

The main aspects of precision forging

Z. GRONOSTAJSKI, M. HAWRYLUK

Wrocław University of Technology, Wybrzeże Wyspiańskiego 25, 50-370 Wrocław, Poland

The article concerns the directions of development the forging and problems with precision forging like tool and preform temperature, slug geometry, press settings, process speed, lubrication and cooling, and tool shape and quality. It was introduced the present state of knowledge as well as crucial problems of the technology. Suggestions solving these problems as well as researches carried out in Metal Forming Processes Department of Wrocław University of Technology were presented.

Keywords: *closed die, precision forging, tool life*

1. Introduction

The main advantage of precision forging over conventional die forging is its lower (by as much as 60%) material consumption. This is owing to the lack of flash and to the fact that the end product has minimum machining allowances. The forgings generally have very good service properties. Because of its advantages, precision forging is the most popular technology for producing car parts from relatively expensive materials. Connecting rods, skew and straight bevel gears, worm gears, tripods, turbines, alternators, constant-velocity joints and so on (Figure 1) are manufactured in this way [1–6].



Fig. 1. Products manufactured by precision forging

Besides its obvious advantages, precision forging has some drawbacks of which the most serious one is the too short life of the forming tools, mainly dies, punches (Figure 2). The tools used in precision forging wear out long before the end of their expect life.

The life-span of the tools depends on the forging conditions, workmanship of staff, tools material, the shape of the preform and that of the slug, etc. The low durability of the tools lowers the quality of the forgings, in spite of their still control. The most common forging defect due to low tool durability are, i.e. shorts, laps, burrs, bends, cracks, delamination, micro- and macro-fractures and so on. This, in turn, affects the functionality of the final product made from the forging. Because of the large number and variety of factors (and their interactions) having an influence on precision forging the process is very difficult to analyze. Therefore a whole range of computer tools, such as CAD/CAM/CAE, mostly based on FEM and physical modelling, are used for the design, analysis and optimization of the forging process [2, 7–11].

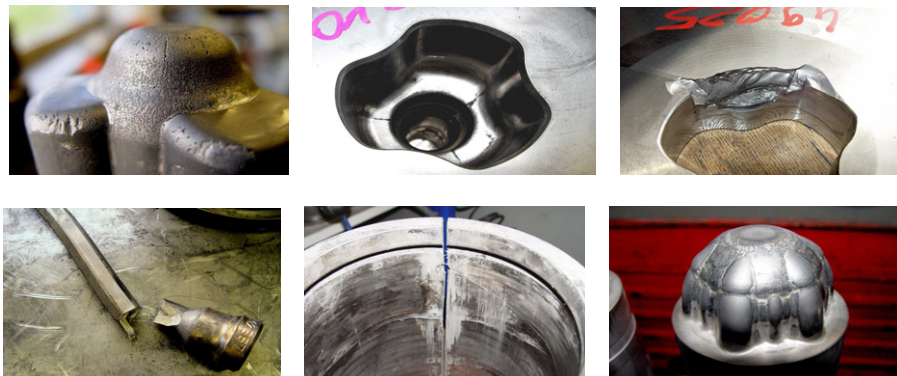


Fig. 2. Most common defects of tools

2. Precision forging

In conventional precision forging the material is formed at ambient temperature or in semi-hot conditions. In the case of very complicated parts, a properly prepared charge is hot formed in isothermal conditions. Sometimes the super plasticity of the formed material is exploited. Initially, enclosed dies were used for forming [5, 12]. Thanks to the material savings and the lower costs of manufacturing products with enhanced properties at competitive prices, precision forging was increasingly applied to alloys of light materials such as aluminium, magnesium and titanium [10, 12].

The expression precision forging does not mean distinct forging process but rather approach to forging. The aim of this approach is to produce a net shape, or at least a near-net shape parts. Precision forging is sometimes described as close-tolerance forging to emphasize the aim of achieving required the dimensional and surface finish tolerances only after forging [13].

Precision forging at ambient temperature, i.e. cold forging, is preceded by making a slug in a few hot forging operations. In conventional hot forging in half dies a substantial amount of the material is lost for the flash and allowances. For this reason closed-die forging (often employing complex formation, i.e. forward and backward

extrusion) was adopted to make preforms for precision forging. Extrusion forging has this advantage that the stress is mostly triaxial compression whereby large deformations can be obtained without losing material cohesion. In addition, no die drafts are used in precision forming. The whole manufacturing process is generally divided into stages. As an example, the process of manufacturing a low-carbon steel product is shown in Figure 3.

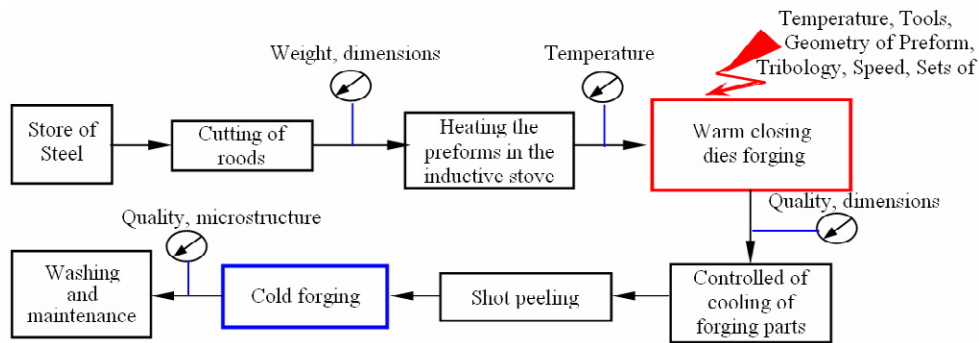


Fig. 3. Flowchart of precision forging process

Metal bundles are delivered from a storeroom to a machine which cuts the rods into pieces with specified dimensions and weight. Then the pieces are heated up to a temperature of about 900 °C in an induction furnace. A constant process temperature must be maintained in order to ensure high quality of the forgings. Preforms heated up to a proper temperature are fed into a press where they are formed in 2–5 operations. The dies are preheated to a temperature close to the operating temperature to reduce the risk of die cracking as a result of thermal shock (Figure 4a).



Fig. 4a. Dies are preheated

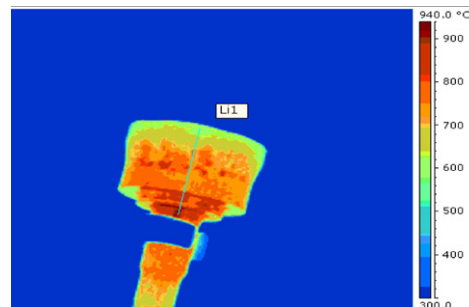


Fig. 4b. Measurement and control of forged object temperature

The forging process lasts only a few seconds. The stability of the process and control conducted according to plan ensure high quality of the forgings. When they leave

the press the forgings are subjected to controlled cooling (Figure 4b). Then they go to a shot peening machine where they are cleaned from graphite. The clean forgings go to cold working where they are oiled and cold formed. In this way the precise shape of the finished forged product is obtained. After cold forming the forgings are washed and greased.

3. Choice of process parameters

As shown above, each of the stages in the forging process is critical. Any shortcomings even at one of them may result in bad quality of the forged products, press jamming and production stoppages. Therefore the process specifications must be adhered to during production, which requires proper shopfloor customs and technical culture. For example, if the hot forging die is improperly lubricated and preheated and there is improper cooling during production, the die heats up excessively, which quickly results in its plastic deformation or thermal fatigue. In the available literature much attention is devoted to the design and optimization of the whole forging process or its key stages [2, 12–16]. Proper design of the particular process stages is the precondition for the optimization of forging parameters [3, 18]. Through the optimum choice of process parameters one may significantly increase the life of the tools and improve the quality of the forgings and consequently, increase the productivity of the whole process. The main factors having an effect on the process of forging are: tool and preform temperature, slug geometry, press settings, process speed, lubrication and cooling, and tool shape and quality.

3.1. Tool and preform temperature

Proper temperature is critical for the reliable operation of the tools. It can affect the die's narrow tolerance zones and the small spaces between the moving parts and the fixed parts of the tools. As a result of thermal expansion the clearance may decrease and the tool components may lock up. Also the thermal expansion of the die affects the quality of the forgings. Numerical simulations of the forging of CV joints showed large temperature differences in the die in the contact area, whereas already at a depth of about 5 mm from the die's inner surface the temperatures are much lower (Figure 5a). So large temperature gradients may adversely affect the state of stress inside the tools. This means that the temperature of the tools needs to be monitored, for example, by a thermovision camera (Figure 5b).

An equally important parameter is the temperature of the slug since it has an effect on the forged object's microstructure and its material flow curve (its formability) and through thermal expansion it causes a change in the slug volume. The temperature distribution in slugs (Figure 6) for different preform diameters was examined in [8]. The initial temperature of the preforms was 920 °C. Then the specimens were cooled for 2 s at a temperature of 50 °C in the press chamber as they were waiting to be

forged. In spite of such a short cooling time the temperature difference in the outer layers amounted to about 50 °C. This can have a significant effect on the forging process.

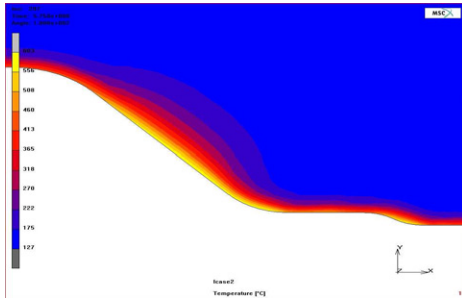


Fig. 5a. Die thermal field distribution determined by FEM [8]

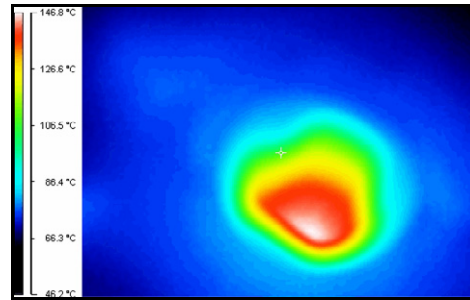


Fig. 5b. Thermovision camera photograph of die

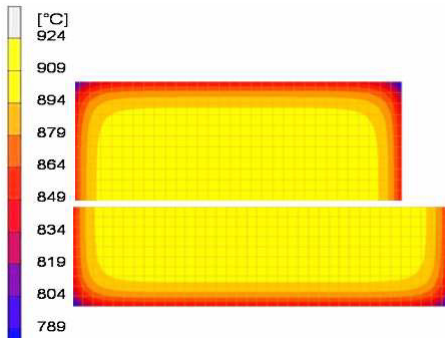


Fig. 6. Temperature field distribution in slugs after 2 s long cooling at temperature of about 50 °C in press chamber [8]

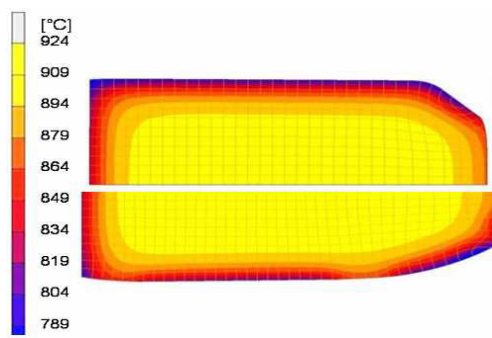


Fig. 7. Temperature field distribution in slugs after 1st forging operation (about 4.5 s) [8]

3.2. Slug geometry

In precision forging there is no flash gap and the charge material volume must be the same as that of the finished part. The allowable differences in mass can amount to 0.5–1%, the angle deviation in the cutting zone to 0.5–2° and the roundness deviation to 2 and 6%. This can be achieved by using special cutting. It is necessary to maintain so narrow tolerances for the preform in order to ensure high quality of the forged product. A too large slug volume may result in damage to the die or the press. During multioperation forging in closed dies proper distribution of slug material volume and slug preparation through upsetting are critical for the proper filling of the die cavity. There exists a notion of an ideal metal body of revolution with appropriately distrib-

uted material masses. Therefore the design of preforms and slugs in forging processes is an important activity aimed at improving product quality and reducing production costs [1, 3, 11]. The preform's shape and mechanical properties will affect the friction conditions at the die/slug interface while its geometry will have an effect on the die and the slug.

In [8] it was shown that the preform's initial dimensions have an effect on temperature distribution. It was found that a larger drop in temperature occurs in a slenderer slug since the surface of contact with the tools is then larger (Figure 7).

3.3. Process speed

Precision Forging processes are usually conducted at high speeds. Currently, tendencies of increasing the speed are dictated by economic reasons. The faster the forging process, the higher the productivity. As many as 30 forgings per minute can be produced in multioperation hot forging in closed dies in crank presses. [7]. The time in which a single forming operation is performed in industrial precision forging is about 0.2 to 1 second. Hence, as mentioned in pt. 3.1, it is so critical to ensure a constant preform temperature (Figures 6–7). Currently attempts are made to maximally utilize the capacity of the forming machines and to reduce the number of forging operations. If the number of strokes during forging is too large, the whole time increases and so do the costs [1]. But the higher the speed of a single operation, the higher the deformation resistance and the greater the required forming forces.

3.4. Press settings

The settings of the forming machines are an important factor affecting the forging process. The main settings include:

Press workspace. The precision forging process and tools require that the tool workspace between the anvil and the press slide should be sufficiently large for the whole system of tools, including the auxiliary components. Moreover, the cooling and lubricating equipment should be integrated with the press.

Constant forging energy. Constant press energy is critical for reproducibility in precision forging in every stroke. Especially, when speed is increased during redesign a new forging process. Excessive energy causes an increase in the pressure inside the die, which may result in the elastic deformation of some tools (such as punches and counterpunches) and ultimately lead to an elastic rebound of the tool. Elastic deformations of tool components should be avoided since they can cause changes in geometry during forging.

Precision guidance of tool components. Precision guidance of the punch is required when the die is closed by the upper punch during forging. The gap between the punch and the die is usually smaller than 0.1 mm in order to avoid a material flash. Moreover, accurate positioning of tool components is necessary to obtain proper forged product geometry.

Accurate positioning of slug inside die. In order to ensure proper die cavity filling the slug must be accurately positioned inside the die, especially when the slug is automatically delivered to the successive forging stations. Using physical modelling to analyze the flow of material it was found in [9] that too slender specimens, incorrectly positioned in the die impression, would undergo buckling. Despite the buckling, the forged object had the correct shape, but the uneven flow of material may affect the durability of the end product (Figure 8).

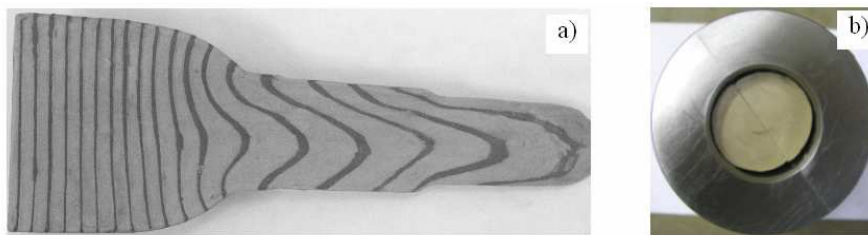


Fig. 8. Uneven flow of material caused by specimen buckling:
a) cross section and b) view from punch

Reliable die closure. Die closure is essential for the proper operation of the set of tools at the machine settings. For many precision forged products the split line lies in the vicinity of the work surfaces and so they may be deformed at improper closure. The die should be closed by accessory elements or simultaneously with the motion of the punches.

3.5. Lubrication and cooling

To a large extent the correctness of forming process depends on the lubricant used. The latter is used to both lubricate and cool. The lubricant should be characterized by a high flash point (so that it does not lose its tribological properties at high temperatures), low heat conduction (to prevent the object being forged from cooling down and the tool from overheating), proper viscosity at the operating temperature and a low coefficient of friction. Moreover, an optimum lubricant should not contain any components having an adverse effect on the process [19]. Graphite, teflon, glass and other substances as well as intermediate metallic layers characterized by low flow stress are usually used in hot forging.

In order to ensure healthier working conditions in the forging industry and minimize its environmental impact as well as to increase the life of the tools, the European Community has recently funded an industry research project called Brite-Euram aimed at developing environmentally friendly systems of tool lubrication (based on lubricants with optimum lubricating properties) for the warm forging of steel and to promote a wide use of forging with a smaller pollutant burden, better working conditions and higher productivity [19]. It was found that in most hot forging processes no proper

tribological conditions were ensured. This is mainly due to the high contact pressures and metal surface gains typical for hot forging, especially forward and backward extrusion forging. In all the cases it is necessary to provide additional lubrication in the form of lubricating film on slugs. Thanks to the project a comprehensive tool lubrication system has been developed. As regards the environmental impact and tool life, the best results have been achieved through the use of tool lubrication systems consisting of a graphite-based slug lubricating film and graphite-free oil greases for dies.

3.6. Tools

The choice of a tool material is a very difficult task for designers and process engineers. The life of a tool and its suitability for production depend on many factors which often have opposing consequences. So far there are no clear-cut criteria for selecting tool materials and to a large extent one must rely on the experience of the manufactures and tool users. Statistical data provided by different tool manufacturers indicate the most common causes of tool failures to be: tool fatigue cracking in cold working and excessive abrasive wear, material plastic flow and thermal fatigue in hot working [20]. The worst situation is in warm working since each of the phenomena can be equally critical. In such conditions the tools must withstand high pressures (as in cold working) and at the same time must be made of heat resistant materials (as in hot working). According to Lange et al. [21], the life of a tool at high forging temperatures depends on wear in over 70% of cases. Therefore tool materials, their heat treatment and machining and tool design and fabrication accuracy must meet very high requirements. Tool materials should be characterized by hardness in a range of 50–55 HRC (considerably higher than that of the forged product), good hardenability, high tensile strength, high impact strength and low abrasibility.

Currently, warm- and hot-work tool steels: WCL, WWV, WNLV, which are characterized by very good mechanical properties (high tensile strength, high hardness, high abrasion resistance, high yield point – 2200 MPa) are quite popular tool materials. Also other alternative tool materials are considered. Moreover, special treatment, such as nitriding, surface coating and laser silicon carbide surface alloying, etc., can significantly reduce the abrasive wear and increase the hardness of the tool materials, particularly of their surface layer [24].

4. Heat treatment

Heat treatment has a decisive effect on tool life. Figure 9 shows a heat treatment diagram for a hot-work tool steel.

For instance, cracks which appear on the surface of a ground tool made of tool steel can be caused by improper tempering or by overheating during austenitizing. Such heat treatment faults can limit the possibilities of grinding the tool, even if proper precautions are taken.

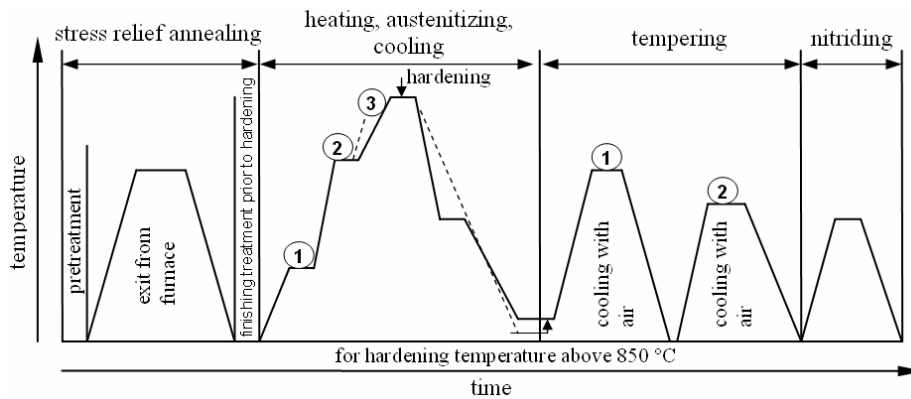


Fig. 9. Exemplary tool material heat treatment diagram

Stress relief annealing. Tool steels are usually delivered annealed; further treatment is done by the user or in toolrooms. The treatment causes stresses to arise, which during heating up to the hardening temperature are released and cause, among others, changes in the dimensions. Therefore tools which must meet high requirements for retaining their dimensions should be annealed after mechanical pretreatment (before the final treatment).

Hardening. It is impossible for steels subjected to hardening to ideally fully retain their dimensions. A change in the structure (from the annealed-state structure to the structure after hardening) means an increase in the volume, which as a result of tempering that follows is again reduced but not restored to the annealed-state volume. Because of buckling it is recommended to use the gentlest possible cooling medium and to perform intermediate cooling at 900 °C for steels whose hardening temperature is above 900 °C. Since there is a risk of strain cracking one should avoid cooling the tools to room temperature. The latter are usually cooled down to about 150 °C. Then at a temperature of about 100–150 °C equalization takes place aimed at eliminating the differences in temperature and structure between the surface and the core. Quenching in a hot bath and in vacuum (as a hot bath simulation) for hot-work tool steels has proved to be effective.

Austenitizing (keeping at hardening temperature). The hardening temperatures specified by the manufacturers should be adhered strictly to. If the hardening temperature is too low, the increase in hardness is insufficient. If it is too high, it results in brittleness, increased grain size, a risk of cracks and so on. Also soaking times are important. An approximate soaking time for hot-work tool steel is 0.5 min per 1 mm of thickness.

Tempering. Immediately after hardening, steel is tempered several times. The aim is to remove any stresses which arose during hardening and to reduce the often too high postcooling hardness in favour of shock resistance. Depending on the desired hardness, a tempering temperature should be chosen in accordance with the proper

tempering diagram. It is reported in [7] that triple tempering gives the best results in the case tool steel W303.

Machining. In order to increase tool life, die cavities and punch work surfaces should be made appropriately smooth. During forging the heated up material rubs against tool work surfaces and abrades them. The degree of abrasion can be reduced through the use of a proper material, but this will not replace finishing consisting in grinding and planishing of the work surfaces. One should note that during such working the tool surface is often overheated and weakened as a result. In some cases, the tempering temperature of the tool steel may be exceeded by overheating. Machining may cause microcracks to appear in the tool. The microcracks will grow during work and result in a premature fracture.

Thermochemical treatment. Sometimes as a result of prolonged operation of the tools at a high temperature the tool material suffers thermomechanical fatigue and its properties sharply deteriorate, whereby its elastic limit is exceeded or the metal spontaneously heats up. Then nitriding is applied to increase the life of the tools by increasing their surface hardness and abrasive wear resistance. The treatment can be applied several times.

5. Optimum die profile

One of the main parameters having an influence on the forging process is the shape of the adopted die. The magnitude of deformation obtainable in a single operation is limited not by material decohesion (cracks) but by material strength (too large hoop stresses). For this reason, instead of producing a forging in one operation, multioperation industrial precision forging is used. Still this does not sufficiently reduce the great forming forces and thereby the wear of the tools.

Die shape optimization receives much attention in the literature [2, 4, 11–15, 22]. It turns out that one of the ways of reducing excessive pressures on the die or the punch is the choice of an optimum die profile (outline). Three types of die profile: streamline, curvilinear and conical are generally used in industrial applications. In forward extrusion the streamline profile ensures the smallest excessive deformation, the smallest extrusion forces and the least deformation inhomogeneity in the cross section. But the problem is with determining the correct profile and fabricating it (the profile is usually to long time). For this reason the profile is often replaced by any curvilinear outline, which often leads to even worse results than when conical profile dies are used. A conical profile, with an angle minimizing excessive deformations, may result in good extrusion parameters and good product quality and it can be very easily made.

Today research on die profile optimization aimed at improving product quality and productivity combines classical mathematical optimization methods with FEM. The die profile optimization problem can be solved by applying one of the mathematical programming methods [18]. Usually Bézier curves and other specially adapted optimization methods are employed to mathematically describe die profiles. Ales and Boris

[12] investigated tool design optimization for stationary extrusion by imposing two-criterion optimization. Wife et al. [16] proposed a special incremental computing method combined with FEM in order to obtain the distribution of pressure on the die walls (for the adopted die profile) during the hot extrusion of a bar. Thanks to studies of optimum die profiles by Lee et al. [18] a more uniform structure of hot forged products can be obtained. In [4] the die profile was optimized by sequential quadratic programming (SQP) which is now successfully applied to solve nonlinear optimization problems.

The present authors et al. in [8] assessed the flow of material in arch and conical dies for forging CV joint tulips.

CV joints are irreplaceable components of front-wheel drive cars. They transmit torque from the gearbox to the front wheels. Their production has been steadily increasing in recent years. A CV joint consists of a spider, a race and a casing. The most difficult to manufacture is the casing, the more so that because of its irregular shape machining is made very difficult. Currently hot and cold multioperation forging in closed dies with a complex formation scheme (forward and backward extrusion) is used in long-run production. The authors employed both physical modelling, using soft modelling materials (synthetic filia wax and Plasticine), and numerical modelling by means of the MSC software package to study material flows. A macroscopic analysis revealed differences in the flow of material in the particular tools. In the case of arch tools the material flow in the specimen's cross section is more uniform than when for conical tools (Figure 10). This is confirmed by the fact that the mesh line curves for the object forged in the arch die are less elongated than the ones for the object forged in the conical die ($L_a < L_b$).

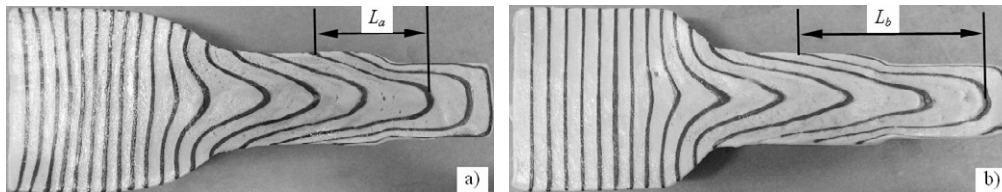


Fig. 10. Comparison of model material flow in: a) arched tools and b) conical tools [8]

The investigations showed that the material flow in the arched dies was more uniform than in the conical dies, whereby the distribution of strains was more uniform too (Figure 11). In addition, the punch forces were smaller for the arched dies.

Figure 12 shows a vector distribution of unit pressures for the tools, obtained by means of the SuperForm2005 software. The unit pressures at the first reduction stage were similar for the two kinds of dies, but at the next stages they were much higher for the conical die.

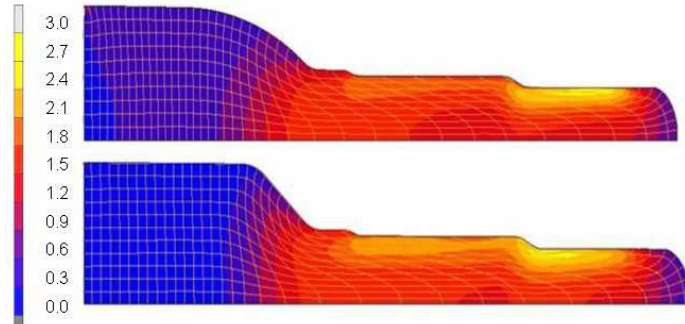


Fig. 11. Distribution of plastic strains in: a) arched tools and b) conical tools [8]

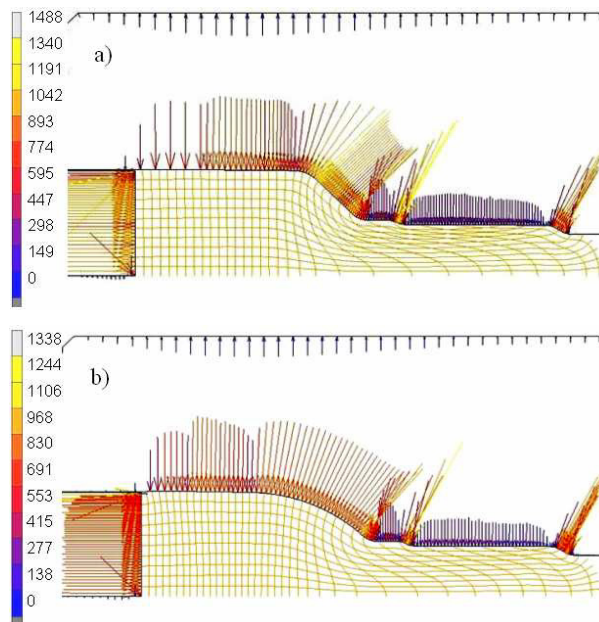


Fig. 12. Vector distribution of unit pressures in: a) conical, b) arched tools [8]

6. Die design

Currently, in order to increase the crack resistance of precision forging tools, pre-stressed dies (i.e. reinforced with a single concentric ring or a larger number of such rings with thermo-compression or forced-in joints in-between) are used. It turns out that by changing the state of stress one can significantly reduce tool cracking [7]. The application of an appropriately high pre-stress (compressive hoop stress) during assembly should compensate for the very high tensile hoop stresses which occur during forging.

The present authors et al. analyzed (using numerical modelling and actual negative allowance measurements) the effect of negative allowance in pre-stressed dies (used in the production of the CV joint casing) on their strain [7].

Numerical modelling was done using the MSC Marc2005 and Super Form 2005 software. It was carried out in two stages: 1) forcing of a compensation ring together with a die onto an elastic sleeve and 2) actual forging based on the first-stage conditions. Figure 12 shows the analyzed set of tools. The function of the compensating ring is to pre-stress the die via the slit elastic sleeve.

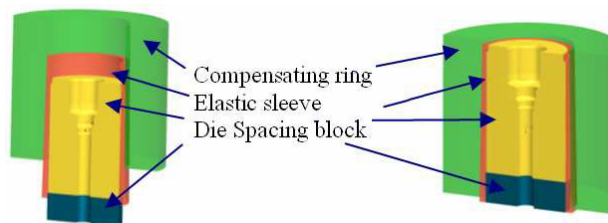


Fig. 12. Schematic of die prestressed by single ring [0]

The nominal negative allowance was $w_{\text{nom}} = 0.4$ mm. But it was found that the actual negative allowance depended on the tools' dimensions determined by their tolerances and wear.

From the field of execution tolerances for the particular tool system components it followed that the negative allowance could range from $w_{\text{min}} = 0.225$ mm to $w_{\text{max}} = 0.45$ mm. Hence one could assume that the expected average negative allowance would be $w_{\text{av}} = 0.34$ mm, i.e. much less than the nominal negative allowance.

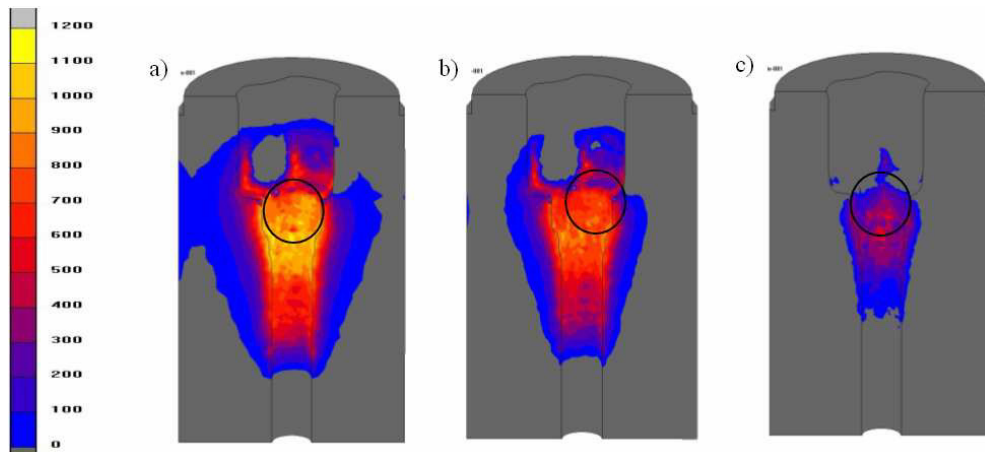


Fig. 13. Distributions of hoop stress in die during forging at negative allowance:
a) $w = 0.25$, b) $w = 0.4$, c) $w = 0.7$ mm [7]

The aim of the research was to determine how the change in negative allowance (resulting from the tolerance fields) can affect the strain of the dies during forging. A negative allowance of 0.25 mm (close to the minimum negative allowance), the nominal negative allowance of 0.4 mm and an increased negative allowance of 0.7 mm were analyzed. Figure 13 shows hoop tensile stress distributions for the different negative allowance values. The maximum hoop stresses occur at the second reduction stage (the circle marks this place).

The hoop tensile stresses at a negative allowance of 0.25 mm are very high, amounting to 1000 MPa. This means that at such low negative allowances the dies may quickly fail.

Then reduced stresses were analyzed. Figure 14 shows reduced stress (von Mises stress) distributions for the assumed negative allowances.

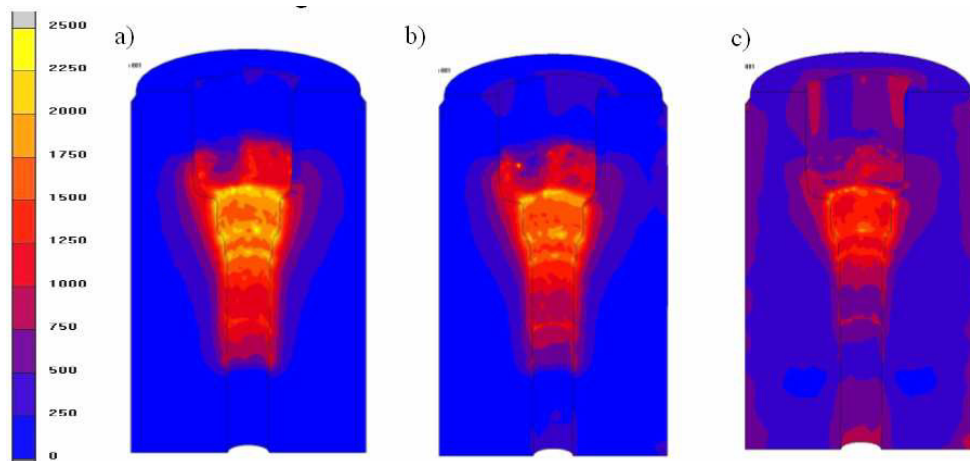


Fig. 14. Distributions of von Mises stress in die during forging at negative allowance: a) $w = 0.25$, b) $w = 0.4$, c) $w = 0.7$ mm [7]

Figure 15 shows the dependence between reduced stress in the most heavily loaded places (the first stage of cross section reduction) and negative allowance. Even though all the flow stress values are below the yield point of the die material, the smallest negative allowance of 0.25 mm may be too small since in the places where the die is most heavily loaded the temperature significantly rises. As a result, the yield point in those areas may go down to below 2000 MPa. In real experiments, plastic flow of die material would be observed at the first stage of reduction. The analysis showed that a negative allowance below 0.4 mm did not ensure sufficient pre-stressing of the dies. This was confirmed by observations of the real process. It was found that the wear of the compensating ring and that of the elastic sleeve and a wide range of execution tolerances of the tools may result in an allowance much smaller than 0.4 mm.

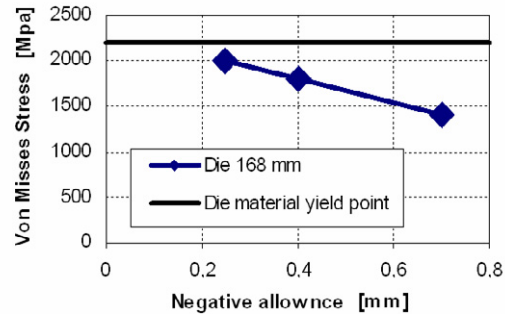


Fig. 15. Reduced stress versus negative allowance at forging stage [7]

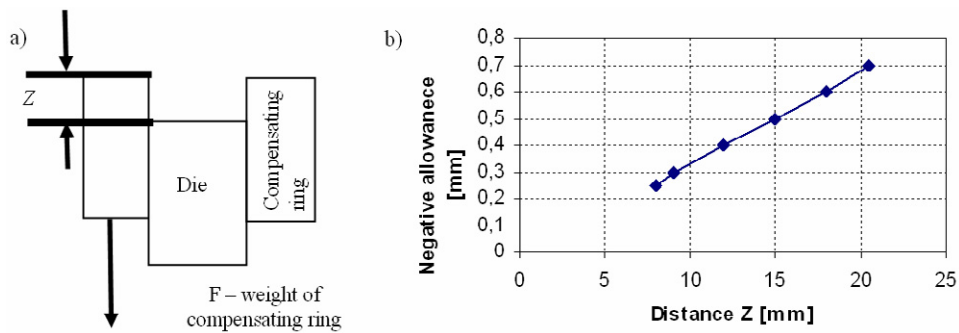


Fig. 16. a) Method of measuring distance "Z" and
b) Relation between distance "Z" and negative allowance [7]

Therefore it is necessary to control negative allowance when the die is forced into the compensating ring. For this purpose a simple indirect method of determining negative allowance, i.e. on the basis of the distance between the upper surface of the die and the upper surface of the compensating ring forced into the die by the force of gravity (Figure 16a), is proposed. It has been found that if this distance is larger than 15 mm, the negative allowance is larger than 0.4 mm. Figure 16b shows the relation between distance "Z" and negative allowance, which allows one to determine the negative allowance value in a simple way during the assembly of the tools.

7. Conclusion

The growing market demand, particularly from the automotive industry, has led to very intensive development of precision forging. Its advantage over other technologies is that it offers considerable material savings owing to the fact that there is no flash and that the end product is almost finished whereby finishing is not needed or reduced to minimum. Currently, precision forging is used mainly as multi-operation industrial

forging to manufacture CV joint tulips, gear wheels, connecting rods and so on. However, it is not a perfect technology yet, as indicated here. Its main drawback is the too quick wear of the forming tools. The life of the tools depends mainly on: the conditions in which forging takes place, the design and workmanship of the tools, their heat treatment proper for the selected tool material, the shape of the pre-form and slug, etc.

The large number and variety of factors having a bearing on the process of precision forging as well as their interactions make analysis of this process difficult. Therefore several CAD/CAM/CAE tools, mostly based on FEM and physical modelling, are used to analyze and optimize the forging process.

The continuous development of the precision forging technology should result in solutions to the problems presented here as well as in higher product quality and productivity.

Acknowledge

The licences of programmes in article were used the MSC. The MARC as well as ProEngineer of Wrocław Centre for Networking and Supercomputing.

References

- [1] Bariani P.F., Bruschi S., Dal Negro T.: *Integrating physical and numerical simulation techniques to design the hot forging process of stainless steel turbine blades*, International Journal of Machine Tools & Manufacture, 44, 2004, pp. 945–951.
- [2] Doege E., Bohnsack R.: *Closed die technologies for hot forging*, Journal of Materials Processing Technology, 98, 2000, pp. 165–170.
- [3] Lin S. Y., Lin F. C.: *Influences of the geometrical conditions of die and workpiece on the barreling formation during forging–extrusion process*, Journal of Materials Processing Technology, 140, 2003, pp. 54–58.
- [4] Lin Zou, Juchen Xia, Xinyun Wang, Guoan Hu: *Optimization of die profile for improving die life in the hot extrusion process*, Journal of Materials Processing Technology, 142, 2003, pp. 659–664.
- [5] Osakada K., Wang X., Hanami S.: *Precision forging process with axially driven container*, Journal of Materials Processing Technology, 71, 1997, pp. 105–112.
- [6] Strona internetowa <http://www.gkndriveline.com>.
- [7] Gronostajski Z., Hawryluk M., Niechajowicz A., Polak S., Walczak S., Wodniak A.: *Określenie zmian konstrukcyjnych i montażowych matryc stosowanych do kucia przegubów homokinetycznych w celu podniesienia trwałości narzędzi*, KomPlasTech 2008, pp. 35–44.
- [8] Gronostajski Z., Hawryluk M., Jaśkiewicz K., Niechajowicz A., Polak S., Walczak S., Wodniak A.: *Application of physical and mathematical modelling to analysis of different forging processes of constant velocity joint body*, Computer Methods In Materiale Science, 7, No. 2, 2007, pp. 231–236.

- [9] Hawryluk M.: *Modelowanie fizyczne procesu kucia obudowy korpusu przegubu homokinetycznego przy zastosowaniu matryc łukowych oraz stożkowych*, FiMM 2005, pp. 133–138.
- [10] Siegert K., Kammerer M., Keppler-Ott Th., Ringhand D.: *Recent developments on high precision forging of aluminum and steel*, Journal of Materials Processing Technology, 71, 1997, pp. 91–99.
- [11] Vazquez V., Altan T.: *Die design for flashless forging of complex parts*, Journal of Materials Processing Technology, 98, 2000, pp. 81–89.
- [12] Yoshimura Hyoji, Tanaka Katsuhisa: *Precision forging of aluminum and steel*, Journal of Materials Processing Technology, 98, 2000, pp. 196–204.
- [13] ASM Metals Handbook Volume 14, *Forming and Forging*, pp. 337–338.
- [14] Ales M., Boris S.: *Tool design optimization in extrusion process*, Comput. Struct., 68, 1998, pp. 283–293.
- [15] Vazquez V., Altan T.: *New concepts in die design — physical and computer modeling applications*, J. of Mat. Proc. Techn., 98, 2000, pp. 212–223.
- [16] Wafi A.S., Shatla M.N., Abdel-Hamid A.: *An optimum-curved die profile for hot forward rod extrusion process*, J. Mater. Process. Technol., 73, 1998, pp. 97–107.
- [17] Bariani P.F., Dal Negro T., Fioretti M.: *Joint use of physical and numerical simulation techniques in predicting process parameters evolution and microstructure in forging Nimonic 80A turbine blades*, Proceedings of the 2nd Esaform, Guimares, Portugal, 1999.
- [18] Lee S.K., Ko D.C., Kim B.M.: *Optimal die profile design for uniform microstructure in hot extrusion product*, Int. J. Mach. Tool Manuf., 40, 2000, pp. 1457–1478.
- [19] Sheljaskow S.: *Tool lubrication systems in warm forging*, Journal of Materials Processing Technology, 113, 2001, pp. 16–21.
- [20] Kocańda A.: *Określenie trwałości narzędzia w obróbce plastycznej metali, rozdział w monografii pt. Informatyka w Technologii Metali*, red. A. Piela, F. Grosman, J. Kusiek, M. Pietrzyk, Wydawnictwo Politechniki Śląskiej, Gliwice, 2003, pp. 213–256.
- [21] Cser L., Geiger M., Lange K.: *Tool life and tool quality in bulk metal forming*, Proc. Inst. Mech. Eng., 207, 1993, pp. 223–239.
- [22] Byon S.M., Hwang S.M.: *Die shape optimal design in cold and hot extrusion*, Journal of Materials Processing Technology, 138, 2003, pp. 316–324.
- [23] Bin Y.: *The Optimal Design and Computer Program*, Haerbing University of Technology Publishing Company, 1991 (in Chinese).
- [24] Bonek M.: *Struktura i własności warstw wierzchnich uzyskanych w wyniku obróbki laserowej stali narzędziowej stopowej do pracy na gorąco*, Biblioteka Główna Politechniki Śląskiej, Gliwice, 2003.

Najważniejsze zagadnienia dotyczące kucia precyzyjnego

Artykuł dotyczy kierunków rozwoju kuźnictwa i problemów związanych z kuciem na gorąco gotowych lub prawie gotowych wyrobów. W pracy przedstawiono obecny stan wiedzy oraz zwrócono uwagę na problemy kluczowe. Zaprezentowano rozwiązania tych problemów oraz badania prowadzone z tego obszaru w Zakładzie Inżynierii Procesów Kształtowania Plastycznego Politechnik Wrocławskiej.