to the expected based on conventional forming processes. At the same time, for the same level of forging force, slightly better die cavity filling is obtained in case of open die coining process. Further researches should be focused on investigations of various geometries of the die cavity and different workpiece materials.

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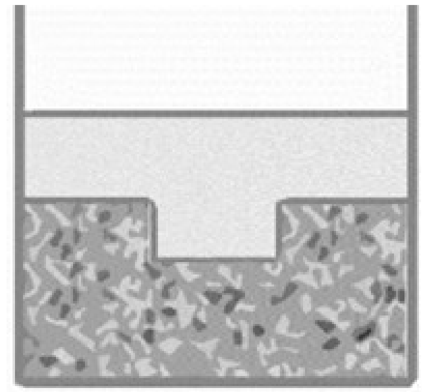
ARTICLES

Coining process can be identified as microforming. Size effect defines all micro-forming processes and influences the cavity filling process. Its influence is changing in open and closed die case, with different grain sizes. Radiography testing procedures are applied for observing the specific points of die cavity, characterized with very small dimensions (less than 0.5 mm).



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