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THE SIMULATED DESIGN OF DIE FORGING TECHNOLOGY OF PRECESSIONAL BEVEL GEAR BY SEVERE COLD PLASTIC DEFORMATION

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Abstract: *Simulation of closed die forging processes is a powerful tool for technological design-optimization that provides details regarding the shape evolution, plastical flow, required forging forces, stress and deformation states, allowing like this the exclusion of costly real repeated tests. In this paper, the LS-DYNA simulation tool is used to design the precessional bevel gear's forging technology in closed die, following preliminary simulations on partial models reduced to one tooth, respectively to one gap, simulations on models reduced to 1/4 of the wheel and on the integrated model.It is found that it is preferable to form the wheel with a bore in the hub, because this ensures a better balance between the masses of material located in different areas of the die forged bevel gear starting from a blank in the form of a disc. The formation of the bore in the hub requires plastic deformation actions located both in the teeth area and in the hub area, making it necessary to include in the closed die's structure a mandrel with an action separate from the punch, but synchronized with its action.*

Key words: *precessional bevel gears, digital simulation, cold forging technology, closed die*

1. INTRODUCTION

Theoretical research, through simulation and experimentation, in the field of materials science and plastic deformation processes has successfully developed new directions for improving functional performance and enhancing the technological workability of metal alloys. A good part of the research is focused on the issue of designing plastical deforming technologies through numerical simulation. [1, 2, 3, 4, 5, 6]. Special attention is paid to closed die forging of a parts with complex geometric shapes. [1, 2], including bevel gears [4, 5, 6, 7]. One of the problems of the closed die forging of parts is the substantial increase in the pressing force when filling the die cavities [8]. Preforming the blank, so that its shape ensures the facilitation of natural plastical flow in hard-to-reach areas, is one of the solutions [2, 9]. In the case of bevel gears, the tooth formation occurs either at the end of the pressing process [10] or in a separate mold as the last operation [4, 7]. Another solution that can be established through numerical simulations refers to the division in time and space of the plastical deformation process into distinct phases with effects of separate filling of the cavities and reduction of the pressing force, the necessary energy and the degree of mechanical stress of the mold components [3]. Separating the process into distinct phases leads to the constructive and kinematic complication of the die. The complexity of the shapes of the forged parts places the process of plastic deformation in closed molds in the space of severe plastic deformation with the imminent increase of the pressing force, but also with ensuring the workability of metallic materials in a parts of complex shape [8, 11].

Formability and workability are terms that refer to the property of a material with regard

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to its ability to be shaped in metal forming without breakdown during the forming operation. The workability of metal is defined as the degree to which it is deformed in a particular metal forming process without the cracks' formation [12]. Thus, the workability of metal has two origins: the properties of the metal as such and the particularities of the forming process determined by the geometry of the formed object. In the process sense, workability is determined by the state of tension achieved, more precisely, by its compression triaxiality.

The area of plastic deformation without failure is determined by the workability limit diagram (WLD) [13, 14] $\varphi_{ef.f} = \varphi(\beta)$ represented in figure 1. Here, $\beta = \sigma_0 / \bar{\sigma}$ - triaxiality ratio at the site of fracture initiation, $\varphi_{ef.f}$ – effective plastic strain (Mises) to fracture, $\sigma_0 = (\sigma_1 + \sigma_2 + \sigma_3)/3$, $\sigma_1, \sigma_2, \sigma_3$ are the principal normal stresses, $\bar{\sigma}$ - the effective stress according to the von Mises as follows

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma 1)^2}$$

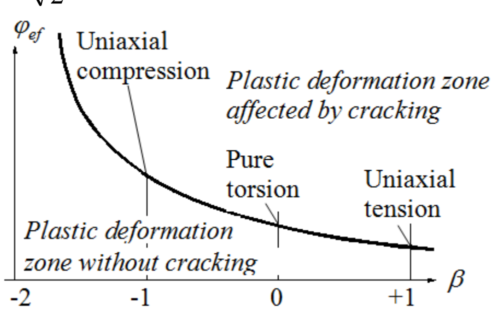

Fig. 1. Workability limit diagram (WLD)

The positive effects produced in the material during severe plastic deformation are largely due to the transformations that occur at the level of the crystal lattice. As plastic deformations increase, the crystal lattice becomes finer, resulting in a considerable increase in mechanical properties (yield strength, tensile strength, hardness, balance between strength and ductility, wear resistance, fatigue resistance, etc.) [11, 15, 16]. In the case of aluminum alloys, severe plastic deformation leads to ultra-fine structures with a considerable increase in mechanical strength [16].

Technologically, a plastic deformation process with a negative triaxiality index is preferable, i.e. with a predominant compressive stress. Tensile stress limits workability to lower values of effective plastic strain to fracture (fig. 1) compared to those achieved under triaxial compression stress, but with a three- to four-fold increase in yield strength [13, 14].

Friction between the plastically deformed part and the die negatively influences the natural flowing of the material. The braking of the sliding on the die walls causes the forces required to fill the die to increase. At the same time, the constraints of plastic flow increase and the severity of plastic deformation is more pronounced and, respectively, the workability increases.

Thus, the steps for developing the technology of plastical deformation of parts through die forging and the prospects for their more efficient use can be established: establishing and analyzing the reference model of the formed part with its adaptation to the specifics of closed die forging, stabilirea formei inițiale a semifabricatului piesei și a caracteristicilor materialului acesteia, crearea modelului parametric CAD al matriței închise, simulation of the plastic deformation process while respecting the requirements for the functional - target surfaces of the gear wheel and operating with the geometric parameters of other surfaces as process optimization factors.

1.1. Reference model

The bevel gear chosen as the object processed by the technology proposed in this work is the TTP-03.05 driven precessional bevel gear shown in Figure 2, along with the resulting model of one of the first numerical simulations.

The original bevel gear is bi-material. The reference bevel gear model formed by plastic deformation is reduced to a single material,

the metal component, while maintaining functional dimensions and tolerances.

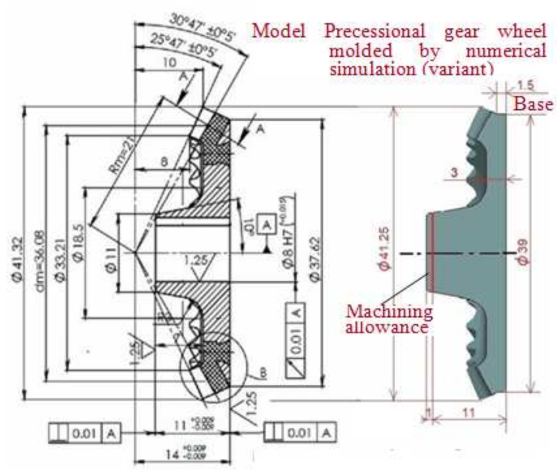

Fig. 2. Reference model

From a geometric point of view, the most important line of this bevel gear, represented in the figure and marked with the nominal angle of $59^o13' \pm 0^o05'$ (complementary to the angle $30^o47' \pm 0^o05'$), is the generator of the bottom cone. Starting from the bottom line, the axis of the conical roller in the proximal position, with an external angle of 26°, is also noted. The tip cone completes the data, but this is not necessary for defining a reference base. For the bottom line, in addition to the orientation γ_f, the measurable heights at the ends D, h and h the length b (fig. 3) are also taken into account.

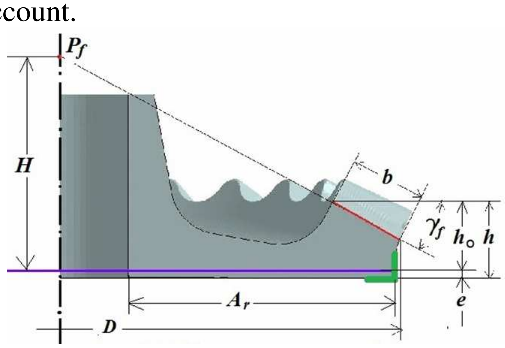

Fig. 3. Locating on the gear's ring

The constructive datum surfaces are placed as close as possible to the teeth and are two surfaces, one cylindrical on the side and another flat on the sole (fig. 3).

Since the gear crown is formed in the die zone that closes with self-centering, we consider the installation solution in figure 3 to be correct. But model validation for dimensional control is required to be done for each simulated model. Figure 3 shows the method of achieving high-precision dimensions $H = 14 \pm 0.009\ mm$, which is reduced to calculating the technological machining allowance:

$$e = h + \left(\frac{D}{2} - b \cdot cosY\right) \cdot tgY - H \quad (3.100) \quad (1)$$

After removing the technological allowance, the datum's flat face moves to the wheel reference sole (zero line). In this situation, the gap position control dimension $h_o = h - e$ is measured from the zero line.

2. ESTABLISHMENT AND OPTIMIZATION OF SEVERE COLD PLASTICAL DEFORMATION TECHNOLOGY

The design of the cold closed die forging technology was carried out under the virtual control of numerical simulations with "LS-DYNA - metal forming", and new proposals or modifications of shapes and actions were made in the numerical space, which replaces expensive real experimental tests-verifications. Precessional bevel gears have a complex geometry, operating in multiple simultaneous contacts, thus the teeth are relatively weak mechanically stressed. The requirements for the material properties of this gears are relatively lower than traditional ones and it is possible to be form them from aluminum alloys and in particular from the aluminum alloy EN AW 6082 by cold forming processes at sufficiently high plastic deformation intensities without cracking. Namely this alloy was chosen as the material for the in closed die forging of the bevel gear wheel.

Very important for the design process of the proposed technology are the experimental tests to establish the mechanical characteristics of the deformed material. The plastic characteristic curve of the material (established experimentally with deviations of ± 3%) was extended to cover the largest possible plastic deformations in the applied technological process (fig. 4). The extension was made starting from the real characteristic diagram obtained on the compression of the series of 10x10 and 20x20 cylindrical samples, from which the elastic component of the deformation was eliminated.

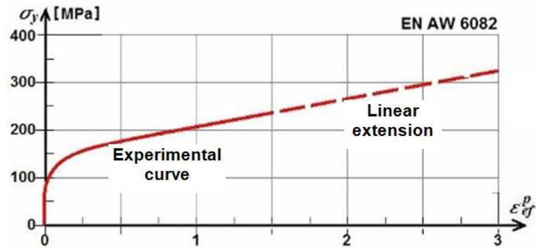

Fig. 4. Extrapolated plastic characteristic

The design of the technological process of closed die forging of a complex-shaped precessional bevel gear, by severe deformation, was based on three technological-economic criteria:

- the geometric shape of the initial blank should be simple – disc-shaped,
- the minimum possible amount of material consumed - minimum flash and machining allowances,
- the minimum energy and forces necessary to form the part by scheduling in time and synchronizing the plastical flow processes on distinct stages.

At the heart of the activity of establishing the technological process of plastical forming, at an industrial level, is the interaction between the active parts of the closed die's elements with the blank, in various distinct stages of the deformation process.

The aim was to establish the shapes of the closed die's active parts, as well as their optimally synchronized actions. The complexity of the closed die implies a complicated action system. The adaptation and virtual integration of the closed die in various aggregation variants were activities carried out by controlling the plastic deformation process provided that the effective value of the plastic strain to fracture was not exceeded (fig. 1).

2.1. Shape analysis

The shape and dimensions of the gear wheel, obtained by cold pressing, must correspond to the reconsidered dimensional requirements according to figure 3.

The existence of the toothed crown makes the product be assigned to the class of objects of medium complexity. The solid wheel hub with a lot of embedded material increases the degree of complexity of the shape, without essentially modifying the plastic deformation scheme. If, however, the profiling of the central bore is included in the unique deformation operation, then the term used in the work of *severe plastic deformation in complex shapes* becomes justified. The complexity of the shape also implies an increase in deformations as a result of the intensive transit of the material.

Another shape characteristic, with influence on the technological design process, is the variable thickness of the product. The flow of material through the narrowed areas is slowed down due to the hardening of the material following the increase in effective deformation and due to the increase in the influence of frictional forces.

From an economic point of view, regarding material consumption, a closed forging is clearly superior to a free one. However, the closed die is subjected to a very harsh mechanical stress regime. In a closed die, towards the end of pressing, when the internal free space is reduced to zero, the pressure in the constrained material the yield stress to three to four times can increase. The protective measure against this phenomenon is the provision of security flashes. The main advantage of using a closed die is to create a product as close to the final shape as possible, in a single pressing. For this reason, the closed die forging is a special construction, which operates with pre-tightening, in a conical hooping regime, which must be covered by a resistance calculation with reasonable safety coefficients and by choosing superior materials for the components in order to reduce the risk of unauthorized production of flashes. Based on the experience of UPS PILOT ARM in the field for similar applications, the use of high alloy tool steel EN X210Cr12 was envisaged. At the same time, the aggregate in which the closed die is incorporated must be capable to developing the forces necessary in the pressing process.

The initial technological project was developed for two forms of the bevel gear, both with a hub, one solid, the other with a bore, pressed in a closed die in a single operation.

The first variant is achieved through two main operations: severe plastic deformation in the closed wheel die with the formation of the solid hub; drilling the hub. The second technological variant, more direct and efficient, is achieved in a single operation of severe plastic deformation in a closed die, the hub being formed with a bore.

Preliminary estimates, simulated on reduced models for the technology under design, complement and support the observations regarding the analysis of the product shape and denote plastic flow in different directions and the existence of stagnation zones (fig. 5). Regarding the performance of the power unit, simulations showed that a minimum force of 2MN (200 tf) is required. It is confirmed that the pressing force in the closed die has a rapid growth evolution at the end of the process.

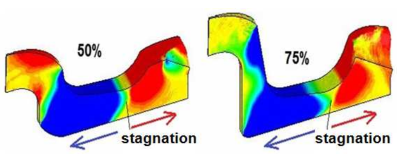

Fig. 5. Radial material flow

In the die-forged bevel gear, the predominant material is found in the crown gear and in the hub, especially if it is provided without a bore (Fig. 3). Using a preformed blank would have been an advantage, reducing the main pressing effort.. In schimb, ar complica procesul tehnologic prin introducerea unei operatii in plus (un dezavantaj major), nu doar prin operatia in sine, ci si din cauza complicarii liniei tehnologice [9]. In order to comply with the basic technological and economic criteria previously established, a blank in the form of a disc with an external diameter of 39 mm, cut from a bar or strip, was adopted. In the simulation process, blanks with variable thicknesses around 4 mm were used. In the simulated technological design process, the product shape in non-functional areas was adjusted minimizing material transit from one area to another.

The final shape of the closed die forged bevel gear in non-functional areas is determined by the rigidity and strength conditions. The variable thickness of the initial blank's disc taken into account allowed the optimization of the wheel shape under conditions of equal resistance. The technological adequacy of the final shape, adopted for the gear wheel, is supported by

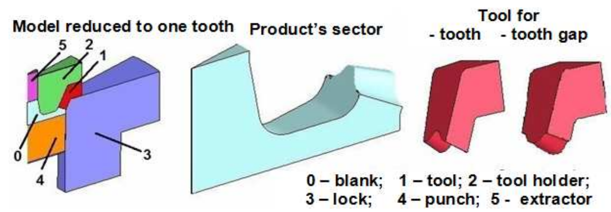

Fig. 6. The reduced model on a sector corresponding to a tooth (gap)

Figure 5, which represents the radial plastical flow of material in the meridian plane. The section highlights two plastical flow zones, with opposing material flows, separated by a small stagnant zone. Two instantaneous deformed states (represented in blue and yellow), halfway and three-quarters of the process demonstrate a practically unchanged position in space of the stagnant zone.

The final shape of the die forged bevel gear was finalized after a series of preliminary simulations in which models for the gear and the die were tested.

2.2. Preliminary tests

Preliminary tests were carried out through numerical simulation on models whose complexity was progressively increased, until the final model. All preliminary tests started from the same blank in a simple disc shape, with an adjustable thickness of approximately 4 mm, made of EN AW 6082 aluminum alloy. During the preliminary testing stage, answers were sought and found to all issues related to the shapes and dimensions of the active surfaces, the parameters of the die components' actions, their synchronization, the die filling, and the state of triaxial compressive stress that ensured the process of severe plastic deformation in complex shapes

The first attempts were made on models reduced to one tooth, and respectively, to one gap, the symmetries allowing the division of the wheel into models suitable for simulation (fig. 6). All parts of the mold (fig. 6), except the punch (4), are shown in the working position. The blank (0) is installed in the die. The punch''s action is provided from bottom to top, being sized to ensure complete filling of the mold within 2 seconds. In the first tests, only the plastic deformation phase in the closed die of the blank (0) in the shape of a sector (fig. 6) was observed. The meridian planes that delimit the sector-shaped model remain fixed and impenetrable. By changing the tool (1) in the simulation, either a tooth or a gap can be formed through plastic deformation.

2.3. The subtlety of the mesh

The meshs, with the conventional names "fine" and "medium", are given for comparison in figure 7. The sparse mesh with 53266 elements is not compatible with the required level of accuracy and has been removed. Fine mesh would be ideal, but it consumes a lot of computing resources. The compromise solution turned out to be the mesh qualified as medium for both the solid hub and the pierced hub variants.

The representation in Figure 7 shows the mesh density in the area where the teeth are to be formed. The entire blank was discretized with approximately 3,000,000 finite elements.

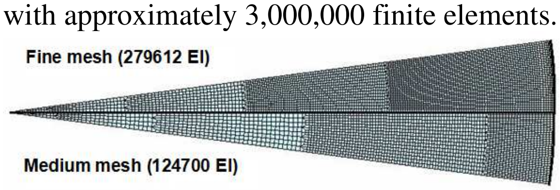

Fig. 7. Discretization of the blank's sector

The structural components of the die are discretized, under elastic operating conditions, with rare meshes.

A very useful test for evaluating the mesh's density is related to the problem of convergence of simulated numerical solutions.

The test consists of numerical simulation, for series of increasing discretization densities. When two successive solutions meet the precision condition and become sufficiently close in value, the calculation stops, declaring the solution convergent. As a convergence criterion, the pressing force on the model reduced to one tooth, hub without bore was chosen (fig. 6), simulated for the three different mesh densities. The Force-Time curves recorded during the simulations are given in figure 8.

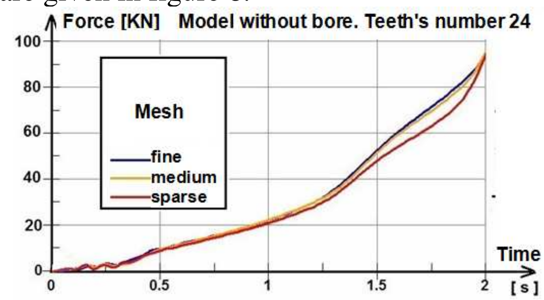

Fig. 8. Deformation force as a function of the mesh's fineness of discretization

The convergence of the numerically simulated solutions is observed and it is noted that the two curves obtained for the cases with medium and fine discretization are very close, even overlapping. The maximum associated deviation on the convergence graph of approximately 2.5% is sufficiently well covered by the permissible technical error of 5%.

2.4. Improving technology

The next solution analyzed, more technological and efficient, is designed to simultaneously produce the gear crown and the hub with bore. The scheme works with separate, but synchronized actions for each of the formed elements.

In the new reduced model, very few changes were introduced compared to the one previously addressed. The teeth area was taken over entirely from the solid hub's model, the bore mandrel was added to the hub area, centered in the punch (Fig. 9). On this model, the plastic deformation (forge drawing and extrusion) of the hub was left free, in order to test several synchronization variants.

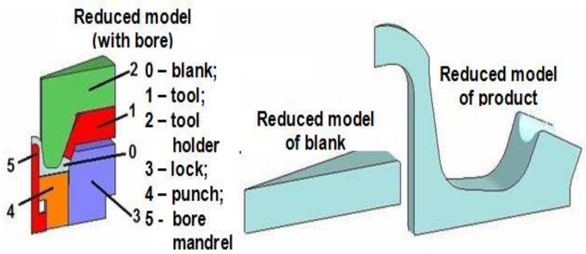

Fig. 9. Forming the hub with a bore, model reduced to a gap

The action mode of the mandrel is synchronized with the main action of the punch, provided that a state of triaxial compressive stress is maintained in the wall's thinned of the hub, in order to avoid exceeding the value of effective plastic strain to fracture (fig. 1) and not producing micro-, macro-cracks or ruptures.

In this combination, the material flows into the wall of the hub, once pushed by extrusion, under the action of the punch and then drawn by forge drawing by the mandrel head.

The coordination of these two actions has been the subject of numerical simulation attempts. If this problem is not correctly solved, it can lead to a situation where the mandrel dominates the action, producing a state of tensile stress in the hub wall, favorable to cracking. At the other extreme, the mandrel can slow down the flow of material and an unjustified increase in extrusion force occurs.

This phenomenological explanation highlights the risks of establishing the aggregate's operating cycle if a thorough analysis of the process is not made.

During a functional cycle, the two mechanical actions are predefined by time durations, which the aggregate must reproduce faithfully.

The plastic flow state in the die, characterized by the stress and deformation states, evaluated through numerical simulations, represents basic arguments for the technological design process.

The establishment of the functional cyclogram required optimization of the internal friction processes in the die.

2.5. Model reduced to 1/4

This model was built by multiplying the reduced model with a solid hub, being delimited by two meridian planes of symmetry, arranged at 90° and comprising 6 teeth (Fig. 10).

To avoid the overload condition of the closed mold, a simpler version was chosen, without a limiting buffer.

The 1/4 reduced model was introduced into the study to validate the solutions and conclusions established on the unitary models. At the same time, on this model, the availability of the simulation program and the performance of the computer were tested.

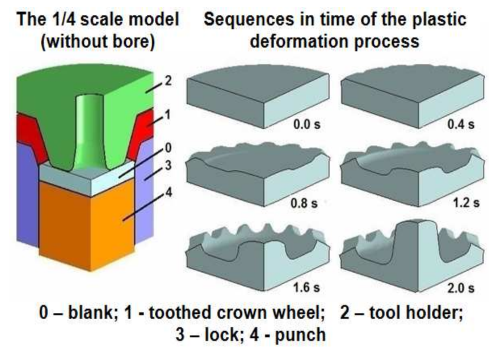

Fig. 10. The 1/4 scale model with the hub without bore

The pressing force was taken as the validation criterion, under identical conditions for both compared models. The plastic formation of the hub in the reduced to one tooth model was considered unlimited by the stop. The condition is satisfied up to 1.9 s, except when the hub extrusion becomes the preponderance to the forge drawing.

In figure 11, the pressing forces are compared and, next to them, the pressures in the material of the wheel teeth are represented at the moment of completion of the pressing process of the wheel with solid hub and with pierced hub. There are important differences between the forces, which in the end exceed 50%, but along the way they become double and even more (1.5 s.). The tensions in the material, as a calculation quantity with which the intensity in the die stress is assessed, maintain approximately the same percentage difference (44%)

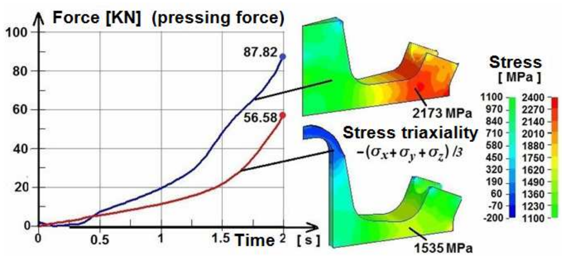

Fig. 11. Pressing force on the reduced 1/4 model

2.6. Finalization of the precessional gear model resulting from severe plastic deformation technology

In figure 12 the effective plastic strain and the effective stress are represented.

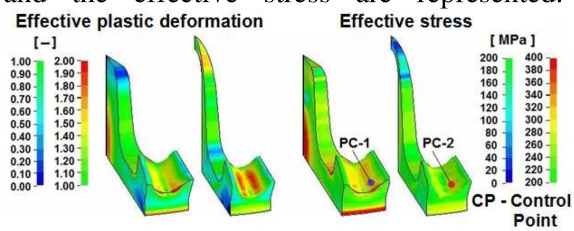

Fig. 12. The plastic state at the end of process

All the aspects analyzed, regarding the advantages and disadvantages (including the state of tension at the control points) of the two technological proposals, undoubtedly guide the option for the gear wheel pressing technology in a single operation, with simultaneous formation of the teeth and of the pierced hub. Following the analyzes of the various aspects of the process of making a model of a gear wheel, which respects the basic conditions in drawing no. TPP-03.05 regarding gearing, tooth profile, size and tolerances, the solution given in figure 13 was reached.

The accepted shape for the gear wheel has some non-essential differences, dictated by technological and conceptual reasons, compared to the reference model (fig. 16).

The formation by severe plastic deformation of the tooth profile, the dimensions and positioning of the teeth crown relative to the central bore are ensured according to the requirements in figure 3. The gear body tends to take a shape of equal strength, with large connection radii (R3), favorable to forge technology in closed die.

Within the framework of numerical simulations, the dimensional control procedure also becomes functional. Details A and B (fig. 16) show the results of measurements made with the LS-DYNA dimensional control system of a die forged virtual bevel gear. The maximum diameter has practically zero deviation, and the bottom cone angle has a deviation of 0.04° - half of the permissible one. This deviation, being determined by physical-technical phenomena of plastic deformation, is a one systematic and can be excluded.

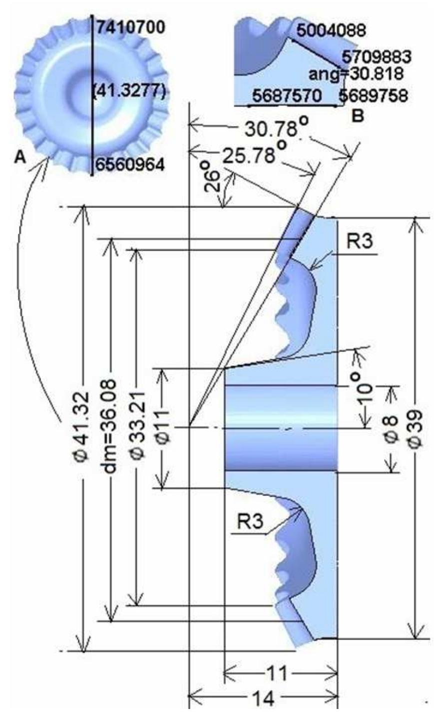

Fig. 13. Precessional bevel gear resulting from the technological project

The die forged bevel gear wheel obtains its final shape and dimensions after bore calibration processing and flat mashining of the free face.

3. CONCLUSIONS

1. The digital simulation of cold plastic deformation processes proves to be an effective tool for designing forging technologies in closed die for components exhibiting complex geometries, including, notably, precessional bevel gears.
2. Analysis of the simulated plastic flow behavior during the closed die forging of a

precessional bevel gear yields the following observations:

✓ Formability and workability by plastical deformation depend on both the material and the shape of the forged part, i.e. it is a material-shape situational term.

✓ High-intensity plastic deformation without the manifestation of cracking phenomena positions the forging process in closed die within the regime of severe plastic deformation. This regime is characterized by pronounced triaxial compressive stress states, resulting in constrained plastic flow and a concomitant increase in the required forging force.

✓ The model of the forged part used in simulations must be mainly equivalent to the reference part model, but also contain elements adapted to the particularities of the plastical flow process.

✓ Precessional bevel gears present complex axisymmetric geometry, exhibiting three distinct zones of material distribution resulting from plastic deformation:

a) the gear crown formed by redistributing material from the inter-tooth gaps to the teeth into almost identical volumes,

b) the solid or bored hub, which, during plastical forming, necessitates significant material transfer via extrusion from the upset forging zone,

c) the rim, formed by upset forging, possessing a geometric shape dictated by the characteristics of radial plastical flow in opposing directions relative to a stagnation zone.

✓ To improve the closed die forging process, a better balance between the masses of material placed in different areas of the die forged gear is necessary. It is preferable to form the wheel with a bore in the hub.

✓ The formation of the bore in the hub requires plastic deformation actions located both in the teeth area and in the hub area, making it necessary to include in the closed die structure of a mandrel with an action separate from the punch, but synchronized with its action.

✓ Preliminary simulations can be done successfully on partial models reduced to one tooth, respectively, to a inter-tooth gap, to quarter-section of the gear, with the meridian planes of symmetry remaining fixed and impenetrable.

✓ Numerical simulations with LS-DYNA allow dimensional control on the virtual forged model, and deviations, being caused by physical-technical phenomena of plastic deformation, are systematic and can therefore be excluded.

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Proiectarea simulată a tehnologiei de matriţare a roţii dinţate conice precessionale prin deformare plastică severă la rece

Rezumat. *Simularea proceselor de forjare cu matriță închisă este un instrument puternic de proiectare-optimizare tehnologică care oferă detalii privind evoluția formei, curgerea plastică, forțele de forjare necesare, stările de solicitare și deformare, permițând astfel excluderea testelor repetate reale costisitoare. În această lucrare, instrumentul de simulare LS-DYNA este utilizat pentru proiectarea tehnologiei de forjare a angrenajului conic precesional în matriță închisă, în urma unor simulări preliminare pe modele parțiale reduse la un dinte, respectiv la un gol, simulări pe modele reduse la 1/4 din roata si pe modelul integrat. Se constată că este de preferat să se formeze roata cu un orificiu în butuc, deoarece aceasta asigură un echilibru mai bun între masele de material situate în diferite zone ale angrenajului conic forjat cu matriță pornind de la un semifabricat sub formă de disc. Formarea alezajului în butuc necesită acțiuni de deformare plastică localizate atât în zona dinților, cât și în zona butucului, ceea ce face necesară includerea în structura matriței închise a unui dorn cu acțiune separată de poanson, dar sincronizată cu acțiunea acestuia.*

Cuvinte cheie: *Cuvinte cheie: roţi dinţate conice precesionale, simulare digitală, tehnologie de matriţare la rece, matriță închisă*

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