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DEVELOPMENT OF A METHOD FOR TOOL WEAR ANALYSIS USING 3D SCANNING

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Abstract

The paper deals with evaluation of a 3D scanning method elaborated by the authors, by applying it to the analysis of the wear of forging tools. The 3D scanning method in the first place consists in the application of scanning to the analysis of changes in geometry of a forging tool by way of comparing the images of a worn tool with a CAD model or an image of a new tool. The method was evaluated in the context of the important measurement problems resulting from the extreme conditions present during the industrial hot forging processes. The method was used to evaluate wear of tools with an increasing wear degree, which made it possible to determine the wear characteristics in a function of the number of produced forgings. The following stage was the use it for a direct control of the quality and geometry changes of forging tools (without their disassembly) by way of a direct measurement of the geometry of periodically collected forgings (indirect method based on forgings). The final part of the study points to the advantages and disadvantages of the elaborated method as well as the potential directions of its further development.

Keywords: 3D scanning, measurements and volumetric analysis of tools wear, improve a durability of forging tools.

1. Introduction

The basis for the development of industry is the continuous improvement of products and their quality with simultaneous reduction of the production costs, which is indirectly associated with reducing the measurement time during very complicated measurement procedures. In the industrial coordinate metrology, new trends are observed, connected with the use of non-contact measurement techniques. It is possible owing to the continuous improvement of measurement techniques and introduction of new devices and measurement methods, such as fast scanning methods combined with CAD/CAM/FEM [9, 14, 18, 22, 27, 28]. It creates the necessity of applying numerical 3D models to the determination of nominal values during measurements. It is connected with the modern dimensional ISO GPS approach as well as with the integration of software for measurement appliances with numerical CAD models [15, 26, 28]. Additionally, due to the simplicity of their application and improvement of their measurement accuracy, mobile devices are objects of increasing interest of the industry. In reply to the market demand, one can observe continuous improving the measurement accuracy of industrial optical scanners as well as linear laser scanners, which, together with their mobility, significantly increases their competitiveness compared with the classic CMMs (*Coordinate Measuring Machines*) [2, 4, 12, 18, 32–35]. This is connected with the more and more frequent use of blue light sources instead of red light ones, which largely affects the measurement accuracy and – in the case of optical scanners - makes it possible to partly eliminate the necessity of detail matting. The more and more commonly used mobile devices include different types of optical scanners and measuring arms equipped with linear laser scanners with dedicated specialized software which, owing to their mobility and versatility, are an alternative for the coordinate measurement machines

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in applications requiring lower accuracy [23]. For example, the accuracy of a mobile measuring arm was discussed in [29], whose authors performed tests consisting in evaluation of a representation of the nominal shape by means of an arm and a coordinate machine. The 3D scanning technique, also with the use of scanners, is mainly applied to the control of final quality of a product [30]. These measurements are usually based on evaluation of the form deviations of a selected contour and surface [16]. In many works much space is devoted to the use of CMMs and scanning methods to volumetric wear assessment of retrieved prostheses or bones [2, 3, 17, 19, 20, 25]. The available literature more and more often provides information on the application of this type of methods to the measurement, control and evaluation of the state of shaping tools. An example of such application of the 3D scanning method is the use of an optical scanner for determination of the form deviations of a selected surface and next, based on the obtained data, determination of the geometrical specification for the process of rebuilding [1, 24]. Another application of the 3D scanning methods with the use of scanners is the analysis of the form deviations of a selected surface to evaluate the wear of forging tools which are nitride covered or coated with hybrid layers. These analyses consist in comparison of the image obtained from scanning of a new forging tool before operation − with a reference CAD model and − next – with the image of the same tool after the forging, by way of determining the form deviations of the analysed surface [6, 7].

So far, it has been possible to find in the literature data concerning the use of 3D scanning methods only for analysis of the geometrical changes of a product (forgings) and possibly for the control of new tools, rather than for evaluation of states of the tools producing a given product or other applications of this type [13, 21]. This interest induces an analysis of scanning techniques regarding the possibility of their use and development in the forging industry, *e.g.* for analysis of the geometrical changes of tools during the forging process as well as for continuous evaluation of a forging tool based on periodically collected and scanned forgings, and more and more advanced analyses and applications.

The aim of the study is the elaboration and development of a non-contact measurement method – 3D scanning – for the analysis and evaluation of the wear of forging tools with the use of a measuring arm integrated with a linear laser scanner.

2. Measuring method and test bench description

In order to apply a non-contact method of scanning tools and forgings during the forging process, a ROMER Absolute ARM 7520si measuring arm was selected, together with an RS3 scanner (Fig. 1) and Polyworks software enabling to perform scanning in the Real-Time Quality Meshing technology.

Fig. 1. A Romer Absolute 7520si measuring arm.

The selected arm makes it possible to perform contact measurements with the use of a contact measuring probe as well as non-contact measurements with the use of a linear laser scanner RS3 integrated with the arm.

The arm with the integrated scanner RS3 and the Real-Time Quality Meshing technology makes it possible to collect up to 460 000 points/s for 4600 points on the line with a linear frequency of 100 Hz, with a scanning system accuracy SI 0.058 mm in relation to B89.4.2. In order to perform the measurements, for the purposes of the elaborated measurement technology, laboratory test benches were constructed in a measuring laboratory, presented in Fig. 2.

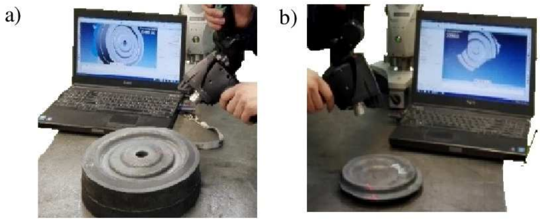

Fig. 2. The test bench for measurements with the use of a ROMER Absolute Arm 7520si measuring arm and an integrated laser scanner RS3, of: a die (a); a forging (b).

The test in relation to B89.4.2. consists in measuring a mat grey sphere by means of 5 different arm deviations. In each arm deviation, the sphere is scanned from 5 different directions, so that most of the sphere surface can be scanned. The result is the maximal 3D distance between the centre and the centres of 5 spheres. An error value obtained in this way is difficult to interpret in our measurement task.

Therefore, it was decided to perform additional accuracy tests that indicated the need to implement a software package – REAL-TIME QUALITY MESHING. This enables to eliminate defects of the linear scanner that are a result of the speed of movement and the position of the measuring head on the measurement accuracy. In the case when the scanning procedure is executed too fast or incorrectly, the model in the program shows unfilled “holes” or special coloured markers controlling the quality parameters of the scan. Such an approach to scanning with the use of a linear scanner, together with the application of the REAL-TIME QUALITY MESHING function, makes it possible to obtain a scan image with similar selected quality parameters.

The measurements with the use of non-contact measurement techniques, also with the application of the measuring arm with an integrated laser scanner, in the case of forging applications, are usually used for two types of objects: forgings and ready forged products, as well as forging tools and instrumentation. In the case of mobile measuring devices (measuring arms and scanners), much more popular are the measurements of forging instrumentation, owing to their mobility and capability of measuring large sized, heavy dies, often directly on the production line.

3. Description of technology

Based on numerous studies and the authors’ experience, the development and evaluation of a 3D scanning method (with the use of non-contact techniques) for forging applications were presented, referring mainly to the measurements of the wear progress of forging tools. Fig. 3 shows a block diagram of the proposed method.

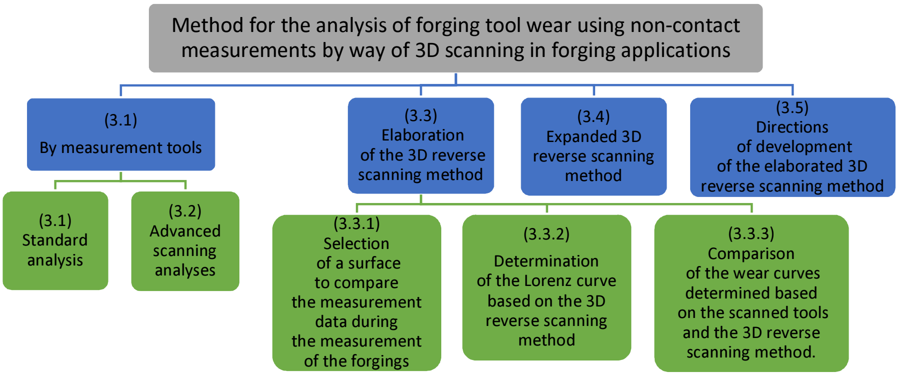

Fig. 3. A block diagram of evaluation of the method of forging tool wear analysis.

The proposed technology of evaluating tool wear based on the diagram presented in Fig. 3 is accomplished in the following stages:

3.1 Standard analysis. Performing a simple analysis of the material loss at the end of a tool's work in order to determine the general (typical) wear of its working surfaces.

- **3.1.1** Selection of reference surfaces for data equalization by the best-fit method.
- **3.1.2** Comparison of tools' images after operation (forging) with either the image of a new (unworn) tool or a CAD model (in the case of difficulty in scanning a new tool, *e.g.* due to deep working patterns).

3.2 Advanced scanning analyses, *e.g.* of the tool wear progress during forging. Determination of the Lorenz curve.

3.3 Elaboration of a 3D reverse scanning method. Analysis of tool wear (material loss) based on periodically collected forgings and measurement of the changes in their surfaces (material growth)

- **3.3.1** Selection of a surface of minor wear from the forging pattern to compare the measurement data during the measurement of the forgings.
- **3.3.2** Determination of the Lorenz curve based on the 3D reverse scanning method.
- **3.3.3** Comparison of the wear curves determined based on the scanned tools and the 3D reverse scanning method.

3.4 Expanded 3D reverse scanning method. Division of the tool into selected areas, according to the occurrence of different degradation mechanisms in these areas.

- **3.4.1** Limitations of the method (temperature, scale, different closings)

3.5 Directions of future development of the elaborated 3D reverse scanning method.

3.1. Standard analysis

The most commonly applied method of analysis by way of scanning is the standard analysis of the material at the end of the tool's work in order to determine the image of degradation of the working tool surface, typical for a given type of insert. The die insert wear is analysed using the data obtained from the measurements made by way of scanning the die before and after the operation, on the test bench shown in Fig. 2a. The data are compared by the GOM software with the function of best-fit data equalization.

The result of the analysis performed with the GOM software is a coloured map of deviations distributed on the scan surface, showing the value of the form deviation from the nominal dimension, that is the scan of the die before the forging process. The measurement results are presented in Fig. 4. Sometimes, in order to perform a simple and fast process analysis, especially for axis-symmetrical tools, visualization of wear is applied on a selected tool section, with an additionally introduced scale of magnitude of the form deviation, *e.g.* 10 times (Fig. 4b).

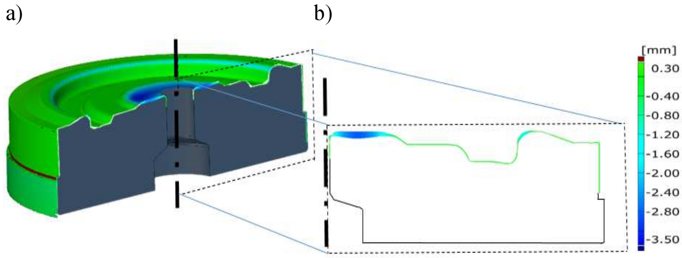

Fig. 4. An example of analysis results: a map of deviations for a die insert (a); scanning results for a selected longitudinal die section (b).

Figure 4 shows a symmetrical ring-shaped wear of the insert in its central part. In this area, radial grooves are visible on the deep ring; the maximal value of wear of this surface equals 3.17 mm. In turn, in the insert bridge area, asymmetrical ring-shaped wear can be seen, with the maximal value of 2.23 mm. No geometrical loss in the other areas is visible in the scan image.

3.1.1. Selection of reference surface for data comparison by best-fit method

A very important aspect is the selection of reference surfaces for data equalization by the best-fit method, in order to minimize errors during the analysis (Fig. 5). It is a crucial aspect in light of the applied mathematical algorithm and the analysis of details concerning the form deviation of a determined surface, often even at a level of a few millimetres, similarly to the case of tools used for preliminary forging operations. The authors' experience, confirmed by the studies, points to the surfaces not participating in the forging process as the ones most often selected for a reference. It should be noted that such an ideal solution is possible only in selected applications.

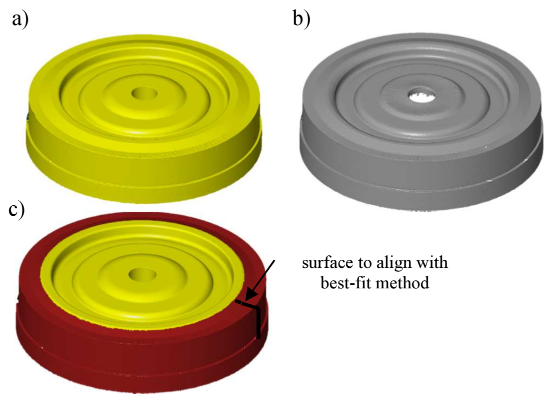

Fig. 5. An insert scan before forging (a) after forging (b) elements selected for the best-fit align with GOM software from the insert scan before forging (c).

For the tool shown in Fig. 4, such a surface is the area marked in red (Fig. 5c), for which it was established that, even with a very big number of forgings, its wear is scant due to their not taking part in the forging process. In the case when it is difficult to find or point to such surfaces which would be ideal for the equalization process, there are selected those tool surfaces for which the wear in the forging process is scant. Of course, at times, the situation is much more complicated, as in the case of a punch-tool used in the second, upper operation of forging a lid (Fig. 6).

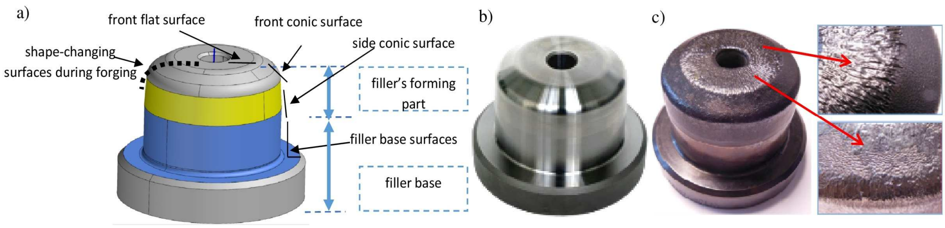

Fig. 6. A functional division of the punch surface with marked surfaces, which change their shape during forging (a); new tool (b); worn punch with with enlarged areas of wear (c).

The analysed filler can be divided into a shaping part and a base (Fig. 6). The base of the filler is responsible for the basing of the surfaces shaping the forging in respect of the other part of the assembled forging tool. The surfaces shaping the forging belonging to the moulding part of the filler (flat front, conical front, conical side) change the geometrical shape together with the number of produced forgings and are responsible for assuring the geometrical characteristics of a final product of the forging process in the second operation. The authors of the study [5] performed a thorough analysis of various variants of reference surfaces, which made it possible to obtain the highest convergence of wear results based on the analysis of the tool scans.

3.1.2. Comparison of tools after work (forging) with either image of new (unworn) tool or its CAD model

In the case of tools with "flat" and convex working surfaces, such as the ones shown in Figs. 4–6, the wear analysis is performed by way of comparing two scan images obtained for a new tool (before work) and a worn tool (after work). In the case when the forging tools, *e.g.* extrusion dies, have deep impressions, it is impossible to measure them before their work. Then, a worn tool after its work is cut into two parts, and its scan image is compared with its CAD model. An example of such analysis can be a die used in the second operation of a multi-operation process of forging a constant velocity joint boot (Fig. 7).

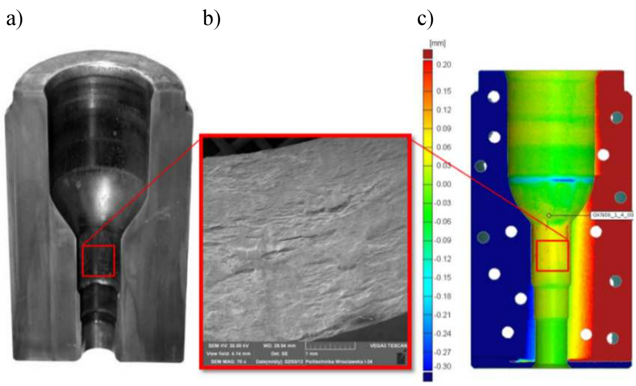

Fig. 7. Wear analysis of a tool with a deep working cavity – a die used to forge a CVJB: a view of the working surfaces of the cut die after work (a); a micro-area with adhesive wear (b); a scan image of the working surface (c) [8].

3.2. Advanced wear analysis

The use of a mobile measuring arm equipped with a scanner can be much more advanced, *e.g.* in the evaluation of changes in the working surfaces of a forging tool as well as progress of its wear. The authors performed measurements of wear of a selected forging tool after an increasing number of produced forgings, by comparing the obtained scan images of many worn tools with the scan image of a new tool (Fig. 8). The presented results of superimposing the images of the worn tools (after an increasing number of produced forgings) point to a progressive wear. In the initial period, for inserts after a small number of forgings, up to 1850 items, practically no material loss is visible. In turn, from 2500 forgings up, we can observe a clear wear in the central part and an increasing wear on the tool bridge. For an insert after producing 12500 forgings, the loss at the front equals to over 1.8 mm, and on the bridge – to about 1.6 mm. It can be seen that, for most of the tools, the wear at the insert front is clearly asymmetrical, while a more uniform wear can be observed on the bridge.

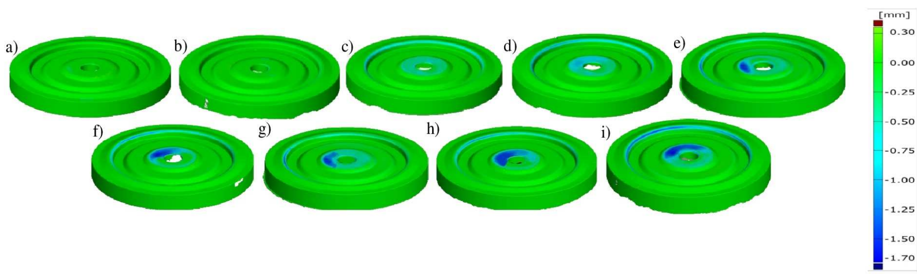

Fig. 8. Results of tool scanning after different numbers of produced forgings: 550 (a); 1850 (b); 2500 (c); 4300 (d); 5000 (e); 6900 (f); 9500 (g); 11000 (h); 12500 (i).

The analysis presented in Fig. 8 can turn out insufficient, and so, based on the collected scan images of a tool that produced an increasing number of forgings, one can elaborate the wear characteristic for this tool in a function of the increasing number of forgings, from 0 to 12500 items. Based on the presented diagram (Fig. 9), resembling the classic (Lorenz) wear curve, one can observe interesting relations and differentiate between scopes (periods) of wear. The presented analysis refers to the volumetric loss from all the working surfaces of selected tools, which can cause certain differences between particular scan images from Fig. 8.

We can see in the diagram (Fig. 9) that the material loss for a selected tool-die insert, based on the scan image analysis, increases very rapidly at the beginning of the forging process to up to about 2000 forgings (period I). This is connected with the adjustment of the whole system, in which we observe a transformation of the initial state of surface layers of co-acting elements of the tool with the forging into the optimal state. However, based on the mathematical analysis of the diagram itself, it can be stated that period I extends to up to 5000 forgings. In turn, on the basis of our own studies, we established that, from about 2000 forgings up, in most die forging processes, almost all types of degradation mechanisms begin to occur (abrasive wear, thermal and thermo-mechanical wear, plastic deformation, fatigue cracking). The intensity of these mechanisms depends mainly on: pressures, a contact time, temperature, a path of friction, the number of forgings, *etc*., and these directly translate to a given area in the tool [8, 10, 13].

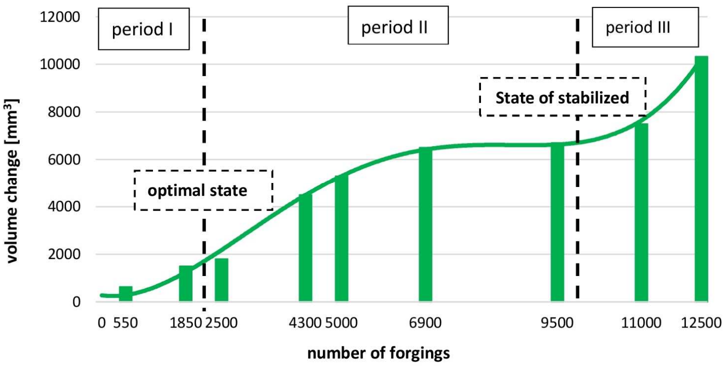

Fig. 9. A material loss (volume changes) from dies in a function of the number of forgings.

The performed research showed that, if a working surface is divided into smaller areas, characteristic for a given mechanism, the interpretation of particular wear diagrams will be identical with the mathematical one.

After reaching the optimal state, that is for over 3000 items, a so-called state of normal operation begins (period II), characterized by an approximately stabilized level of intensity of the mentioned degradation phenomena, which, in the analysed case, reaches the number of about 9500 items. A change in the volume for this scope of forgings equals from 3000 to 6200 mm^3, whereas, for the number of 9500 items up to the end of the tool's operation (over 12000 items), the volume change equals to as much as 4000 mm^3. On this basis we can conclude that the state of stabilized wear can be assumed to be for 3000−9500 forgings, which we can establish as the beginning of wear period III. This state, for the analysed tool, occurs to up to the maximal wear, that is to 12000 items, and ends at the moment when the acceptable change in the tool shape is exceeded, causing its removal from further production. A similar situation takes place for the classic Lorenz curve, which, close to the end of the normal operation period, usually transforms into the state of accelerated wear. It should be emphasized that the shape of the wear curve can differ in the case of other tools, which has been confirmed by the authors' studies, presented in [11].

3.3. Elaboration of 3D reverse scanning method

The following stage of the development of methods of tool wear analysis will be the construction of wear characteristics without the necessity of intervention into the executed forging process.

In this case, the 3D scanning method was used for an indirect control of the quality and geometry changes of forging tools (without the necessity of their disassembly) by way of a direct measurement of the geometrical changes of periodically collected forgings. On this basis, precise wear characteristics are constructed, whose result is comparable with the curve obtained based on the tool scans. The essence of the elaborated technology of die wear evaluation is the use of the changes in the forging shape which occur as a result of the die's wear during the forging process. To that end, the authors used the observed similarity (reflections) of the tool's working surface on a selected forging surface, in which the material loss of the tool is equal to the material growth on the forging. Fig. 10 shows the surface of a die before and after operation, together with the corresponding surfaces of the produced forgings. Fig. 11 shows the measured values of loss on the tool and their corresponding material allowances present on the analysed forging. The presented idea of reverse scanning uses the reflection of changes in the tool on the selected forging surface.

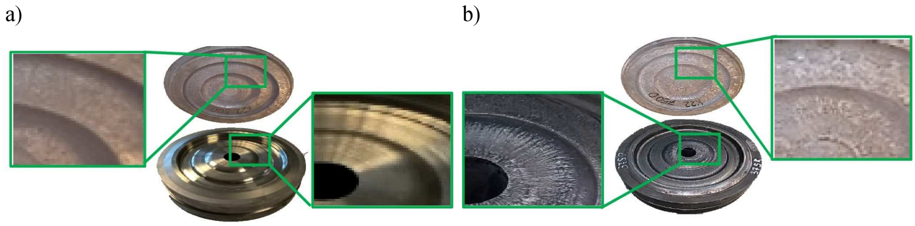

Fig. 10. An example of die insert: new – before work, together with the forging from the beginning of operation (500 items) (a); worn out – after producing 7 500 forgings, together with the forging from the end of the tool's operation (b).

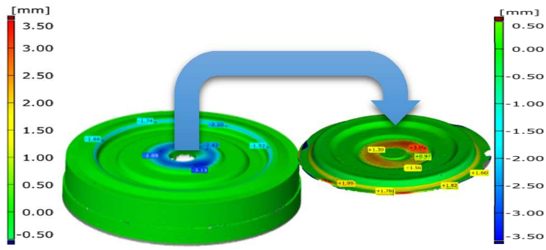

Fig. 11. A diagram of the proposed method of 3D scanning. Comparison of the scan images of a die and the last forging in the form of a shape change of a selected surface.

The elaborated method consists in applying a scanner to measure the proceeding wear of a selected forging tool (in the form of its material loss) based on the shape changes of periodically collected forgings (in the form of material growth of the forging) (Fig. 11).

3.3.1. Surface selection for measurement data equalization during measurements of forgings

In order to analyse the wear based on the periodically collected forgings, it is necessary to measure successive forgings on the measuring bench shown in Fig. 2b, or directly on the production line.

The results of analysis of typical material loss at the end of the tool's operation make it possible to determine the surfaces where the wear is scant in the forging's impression. The determination of these surfaces on a die insert makes it possible to point to the surfaces for measurement data equalization in order to perform the dimensional analysis of the forgings. The effect of proper determination of such a surface was discussed by the authors in the studies [5]. Fig. 12 shows selected surfaces where the tool wear is scant. They are necessary for a proper comparison of the measurement data in the forgings' analysis performed in the following stage of the elaborated measurement technology.

In the case of analysing the wear of the forgings, the scanned data are compared by means of the POLYWORKS software, with the use of the best-fit data equalization. In this process, as the reference surfaces, surfaces of the 100th forging were selected (Fig. 13a), which are formed in the die forging process on surfaces of the die with minor wear. In the considered cases, for the forging, it is the geometry shown in Fig. 13b. Fig. 13d shows a result of comparison of the scan images of the 12 000th (Fig. 13c) and the 100th forgings (Fig. 13a), using a reference for the best-fit equalization shown in Fig. 13b.

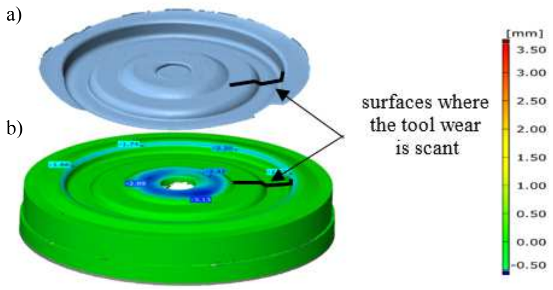

Fig. 12. An example of analysis results in the form of a map of deviations for a die insert with marked surfaces selected for the basing of forgings on the die (a); on the forging (b).

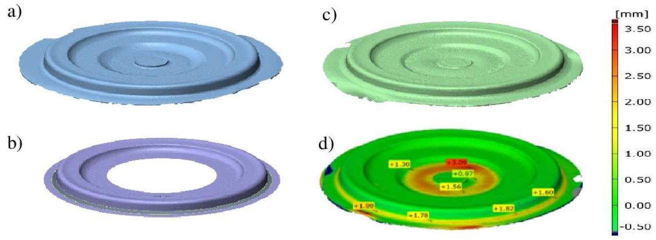

Fig. 13. A scan image of the 100th forging (a); a reference for best-fit equalization, for periodically collected forgings in the form of elements selected from the scan image of the 100th forging (b); a scan image of the 12 000th forging (c); a result of comparison of the 12 000th and the 100th forgings (d).

The result of comparison (Fig. 13d) is a coloured map of deviations distributed on the surface of the forging's scan image, showing the deviation value of error of the selected surface from the nominal dimension, which was the scan image of the 100th forging.

The result of measurements in the 3D scanning technology is a cloud of points. Next, on its basis, using the program, the polygonal surface was calculated, which consisted of triangle elements, reflecting the geometry of the measured object. In order to reconstruct the die wear course, the forgings, selected from the total number of 12 500 items for the selected die, underwent scanning (every 100 and 1000 items).

Figure14 shows scan images of the forgings (every 1000 item) obtained for a die. The results are presented in the form of shape changes of the selected surface in reference to the scan image of the 100th forging, which were obtained according to the measurement technology described above.

The presented results of the die wear analysis in Fig. 14 for an increasing number of forgings point to a proceeding wear of the tool, owing to the use of the reflection of tool image on the surfaces of successive forgings and their comparison with the "unworn" 100th forging.

The wear is located in the central part, in the vicinity of the pusher opening in the front area of the forging and, in the initial stage of the forging process, it is irregular. At the end of the die's durability period, one can see radial grooves on the deep ring (Fig. 14). In the scan images, wear in the area right in front of the bridge can be noticed (vicinity of the flash), in the form of an asymmetrical ring of wear.

The presented results in the form of a deviation in the shape of periodically collected forgings make it possible only to perform a simplified analysis. The latter enables the determination of the die areas where the wear occurs, as well as the areas of the maximal material loss. Such a reconstruction of the wear course makes it possible to perform an analysis at a time interval corresponding with the frequency of collection of forgings.

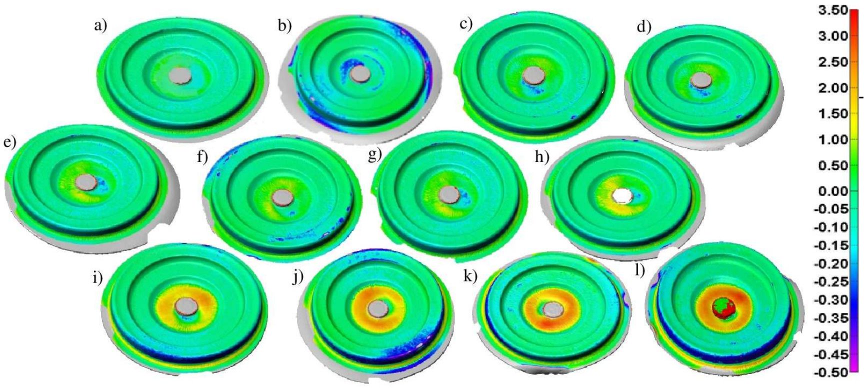

Fig. 14 Comparison of scan images of forgings made in a die, in the form of a shape change in a selected surface, referred to the 100th forging, after: 1000 (a); 2000 (b); 3000 (c); 4000 (d); 5000 (e); 6000 (f); 7000 (g); 8000 (h); 9000 (i); 10000 (j); 11000 (k); 12000 items (l).

The results of measurement by way of scanning of the last forging were compiled with the results of measurement of the die at the end of the forging process (Fig. 15).

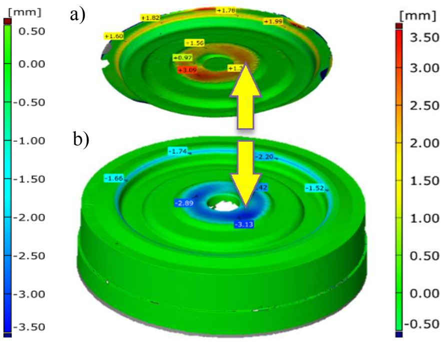

Fig. 15. Compilation of 3D scan results ofthe last forging (a); the die at the end of the forging process (b).

The presented results of the wear analysis calculated based on the analysis of the forging are very similar to the results of a typical analysis of the die wear performed at the end of the forging process. And so, it can be assumed that with the use of the tool change reflection, during the forging process, on the periodically collected forgings, the obtained results are convergent and make it possible to perform an analysis of wear.

3.3.2. Determination of Lorenz curve based on 3D reverse scanning

An expansion of the method of forging tool wear analysis based on a forging measurement is an analysis which uses the volumetric change occurring during the process of die wear. Such an approach enables a global and thorough description of the phenomenon of material loss during the forging process by way of measuring the systematically collected samples.

In order to determine a diagram describing the dependence of the volumetric wear on the number of produced forgings during the forging process, it is necessary to calculate the volume change in the forging areas selected at an earlier stage, marked with circles in Fig. 16.

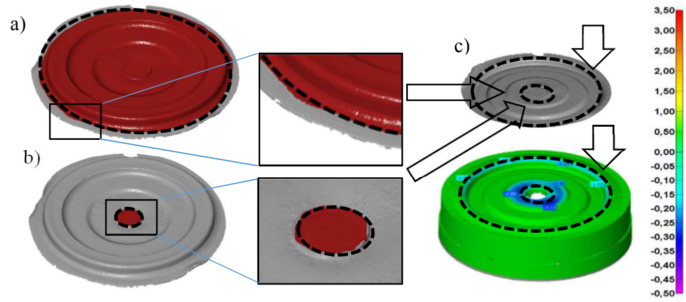

Fig. 16. An example of volume measurements in the areas determined by circles the total volume for the area (a); the core volume for the area (b); a schematic diagram of the volume measurement (c).

During the measurement, an algorithm is applied, consisting in measuring the volume in the areas determined by circles with the use of the POLYWORKS program. The selected software makes it possible to fill the volume between two previously equalized surfaces constructed from scanned triangles generated by means of the Real-Time Quality Meshing technology during the scanning.

The above assumption made it possible to calculate the volumes (Figs. 16a and b), which, when one was subtracted from the other, enabled to determine the desired values of wear in the considered ring-shaped areas of the forging (Fig. 16c).

Based on the volumes determined in the analysis for each periodically collected forging, it is possible to construct a diagram showing the material loss (volume changes) of a worn tool. In this way, it is possible to determine a tool wear curve (Lorenz curve) based on the forgings. Such an approach is a much more practical solution, as it does require neither disruption of the production process nor disassembly of a selected tool after a specific number of forgings.

The reverse scanning method has already been implemented into the industrial forging process of lid forging in the wear analysis of a tool shown in Fig. 6. Details on the implementation of this method are described in the paper [11].

A confirmation of effectiveness of the elaborated method of wear analysis with the use of reverse scanning is, of course, a comparison of both wear curves, determined based on the results of scanning of the worn tools and the periodically collected forgings.

3.3.3. Comparison of Lorenz curve determined based on scanned tools and 3D reverse scanning

Figure 17 shows a comparison of the Lorenz curve determined based on the scanned tools after an increasing operation time (Fig. 8), as well as that based on the method of 3D reverse scanning by way of measurement of the systematically collected forgings (their scan images are shown in Fig. 14).

The comparison, shown in Fig. 17, of both methods of determining the relations describing the tool wear during the forging process (determining their durability), points to a significant convergence. The highest divergences can be observed at the very beginning, that is from 0 to 2500 forgings, as well as in the scope from 4500 to 9500 forgings. Analysis of the curves in the Fig. 17 is similar to those shown in Fig. 9. That is, the stabilized state is obtained earlier than it would look on the basis of mathematical curve analysis.

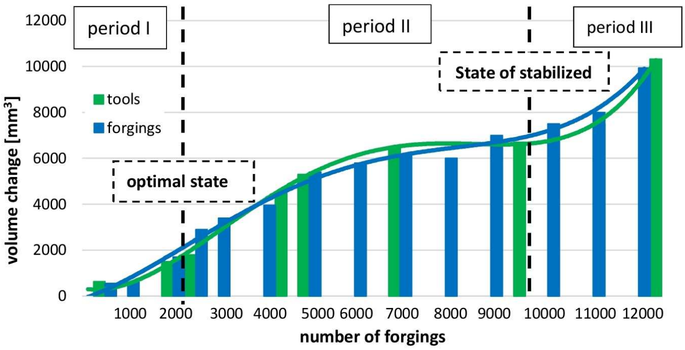

Fig. 17. Comparison of wear curves based on tool (green) and forging (red) scan images in a function of the number of forgings.

The differences in the initial scope probably result from the stabilization of the process (the whole system), that is from the adjustment of a proper temperature of tool operation and optimal conditions of lubrication and cooling (tribological conditions). In turn, the differences in the later period can be explained by the studies performed by the authors, which demonstrated that, for this process, from about 4000–5000 forgings up, one can observe intensification of the destructive mechanisms, which is connected with the detachment of larger particles of the nitride layer and the tool material from the most loaded areas.

Another cause of the small divergences between both curves can be the fact that the forgings for the determination of the Lorenz curve were collected (every 1000 items) from one forging process, for which an average durability is equal to 12 000 forgings, while the tools selected for the determination of wear were collected from a few similar processes, yet after an increasing number of produced forgings. This was dictated by the idea of maintaining similar technological conditions (elimination of the process of cooling the tool for a scan analysis, followed by its heating for the further production process). Also, each tool, after the scan analysis, did not come back to operation, but was cut into samples for further tests, such as: microstructural tests, SEM (Scanning Electron Microscope), micro-hardness measurements, *etc.* Other, less important, causes of the minimal divergences can be a measuring accuracy of the scanner (based on a volumetric performance test according to the standard B89.4.22, its precision is equal to 0.058 mm), as well as the oxidation and scale coating of the measured forgings which were cleaned before the measurement. as Another one can be the errors resulting from the calculation algorithm in the volumetric analysis.

In the case of the presented 3D scanning method (Figs. 9 and 17), the forgings were measured in laboratory conditions with no vibration and constant temperature. The only limitation is the removal of scale from the surface of forgings. The dismantled tools are also scanned in a similar way to the measurement of forgings. So, in this case it is difficult to talk about a significant influence of temperature and vibration (technological break), although the latter are actually present in the production hall. Also, an impact of vibration on the measurement results was not observed during the scanning of tools on the press.

Considering the above, the presented comparison confirms that the determination of wear based on the scanning of the forgings periodically collected during the technological process (without the necessity of their disassembly) is an effective and economically justified method. It should also be emphasized that the determination of wear based on tool scans is an impractical method, generating additional cost and often causing difficulties in maintaining the continuity of production, as well as its disruption and changes in the technological and tribological conditions.

3.4. Expanded 3D reverse scanning method

The presented method of analysing the wear of forging tools can be expanded by a division into additional areas. Such an expansion can be dictated by the necessity of considering different degradation mechanisms. It will also enable to eliminate errors during the total volumetric analysis, occurring in the areas of cracks or excessive local tool wear. The standard use of diagrams of the volume changes occurring during the process of wear in the analysed areas provides additional information. Such an approach enables a comprehensive description of the phenomenon of material loss during the forging process. However, in certain cases, the analysis of the total material loss of a given tool does not provide a full image (Fig. 18). In such special cases, the comparative analyses of a few such tools can contain errors resulting from *e.g.* tool cracking or premature wear of one of the areas, which will distort the calculation results of the material loss volume.

Figure 18a shows an image of a die insert with a division into two selected characteristic areas (A and B), for which, based on the preliminary analysis, the occurrence of different degradation mechanisms was established. Additionally, the performed 3D reverse scanning analysis showed a much faster wear of the forging tool than in area A. In this area, a cross is made in the new tool which plays the role of a marker. As it can be observed in Fig. 19b, the wear in areas A and B is almost identical for up to 2500 forgings. Above this number, the wear intensively increases at the front of the insert (area A), in respect of the wear on the bridge (area B). That is why the performed analysis of the total wear of the insert can be loaded with error resulting from a different intensity of tool wear in different areas of the tool.

In order to perform a precise analysis and create a diagram (Fig. 18) describing the volumetric wear in areas A and B depending on the number of produced forgings, during the forging process, it is necessary to calculate the volume change in the areas selected at the earlier stages. The elaborated measurement technology employs an algorithm consisting in measuring the volume in the areas marked by circles with the use of the POLYWORKS software.

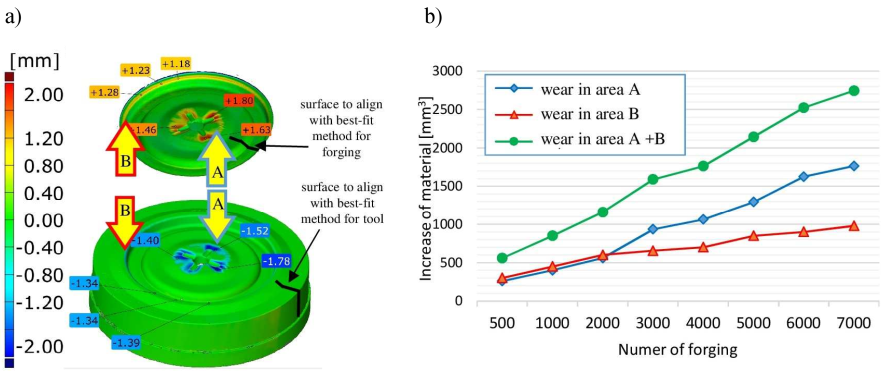

Fig. 18. A method of 3D reverse scanning – division into selected areas (a); wear based on periodically collected forgings (b).

The selected program makes it possible to fill the volume between the two previously levelled surfaces constructed from the scanned triangles generated with the use of the Real-Time Quality Meshing method. To that end, four circles were assumed in the program, two for each of two areas, A and B.

This assumption enabled the calculation of the volumes, which subtracted in pairs, one from the other, made it possible to determine the two desired values of wear in areas A (Figs. 19a and 19b) and B (Figs. 19c and 19d), as well as the total value, that is the sum of A and B.

Based on the calculated volumes for A and B for each analysed, periodically collected, forging, it is possible to construct a diagram presenting the material loss (volume changes), calculated based on the volume changes between the surfaces of the forgings produced on the analysed die, which is shown in Fig. 19b.

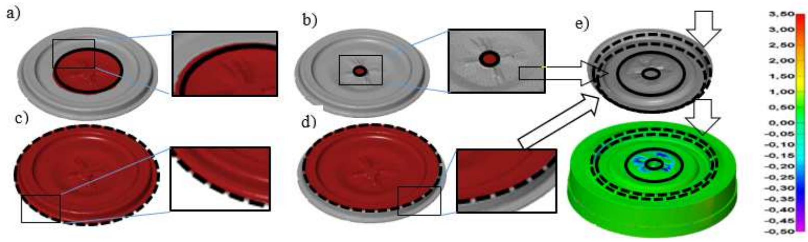

Fig. 19. An example of determining the volume in selected areas: the core volume for area A (a) the total volume for area A (b); the core volume for area B (c); the total volume for area B (d); a schematic diagram of the volume measurement (e).

3.4.1. Pros and cons

The industrial application of the reverse scanning method showed advantages and disadvantages of the elaborated technology. The basic advantage of the 3D reverse scanning method is its practicality in being used in the hard conditions of die forges. For example, Fig. 20 shows the measurement of a relatively large forging of a scraper weighing over 42 kg and a heavy lower die used during forging with a pneumatic hammer MPM 16000 with an impact energy of 171,62 kJ (a mass of the component elements is equal to 5285 kg without the die; a mass of the tool is over 900 kg). In such a case, a fast analysis of the progress of wear of heavy forging dies, based on the measurement of periodically collected forgings, is irreplaceable.

In turn, the main disadvantages of this method are the error resulting from the hindered measurement of a warm forging, which temperature, in extreme cases, is about 150–250ºC and the fact of taking into account the thermal expansion (for the QS1920 steel and this temperature range it is about $1.45 \cdot 10^{-5}$/K). Also, the scale on the surface of forgings, whose thickness, in many cases, is high enough (even over 0.5 mm) to influence the results of both the measurement and the analysis of tool wear based on the forgings. For the 3D scanning method, a verifying measurement of the last forgings – that is the measurement of the tool – is performed during a maintenance shutdown. The working temperature of tools is equal to about 200–250ºC on the surface.

Fig. 20. Measurements of a ”hot” forging of a scraper (the indirect reverse scanning method) and a forging die on a hammer, during a technological break (in order to verify the reverse method).

During the shutdown, the tool is cooled down to about 80°C and cleaned before the measurement. The scanning procedure itself is executed a dozen or so minutes after the press has been put to a stop.

3.5. Directions of development

The use of scanning methods for measurements in the forging industry is at present very extensive. Of course, this development can be considered in two ways. One direction of the development of scanning methods are the measurements of the forgings for the control of their geometry and quality. The other direction is the application of scanning to the analysis of forging tools.

A prospective direction of the development of the reverse scanning method can be the analysis of the tool wear in more than two areas, because, as we know, the shape of the tool will determine the occurrence of various degradation mechanisms in different areas. Fig. 21 shows the areas in the impression of a die, where shape-determined degradation mechanisms occur. As one can notice, abrasive wear will be dominating in the areas where the deformed material intensively moves, filling the die impression. In the areas of stress concentration, that is the ones with small internal radii in the impression, sharp edges *etc*., we will observe mechanical and thermo-mechanical fatigue causing brittle cracking. The areas of a long contact of hot forging material will be characterized by the occurrence of plastic deformations caused by local material tempering as well as thermal fatigue, which will also be present together with abrasive wear in the areas where the hot material flows, thus intensifying the degradation process of the substrate in these areas.

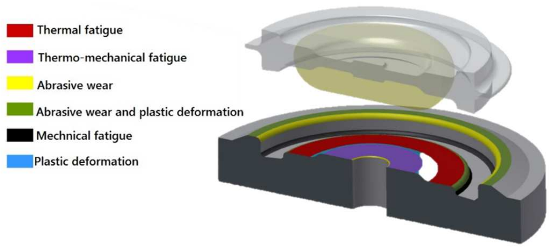

Fig. 21. A diagram illustrating the areas of dominating degradation mechanisms in the impression of a forging die.

Such a detailed analysis of tool wear, in a few or a dozen areas, especially based on the scanning of forgings, provides very valuable information (on the quantitative material loss), which can be used *e.g.* in the construction of a data base in expert systems, which enable the prediction of the forging tool durability [10].

4. Conclusions

At present, in the process of production of forgings, in die forges, different devices and measurement methods are used. The latter include methods applying the universal, classical measurement equipment, ensuring lower measurement accuracy for the control of the key geometrical characteristics in a hot forging, through more complicated measurement techniques using the universal measurement equipment, which, in combination with specially designed tests, makes it possible to fully control the tool quality and properties, of a non-complicated geometry, to measurement methods based on Coordinate Measuring Technique as well as scanning techniques for both forgings and forging tools of a complicated geometrical specification. Also, new trends are being created, which are mainly connected with the possibility of applying portable measurement systems, such as: optical scanners or linear scanners mounted on portable measuring arms. This technology enables effective control of the quality of medium- and large-sized forgings, as well as forging tools of very large sizes, whose measurement takes place directly on the production line.

The methods of 3D scanning and forging tool wear analysis discussed in the study make it possible to perform simple as well as complex and extensive analyses of the wear of forging tools and instrumentation.

The presented results of the studies performed with the use of a measuring arm together with an integrated laser scanner for the analysis of wear, enabled the elaboration of a 3D reverse scanning method based on measurements of the shape changes in the successive forgings (directly on the production line). The performed studies showed the validity of using new, non-contact measurement technologies for a direct and indirect analysis of tool quality and shape changes (without disassembling the instrumentation from the forging aggregate). Owing to the implementation of non-contact measurement methods, the analysis of tool wear has become possible to be performed directly on the production line.

Nevertheless, the presented approach to measurements, assuming the possibility of using more accurate scanning techniques, can be used to analyse tools in plastic moulding, foundry, as well as in the food industry [22, 23, 31].

The analysis of the volume increase of the successive forgings based on the measurements makes it possible to precisely determine the material loss of a forging tool in the successive stages of its performance. This is proved by the full correlation between the results of measurements of the volume changes of an increasing number of produced forgings and those of the tool, which is suggested by the verification of the wear (Lorenz) curves performed in the study.

The innovative approach to evaluation of the current state of a forging tool performed by the authors makes it possible to make decisions about a prolongation or shortening of its operation time, based on the actual (current) wear, rather than based on the fixed durability data (a maximal number of produced forgings). This enables an optimal use of a given tool, preserving the highest quality of produced forgings.

The demonstrated advantages and disadvantages of the proposed approach to analysis of tool wear with the use of 3D scanning certainly make it possible to prolong the operation time of forging instrumentation and significantly lower the production costs.

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