ARCHIVES OF METALLURGY AND MATERIALS
Volume 56 2011 Issue 2
DOI: 10.2478/v10172-011-0059-z

Z. GRONOSTAJSKI*, M. HAWRYLUK*, M. KASZUBA*, A. NIECHAJOWICZ*, S. POLAK*, S. WALCZAK**, D. JABŁOŃSKI**

DIE PROFILE OPTIMIZATION FOR FORGING CONSTANT VELOCITY JOINT CASINGS

OPTYMALIZACJA PROFILI MATRYC DO KUCIA OBUDOWY PRZEGUBÓW HOMOKINETYCZNYCH

This paper presents the results of a search for an optimal shape of the die for forging CVJ (constant velocity joint) casings. The aim of the optimization was to increase tool life by reducing the pressures acting on the die. Therefore the minimization of the forging force was adopted as the optimization criterion. In order to verify the optimization results, the graphs of the calculated forging forces were compared with the real forging force registered by a dedicated measuring & archiving system.

Then new dies with the optimal shape obtained from the numerical modelling were made and used in the industrial forging process. It was found that the maximum forging force values for the optimized dies were by about 10-15% lower than the ones for the dies with the original shape, which indicates an increase in die durability.

Keywords:forging, constant velocity joint, optimization

W pracy przedstawiono wyniki poszukiwania optymalnego kształtu matrycy dla procesu kucia obudowy przegubu homokinetycznego. Optymalizację przeprowadzono pod kątem zwiększenia trwałości narzędzi poprzez zmniejszenie obciążeń na narzędziach. Jako kryterium optymalizacyjne przyjęto minimalizację siły kucia, której wartość zależy między innymi od kształtu matrycy. Następnie wykonano nowe matryce z optymalnym kształtem uzyskanym z modelowania numerycznego i zrealizowano przemysłowy proces kucia dla zoptymalizowanych kształtów. Przeprowadzone badania wykazały, że maksymalne wartości sił kucia w drugiej operacji dla nowych narzędzi są mniejsze o około 10-15% w porównaniu do sił uzyskiwanych dla wcześniejszych kształtów matryc, co z kolei wskazuje na zwiększenie ich trwałości.

1. Introduction

Precision forging is the most popular technology for producing parts from relatively expensive materials [1-4]. Numerical and physical modelling methods contribute to the development of new technologies of forging for manufacturing products with complicated shapes, especially for the automotive industry, e.g. cold forging of gear wheels or constant velocity joint body casing [5-9]. Constant velocity joints (CVJ) are irreplaceable car components. They transmit torque from the gearbox to the front wheels (Figure 1). Their production has been steadily increasing in recent years. A CVJ consists of usually 6 balls, a cage and an inner and outer race – casing (Fig. 1) [10-11].

The main problem in the production of CVJ is correct manufacture of the outer race - casing, particularly because of their irregular shape. Currently precision forging with hot multi-operation forging in closed dies with a complex deformation scheme (forward and backward extrusion) is used in mass production (Fig. 2). In forging process of CVJ casing problem is the low durability of tools [13-14]. Not far ago the most common forging defect was abrasive wear and fracture of die [11].

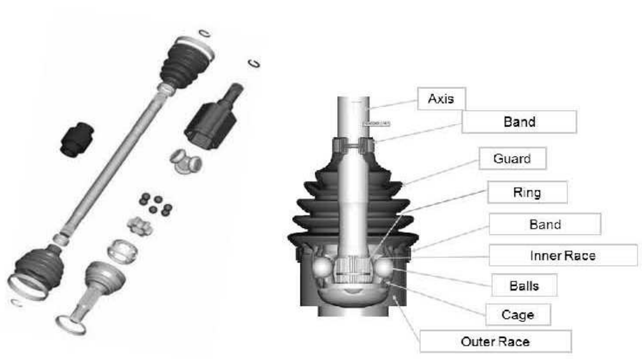


Fig. 1. Constant velocity joints (CVJ) [12]

---

[*] WROCŁAW UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL AND POWER ENGINEERING, 50-371 WROCŁAW, 51 ŁUKASIEWICZA STR., POLAND

[**] GKN DRIVELINE OLEŚNICA, 56-400 OLEŚNICA, 18 POŁUDNIOWA STR., POLAND

Recently the fracture was eliminated due to improve all technology parameters of processes such as temperatures of tools, materials, lubrication etc. and now dies have been destroyed mostly due to abrasive wear. According to literature also the optimization of shape die is very efficient method of improvement the forging processes therefore one can expect further decrease in abrasive wear of the tools for forging CVJ casing by changing the profile of die [15, 16].

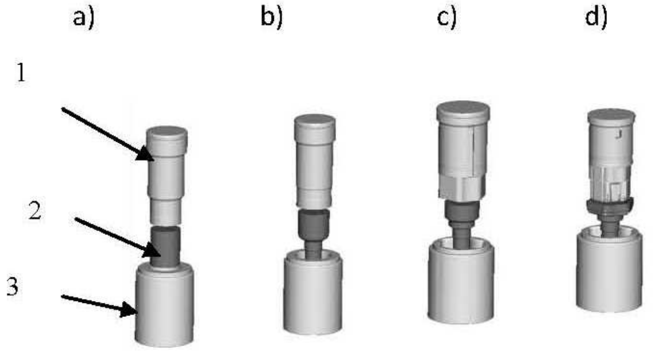


Fig. 2. Schematic of tools used in investigation of successive operations: 1 – punches, 2 – preforms, 3 – dies

As wear proceeds, material is removed from the body's surface whereby its dimensions decrease. The amount of the removed material can be estimated using a wear model. In the literature on the subject, measures of wear are defined relative to: the mass of the material removed from the body, the volume of the removed material or the change in the body's dimensions. The magnitude of wear in the forging process depends on the geometry of the contacting surfaces, the friction path, the contact temperature and the properties of the materials (the oxide film). Because of the complexity of the phenomena involved, the models describing them tend to be simplified [17, 14].

The most commonly used wear model is the Archard model [18]. It belongs to the measures based on the amount of the material removed from the body. According to this model, the abrasive wear of a tool may be due to the disintegration of microroughness on the surfaces of the two contacting bodies. This is mathematically described as follows:

$$V = K\frac{P * s}{H}\left[mm^2\right] \tag{1}$$

where: V – the magnitude of wear (the amount of removed material), P – the normal force, s – the friction path distance, H – the material hardness, K – a constant (a dimensionless wear coefficient).

According to this model, the magnitude of wear is directly proportional to the normal force on the contact surface and the friction path distance and inversely proportional to the material hardness. Dimensionless coefficient K can be determined in different ways depending on the physical model adopted for deriving the equation of wear. Basically, K is a material removal effectiveness for a set amount of work. According to the Archard model, since wear depends mainly on the tool pressures and the latter are directly proportional to the forging force, the minimum force criterion should yield correct results.

Considering that the shortest tool life characterizes the second operation of forging CVJ casing (in which the forging's leg is formed, Fig. 2 b), optimization was done for this operation. The die then suffers the severest wear. This particularly applies to the place in the die where the forging cross section undergoes change (region marked in the Fig. 3).

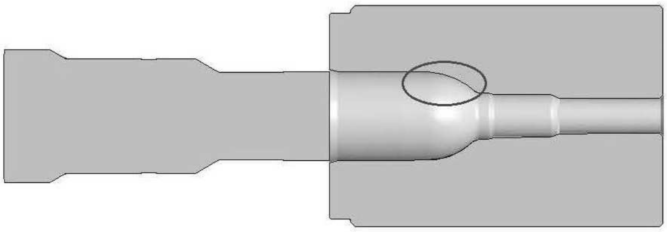


Fig. 3. Place in die where severest wear occurs

Numerical simulations of the multioperation forging of CV joints casing were run using the Simufact.Forming SFM software by Femutec. The computations were done for simplified mechanical models with stiff tools for a constant coefficient (0.2) of friction between the material being deformed and the working surface of the die. The whole simulation is described in [19, 20]

The most simple Hooke-Jeeves optimization method was chosen because the main aim was to improve tools durability of existing forging process, and this method according to literature is the most efficient especially for optimization shape of die in metal forming processes [21].

2. Results

Searching for an optimal die shape it was assumed that the profile of the die working part varies between points P1 and P5 (Fig. 4). The original shape of the die is described by the Bézier curve defined for points W_0, W_1, ..., W_n by the formula:

$$P(t) = B_0^n(t)\,W_0 + B_1^n(t)\,W_1 + \ldots + B_n^n(t)\,W_n \qquad (0 \leqslant t \leqslant 1) \tag{2}$$

Points W_0, W_1, ..., W_n are *control points* for curve P and n is its degree.

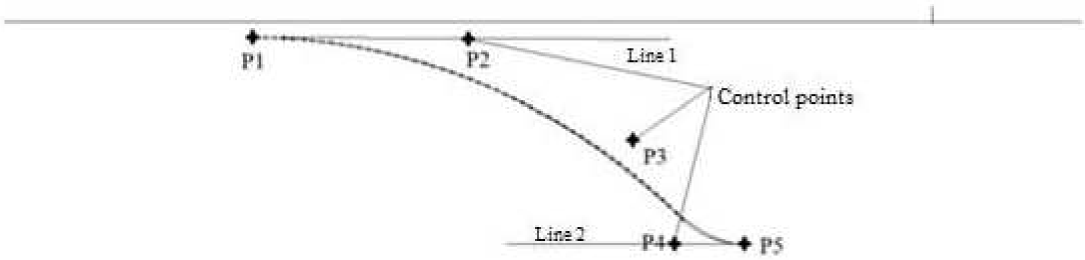


Fig. 4. Profile of analyzed die

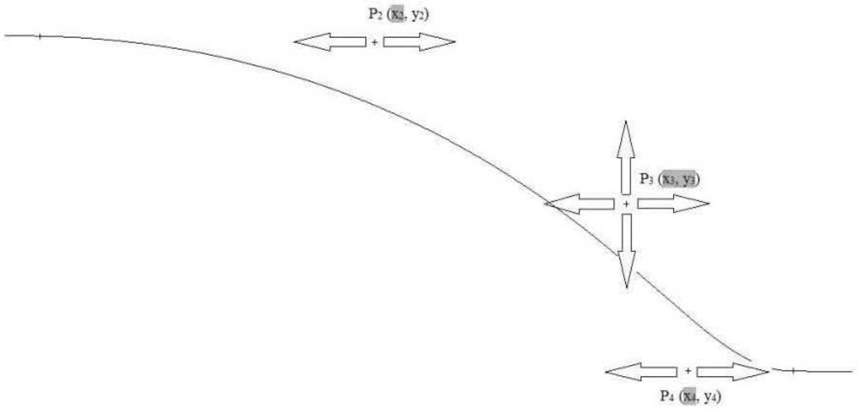


Fig. 5. Bézier curve with marked controlled points

In the formula, $B_k^n(t)\,(\mathbf{k = 0.1}, \ldots, n)$ stands for the k-th Bernstein polynomial of degree n

$$B_k^n(t) = \binom{n}{k} t^k (1-t)^{n-k} \tag{3}$$

and $\binom{n}{k} = (n, k \in N)$ is the so-called Newton symbol,

$$\binom{n}{k} = \frac{n!}{k!\,(n-k)!} \tag{4}$$

where n ! is the product of successive numbers from 1 to n (n= 1,2,.........), and

The objective function is the minimum of forging force.

$$\min \sum_{i=1}^{n} F_i(W_j)$$

Where F_i is the forging force in the ith node, n is numbers of nodes, W_j is Bézier curve parameters.

Only the die's arc part between points P1 and P5 (where reduction in cross section takes place), marked in the Fig. 4, was subjected to topological optimization.

The shape of the Bézier curve is defined by five points: two end points (P1, P5) and three control points (P2, P3, P4). The curve interpolates the two end points and approximates the three control points. When the position of P2, P3, P4 is changed, the shape of the Bézier curve changes, and so does the profile of the die. In order to maintain continuity, points P1 and P5 may not be shifted and moreover, points P2 and P4 may change x-coordinate and P3 x and y – coordinate. For the local coordinate system the coordinates of the points are written as follows: P_1 (x_1, y_1), P_2 (x_2, y_2), P_3 (x_3, y_3), P_4(x_4, y_4), P_5(x_5, y_5)

The optimization variables were: x_2,x_3, y_3,x_4. The directions in which the trial steps were performed in the successive iterations are shown in Fig. 5. In each iteration the step was equal to 1mm in all directions. The point became the new starting point, where value of forging force reached minimum.

In the optimization process, forging force values for 81 iterations were determined in order to find the best solution.

As analyzed by optimizing the shape, obtained a new shape, for which the forces were reduced by about 10-15% (Fig. 6). Figure 6 shows forging force versus punch path distance for respectively the original die shape and the optimized shape.

Under the adopted shaping conditions the optimal die shape shown in Fig. 7 was found in the searched area.

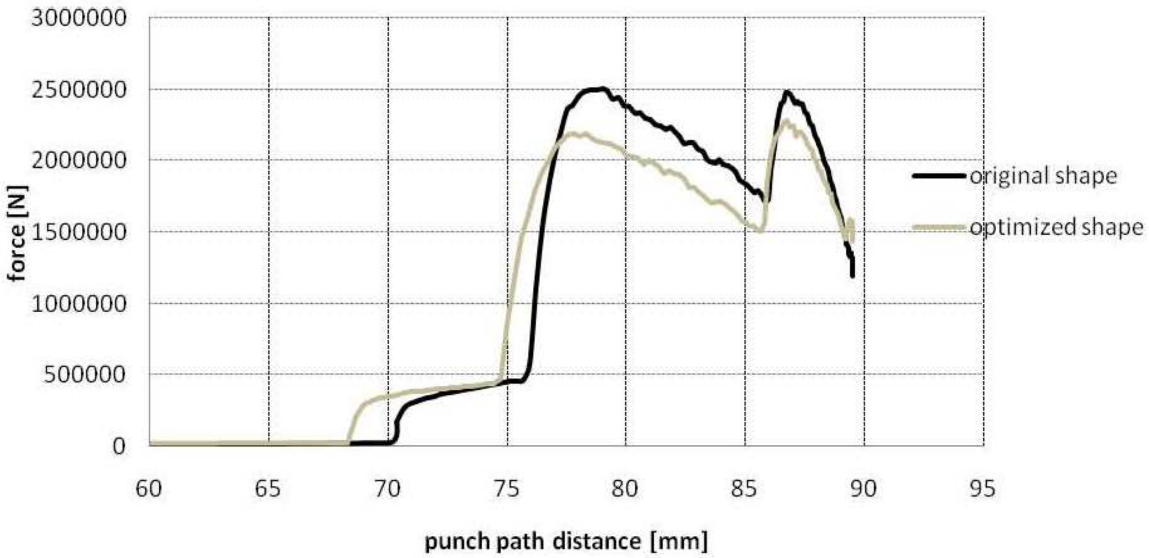


Fig. 6. Forging force versus punch path distance for respectively original die shape and optimized die shape

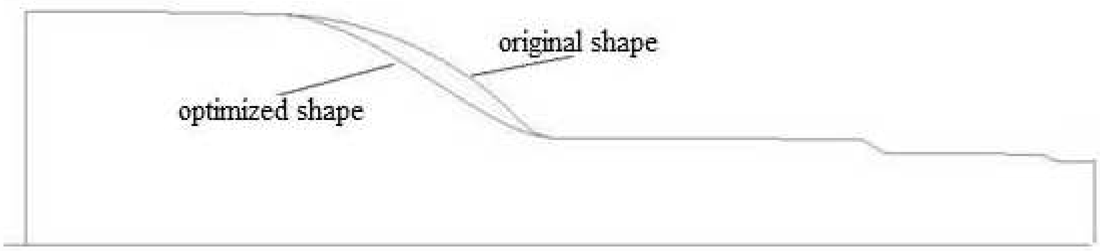
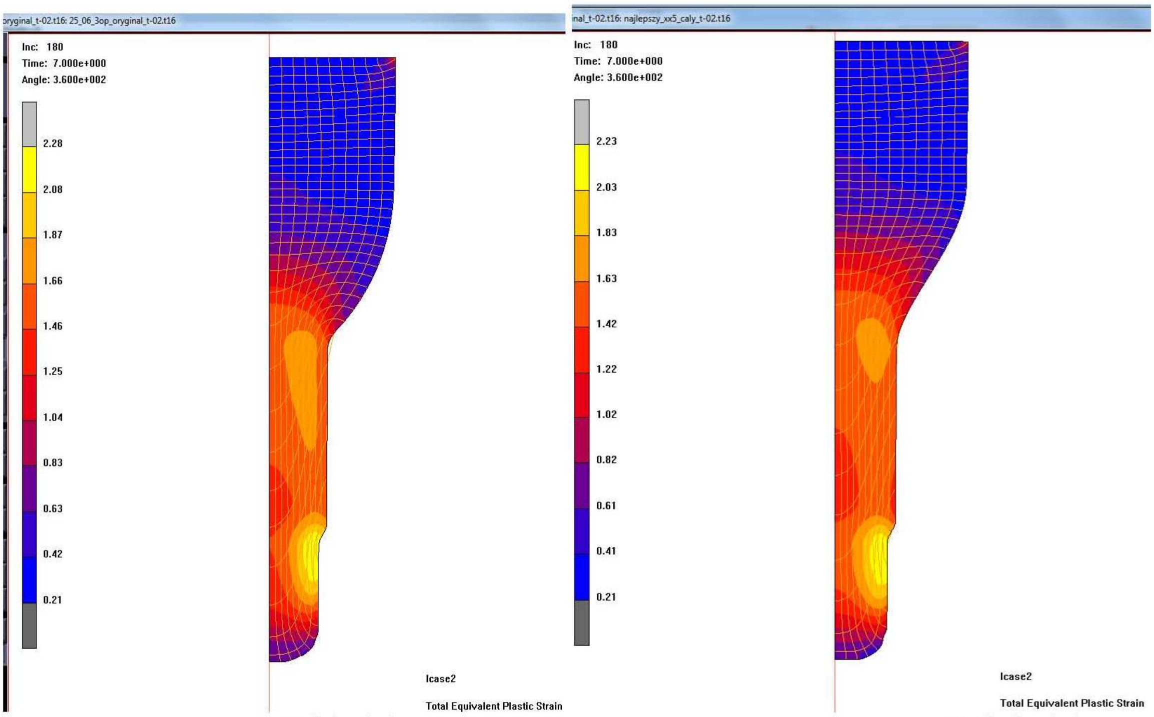


Fig. 7. Comparison of optimized shape with original shape

Figure 8 shows strain distributions obtained from mathematical modelling for respectively the original die and the optimized die. The results indicate that in the case of the optimized die not only lower forming force values (which, according to the Archard model, should result in lower wear intensity), but also more uniform strain distributions (which may significantly improve the quality of the forgings) were obtained. In order to demonstrate the improvement in material flow, radial strain distributions in the forging were determined for the die before and after optimization. The distributions (Fig. 9) corroborated the above results.

Original shape Optimized shape



Original shape

Optimized shape

Fig. 8. Distribution of equivalent plastic strain after 2nd operation

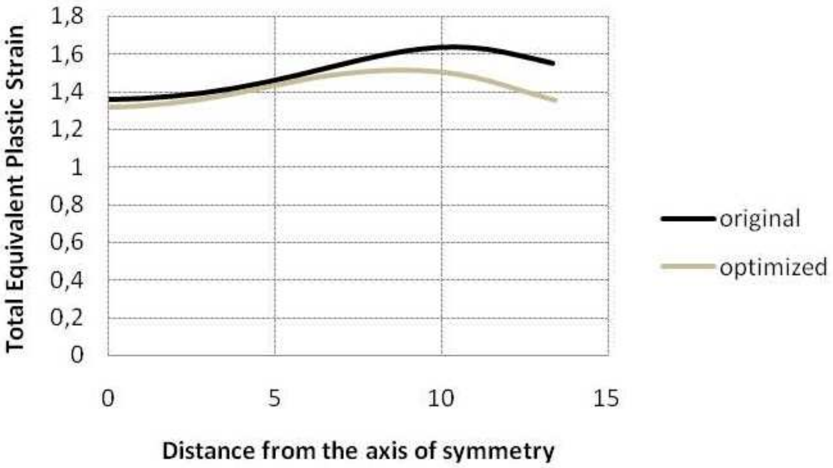


Fig. 9. Radial distribution of strain. Distance from the axis of symmetry

The optimal dies for the second forging operation were made by the firm ISKRA CNS. The tools with the modified inner shape were subjected to industrial testing in the firm GKN in Oleśnica. Since this technology is still at the stage of industrial testing, no production drawings of the tools and only the whole tools are presented here (Fig. 10).

Figure 11 shows the shapes of the forgings after the second operation before and after optimization. As a result of die profile optimization, the forging's transitional section between its head and leg is longer, but this has no effect on the shape of the final product since the difference is eliminated in the next operation.

An industrial process for the new optimized and original tools, together with a measuring & archiving system registering the forging forces in the particular operations was launched. The force versus time traces are shown in Fig. 12.

Fig. 10. Optimized tools for forging CVJ casing

Fig. 11. Shapes of forgings obtained a) after optimization, b) before optimization

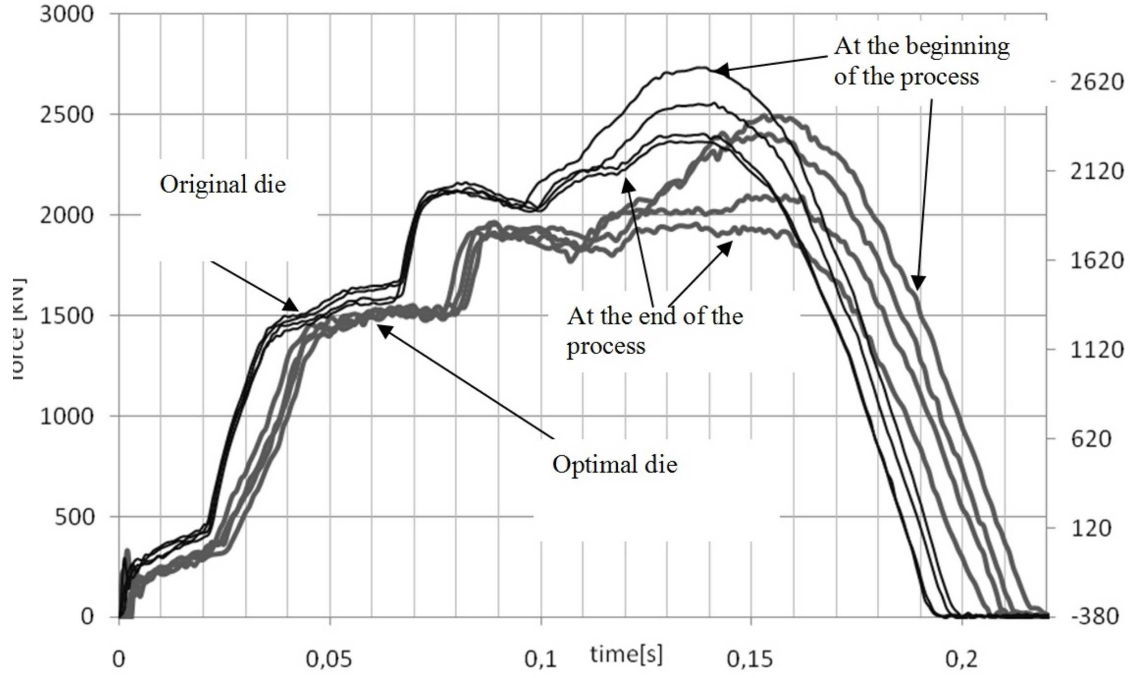


Fig. 12. Force versus time graphs for original die and optimized die in real processes

Initial industrial testing shows that the average production of the forgings by using optimized tools is about 18 000 pieces, it is about 10-15% than for the original tools. In order to confirm this result more industrial testing and statistic analyses is needed because the durability of the tools is very complex phenomenon and depends on many parameters which could be changed during the each shift. The improvement is mainly due to the reduced forming forces. The change in the die profile reduced the force along the whole punch path. It also resulted in the elongation of the working part of the die whereby the local force maxima corresponding to the degrees of reduction are shifted on the force graphs. Consequently, the material deformation time slightly increased, but at a much reduced forming force. The graphs in Fig. 12 show that despite the slightly longer deformation time, no increase in plastic deformation work occurred in the particular work cycles. Fig. 12 also shows the forging forces in the successive forging cycles. At the beginning of the process the forces are much larger than towards its end, which indicates tool wear. The force reductions are much larger for the die with the optimal shape than for the original die. In order to reveal the surfaces of the worn out tools, the latter were cut in half (Fig. 13).

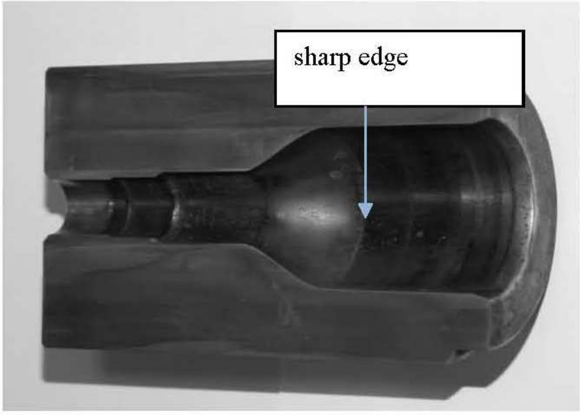
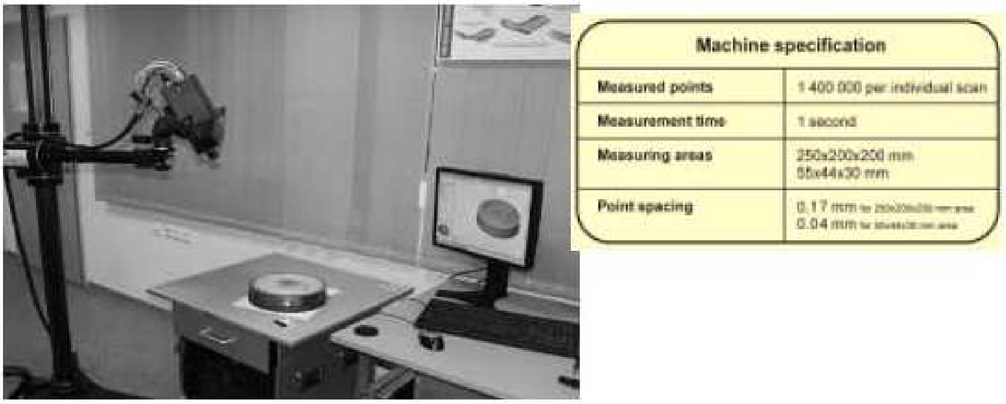


Fig. 13. Cut in half die after forging process

No significant abrasive wear or cracks were found on the tool surface, but a new flaw, i.e. a sharp edge, appeared at the beginning of cross section reduction.

In order to confirm the finding about wear, the tools were scanned by means of an optical scanner GOM ATOS II (Fig. 14). The scanner can be used to scan the whole surface (macroanalysis) or a selected area of the die at a high resolution (microanalysis) and then the obtained image is compared with the image of the tool prior to forging or with the CAD model used to make the tools.

The shape of the scanned die is compared with the CAD model in Fig. 15. One can see there the deviations from the initial dimensions. The determined deviation distributions confirm that the initially observed sharp edge represents the largest wear (about 0.1 mm). Also material adhesion to the forging leg was observed.



Machine specification	
Measured points	1 400 000 per individual scan
Measurement time	1 second
Measuring areas	250x200x200 mm 55x44x30 mm
Point spacing	0.17 mm 0.04 mm

Fig. 14. Optical scanner and its specification

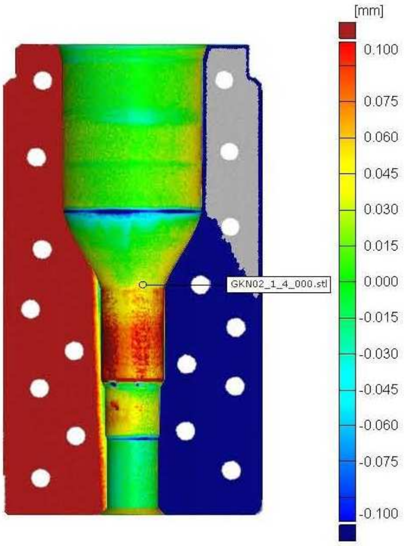


Fig. 15. Comparison of scanned images of post-work dies with pre-work CAD model

3. Conclusion

In spite of improving the durability of tools in closed die forging processes by changing parameters of process, materials of die etc, the final profile of the die should be optimized for example by very convenient method of Hooke-Jeeves.

The optimization of the shape of dies used for the multioperation hot forging of CVJ casings in the firm GKN Driveline forge in Oleśnica has been presented. The second operation of precision forging in the closed die was analyzed using FEM and Bézier curves in order to determine an optimal die profile ensuring a longer tool life by reducing the forging pressures. Therefore the minimization of the forging force (whose strength depends on, among others, the die profile) was adopted as the optimization criterion.

In order to verify the optimization results, the graphs of the calculated forging forces were compared with the forging force traces registered by a dedicated measuring & archiving system.

Then new dies with the optimal shape obtained from the numerical modelling were made and used in the industrial forging process. It was found that the maximum second-operation forging force values for the optimized dies were by about 10-15% lower than the ones for the dies with the original shape, which indicates an increase in die durability.

Acknowledgements

The research is performed within WND-POIG.01.03.01-02-161/09 grant. Project title: „Kompleksowy system ekspertowy do optymalizacji trwałości narzędzi w procesach kucia", under Program Operacyjny Innowacyjna Gospodarka, years 2007-2013. Licences for MARC and ProEngineer software delivered by Wrocławskie Centrum Sieciowo-Superkomputerowe were used.

REFERENCES

[1] V. Vazquez, T. Altan, Die design for flashless forging of complex parts. Journal of Materials Processing Technology **98**, 1, 81-89 (2000).

[2] A. Kocańda, P. Czyżewski, H. Mehdi, Khedheyer, Numerical analysis of lateral forces in a die for turbine blade forging, Archives of Civil and Mechanical Engineering **9**, 4, 49-54 (2009).

[3] H. Yoshimura, K. Tanaka, Precision forging of aluminum and steel. Journal of Materials Processing Technology **98**, 2, 196-204 (2000).

[4] M. Kowalik, Application of longitudinal cold rolling method in mass production of stepped shafts used in combustion engines, Archives of Civil and Mechanical Engineering **10**, 4, 45-56 (2010).

[5] P. F. Bariani, S. Bruschi, T. Dal Negro, Integrating physical and numerical simulation techniques to design the hot forging process of stainless steel turbine blades, International Journal of Machine Tools & Manufacture **44**, 9, 945-951 (2004).

[6] M. Pietrzyk, Ł. Madej, Ł. Rauch, R. Gołąb, Multiscale modeling of microstructure evolution during laminar cooling of hot rolled DP steels, Archives of Civil and Mechanical Engineering **10**, 4, 57-67 (2010).

[7] V. Vazquez, V. T. Altan, New concepts in die design – physical and computer modeling applications, Journal of Materials Processing Technology **98**, 2, 212-223 (2000).

[8] T. Trzepieciński, 3D Elasto-plastic fem analysis of the sheet drawing of anisotropic steel sheet metals, Archives of Civil and Mechanical Engineering **10**, 4, 95-106 (2010).

[9] M. Hyrcza-Michalska, J. Rojek, O. Fruitos, Numerical simulation of car body elements pressing applying tailor welded blanks – practical verification of results, Archives of Civil and Mechanical Engineering **10**, 4, 31-44 (2010).

[10] V. Vazquez, K. Sweeney, D. Wallace, Ch. Wolff, M. Ober, T. Altan, Tooling and process design to cold forge a cross groove inner race for a constant velocity joint – physical modeling and FEM process simulation, Journal of Materials Processing Technology **59**, 1-2, 144-157 (1996).

[11] Z. Gronostajski, M. Hawryluk, The main aspects of precision forging. Archives of Civil and Mechanical Engineering **8**, 2, 39-56 (2008).

[12] www.gkn.automotive.com

[13] L. Cser, M. Geiger, K. Lange, J.A.G. Kals, Tool life and tool quality in bulk metal forming, CIRP Annals – Manufacturing Technology **41**, 2, 667-675 (1992).

[14] G.A. Lee, Y.T. Im, Finite-element investigation of the wear and elastic deformation of dies in metal forming, Journal of Materials Processing Technology **89-90**, 123-127 (1999).

[15] S.M. Byon, S.M. Hwang, Die shape optimal design in cold and hot extrusion, Journal of Materials Processing Technology **138**, 1-3, 316-324 (2003).

[16] Z. Lin, X. Juchen, W. Xinyun, H. Guoan, Optimization of die profile for improving die life in the hot extrusion process, Journal of Materials Processing Technology **142**, 3, 659-664 (2003).

[17] T.H. Kim, B.M. Kim, J.C. Choi, Prediction of die wear in the wiredrawing process Journal of Materials Processing Technology **65**, 1-3, 11-17 (1997).

[18] J.F. Archard, Contact and rubbing of flat surfaces, Journal of Applied Physics **24**, 981-988 (1953).

[19] Z. Gronostajski, M. Hawryluk, M. Zwierzchowski, M. Kaszuba, Analysis of forging process of constant velocity joint body, Steel Research International, spec. ed. **1**, 547-554 (2008).

[20] Z. Gronostajski, M. Hawryluk, M. Kaszuba, P. Sadowski, S. Walczak, D. Jabłoński, Modelowanie numeryczne wielooperacyjnego procesu kucia obudowy przegubu homokinetycznego, Mechanika **226**, 19-24 (2009).

[21] J. Kusiak, A. Danielewska-Tułecka, P. Oproch, Optymalizacja, Wybrane metody z przykładami zastosowań, PWN, Warszawa 2009.

Received: 10 January 2011.