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ANALYSIS OF TWO-DIE AND FOUR-DIE FORGING PROCESSES IMPLEMENTED ON HYDRAULIC FORGING PRESSES AND RFM

Abstract

Presented in this paper is a comparative analysis performed by means of technology simulation based on FEM method using DEFORM 3D tool. The following processes were analyzed:

- forging on a hydraulic press between two dies according to a conventional technology;
- forging on a four-die radial forging machine (RFM);
- forging on a forging press in a four-die forging device (**FDFD**) according to five different technologies;
- combined forging on a forging press consisting of two-die forging and four-die forging in an **FDFD**.

The presented analysis shows that forging in **FDFD** has a beneficial effect on distribution of stresses, strain and temperature in a workpiece. It must certainly improve quality of the forgings and metal yield.

Production output when forged in **FDFD** is 1,6 to 3,0 times higher as compared to two-die forging process and also higher than the forging output of RFM.

Keywords

Four-Die Forging, forging press, ingot, technology, stresses, deformation.

1. Introduction

Process of drawing the ingots using a four-die radial forging machine (RFM) is more advanced forging technique, if compared to the two-die forging process used on a forging press. However, the main characteristic for a forging process performed in RFM is a laminar metal flow with no turbulence and not sufficient reciprocal displacement of metal particles relative to each other; besides this, relatively small single reductions are inherent to this forging technique. This process results in deformation localized mainly in surface zone of a forging and in a poor deformation treatment of its core zone.

Hydraulic forging presses belong to multi-purpose equipment and can be used for a variety of forging operations aside from the drawing. Besides this, forging presses are relatively widely used globally.

At conventional two-dies forging process metal flows between the dies both in the direction of elongation axis and perpendicularly to this axis, too. On the one hand, it contributes to a better deformation treatment of metal structure, but on the other hand, it results in a significantly reduced drawing operation output. Moreover, due to considerable workpiece lateral spreading a risk of metal rupture under high reduction rates appears.

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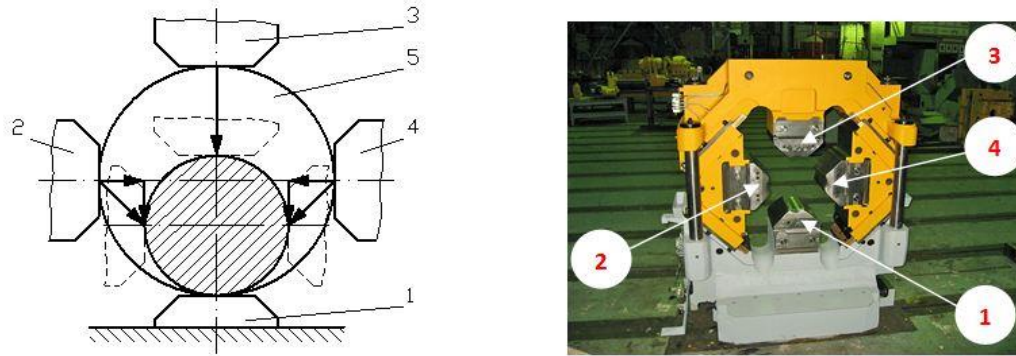


Fig.1. Four-die forging device and reduction schedule

A pattern of dies movements when forged in **FDFD** on a forging press is presented in Fig. 1 [1-4]. During each single reduction a turbulent metal flow is generated, thus, resulting in the intensive deformation treatment of metal structure combined with a high output of the forging process.

Presented and discussed in this study is the FEM-based evaluation of technological capabilities of two-die and four-die forging techniques used for presses, and also for radial forging machines.

2. Finite Element Analysis of Forging Processes

The analysis of various technologies, which are used to forge ingots between two and four dies was conducted using the software package, **DEFORM 3D**, which is intended to study three-dimensional (3D) metal behavior at various metal forming operations. This software has been specially adapted for forging processes performed in RFM's and on forging press equipped with **FDFD**.

Technique No. 1. A two-die forging process for 30 MN hydraulic forging press; 25 passes, diameter of an ingot is $\text{Ø}600$ mm. The forging schedule is as follows:

Ingot: $\text{Ø}600$ mm (1, 0°) \rightarrow 530x630 mm (2, 90°) \rightarrow 530x550 mm (3, 90°) \rightarrow 470x550 mm (4, 90°) \rightarrow 470x490 mm (5, 90°) \rightarrow 400x490 mm (6, 90°) \rightarrow 400x420 mm (7, 90°) \rightarrow 350x420 mm (8, 90°) \rightarrow 350x370 mm (9, 90°) \rightarrow 300x370 mm (10, 90°) \rightarrow 300x320 mm (11, 90°) \rightarrow 260x320 mm (12, 90°) \rightarrow 260x280 mm (13, 90°) \rightarrow 255x280 mm (14, 90°) \rightarrow 255x265 mm (15, 90°) \rightarrow 255x335 mm (16, 45°) \rightarrow 290x335 (17, 90°) \rightarrow 290x300 mm (18, 90°) \rightarrow 255x300 mm (19, 90°) \rightarrow 255x255 mm (20, 90°) \rightarrow 255x255 mm (21, 45°) \rightarrow 255x255 mm (22, 90°) \rightarrow $\text{Ø}250$ mm (23, 45°) \rightarrow $\text{Ø}250$ mm (24, 40°) \rightarrow $\text{Ø}250$ mm (25, 35°) \rightarrow $\text{Ø}250$ mm.

The figures in parentheses provided after the ingot size are the number of the pass and the angle of rotation of the blank around its longitudinal axis. The forging from the 1st to the 19th passes is performed using two flat dies. After the 9th pass, the blank is re-heated. Starting from the 20th pass the finishing is performed between two channel dies. After each pass (1st through 22nd) the blank is turned at an angle shown after the size of the workpiece in parentheses, and during the passes 23^d to 25th the blank is rotated by an angle of 45° , 40° or 35° after each single reduction and each feed step. Workpiece feed rate is 200 to 260 mm.

Technique No. 2. Forging the $\varnothing 600$ mm ingot in a 16 MN four-die radial forging machine; 9 passes. The forging schedule is as follows:

Ingot: $\varnothing 600$ mm (1) \rightarrow $\varnothing 560$ mm (2) \rightarrow ... \rightarrow $\varnothing 250$ mm (9) \rightarrow $\varnothing 250$ mm.

Technique No. 3.1 – 3.4. Ingots forging in **FDFD** installed in 30 MN hydraulic forging press. The workpiece feed rate is 200 to 250 mm for all passes except the last one. Finishing is performed at the last pass. Comparison of the technologies discussed here was made using initial ingots of the same cross-sectional area: round ingots of $\varnothing 600$ mm and square ingots of 532 x 532 mm.

Technique No. 3.1. $\varnothing 600$ mm ingot forging in **FDFD** installed in 30 MN forging press; 10 passes (with no metal spreading between the dies). The forging schedule is as follows:

Ingot: $\varnothing 600$ mm(1, 45°) \rightarrow 560 mm (2, 45°) \rightarrow ... \rightarrow 250 mm (10, 20°) \rightarrow $\varnothing 250$ mm.

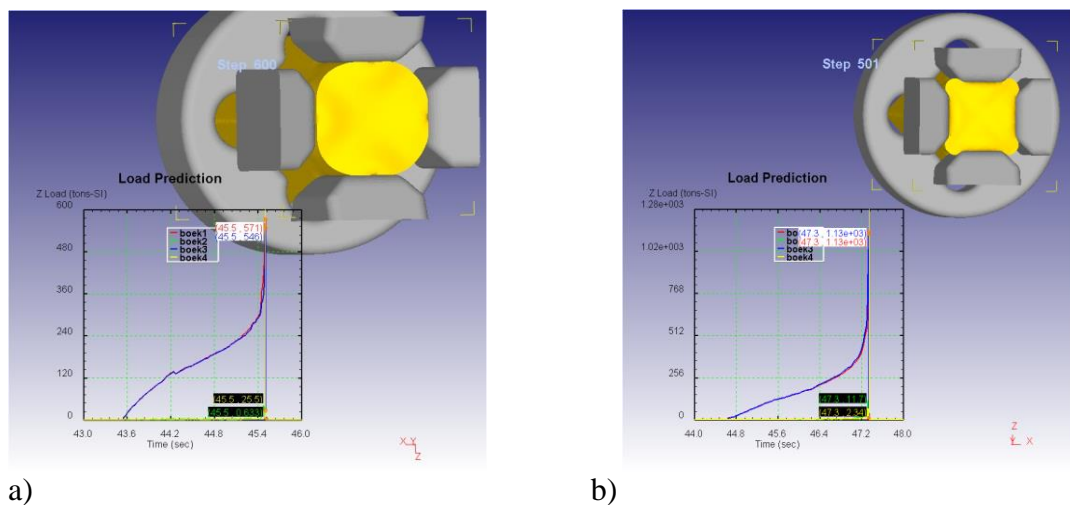


Fig.2. Ingot forging in FDFD according to Technique No. 1.

Technique No. 3.2. $\varnothing 600$ mm ingot forging in **FDFD** installed in 30 MN forging press; 6 passes (with metal spreading between the dies). The forging schedule is as follows:

Ingot: $\varnothing 600$ mm (1, 45°) \rightarrow 480 mm (2, 45°) \rightarrow ... 250 mm (6, 20°) \rightarrow $\varnothing 250$ mm.

Technique No. 3.3. 532x532 mm ingot forging in **FDFD** installed in 30 MN forging press; 9 passes (with no metal spreading between the dies). The forging schedule is as follows:

Ingot: 532x532 mm (1, 45°) \rightarrow 500 mm (2, 45°) \rightarrow ... \rightarrow 250 mm (9, 20°) \rightarrow $\varnothing 250$ mm.

Technique No. 3.4. 532x532 mm ingot forging in **FDFD** installed in 30 MN; 5 passes (with metal spreading between the dies). The forging schedule is as follows:

Ingot: 532x532 mm (1, 45°) \rightarrow 400 mm (2, 45°) \rightarrow ... \rightarrow 250 mm (5, 20°) \rightarrow $\varnothing 250$ mm.

Technique No. 4. $\varnothing 600$ mm ingot forging in **FDFD** installed in 30 MN forging press; 8 passes with pre-forging using the helical paths (1-3 passes). The forging schedule is as follows:

Ingot: $\varnothing 600$ mm (1, 15°) \rightarrow $\varnothing 560$ mm (2, 15°) \rightarrow ... \rightarrow $\varnothing 250$ mm (8) \rightarrow $\varnothing 250$ mm.

Technique No. 5. Combined process technology for $\varnothing 600$ mm ingot forging; 10 passes. The ingot is first forged with two flat dies on a 30 MN hydraulic forging press, and then with four dies on the same press using FDFD. The forging schedule is as follows:

Ingot: $\varnothing 600$ mm (1, 0°) \rightarrow 530x630 mm (2, 90°) \rightarrow ... \rightarrow 250 mm (10, 20°) \rightarrow $\varnothing 250$ mm.

Initial ingots used to study eight process technologies presented in this paper were made of 9Cr1Mo steel and had the same length and cross-sectional size. They were heated up to 1260°C . Before forging, the dies were pre-heated to a temperature of 250°C .

Presented in Figs. 3-7 below are the relationships between longitudinal and transverse stresses in a workpiece.

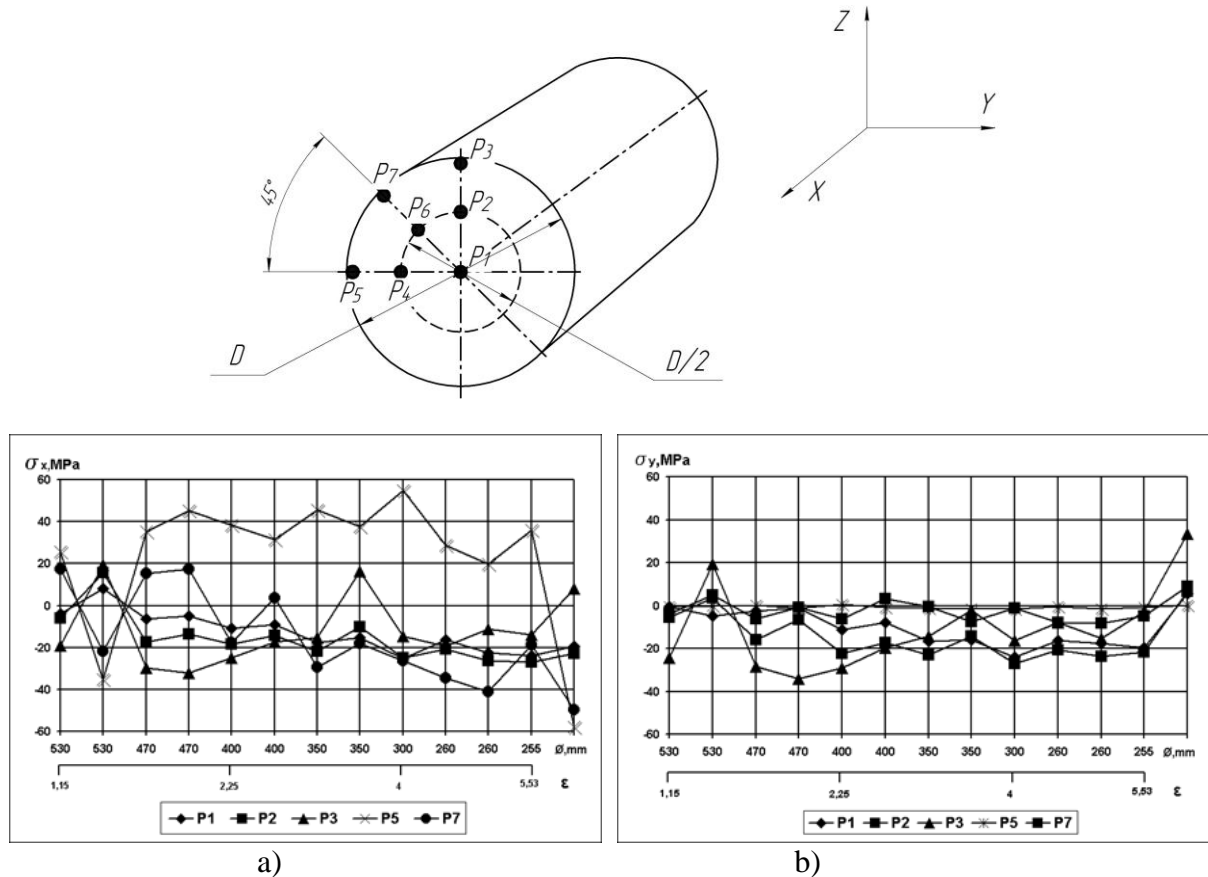


Fig.3. Relationship between longitudinal (σ_x) and transverse (σ_y) stresses in the workpiece depending upon its cross-sectional size (deformation ratio) in case of forging technique No.1

The charts presented above show that a forging operation between four dies in FDFD and in RFM in comparison to two-die forging technique generates mainly compressive stresses. The most considerable tensile stresses are the longitudinal stresses generated on the surface of a workpiece and located at the points of maximum material spreading when forged between two dies (point P5) (Fig.3,a).

Longitudinal tensile stresses at the maximum workpiece spreading locations when forged in FDFD are lower as compared to forging in RFM (Fig.4, Fig.5).

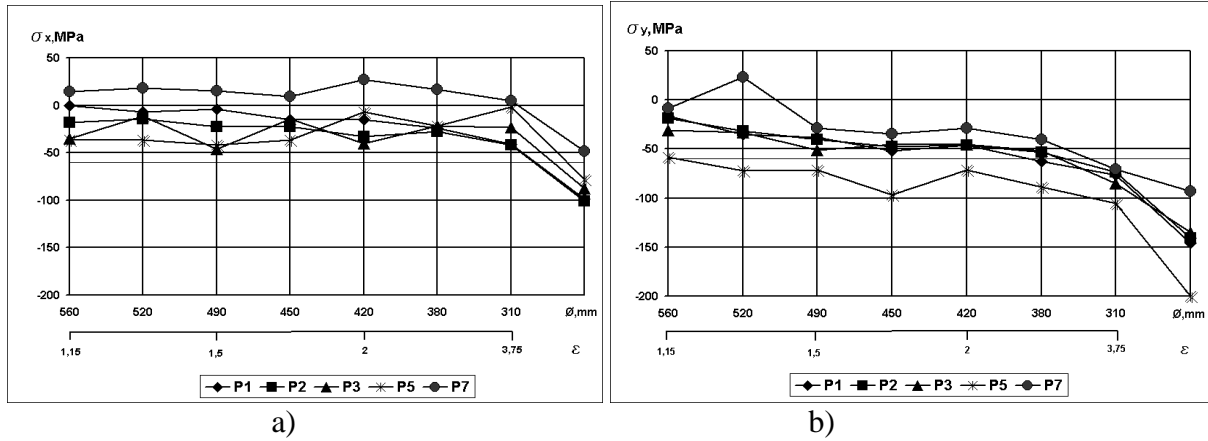


Fig. 4. Relationship between longitudinal (σ_x) stresses in the workpiece and its cross-sectional size (deformation ratio) in case of forging techniques No.3.1 (a) and No. 2 (b).

The transverse stresses are compressive at all analyzed points of the workpiece, and they increase along with the deformation ratio of the workpiece.

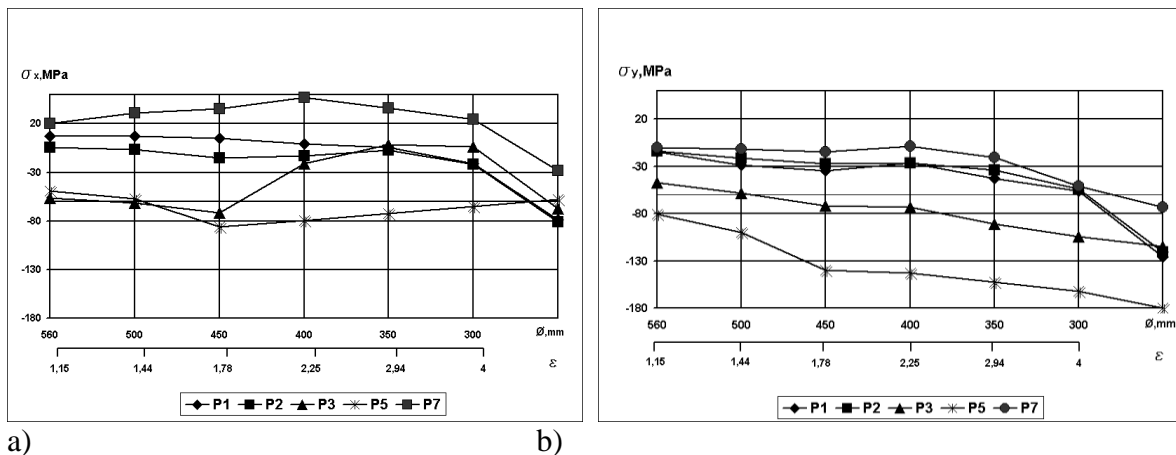


Fig. 5. Relationship between transverse (σ_y) stresses in a workpiece and its cross-sectional dimensions (deformation ratio) in case of forging techniques No. 3.2 (a) and No. 3.3 (b)

Forging operations performed in **DFDs** according to Techniques No. 3.1 and No. 3.3 involve no metal spreading between the dies, and workpiece reduction values at each pass are relatively small. These technologies are normally applicable when the press force is not sufficient to perform forging operations with high reductions or when forging low-ductile alloys. However, when there are no such limitations, process technologies based on Techniques No. 3.2 and No. 3.4 are preferable, as large reductions result in considerable metal spreading between the dies. A comparative analysis of above mentioned **DFD** forging technologies used to forge workpieces of equivalent cross-sectional area into identical forged products proved that in case of square workpiece one pass less was required as compared to the forging of workpieces with round cross-section.

When using **DFDs** to forge round cross-section workpieces with large reductions that result in metal spreading between the dies (Technique No. 3.2, Fig.5), the maximum compressive longitudinal and transverse stresses in the core zone of the workpiece (Points P1 and P2) are much (roughly 2 - 2,8 times) higher than the maximum compressive stresses, which occur not

only during two-die forging processes but also when forging approximately the same workpieces in the FDFD without metal spreading between the dies (Technique No. 3.1.).

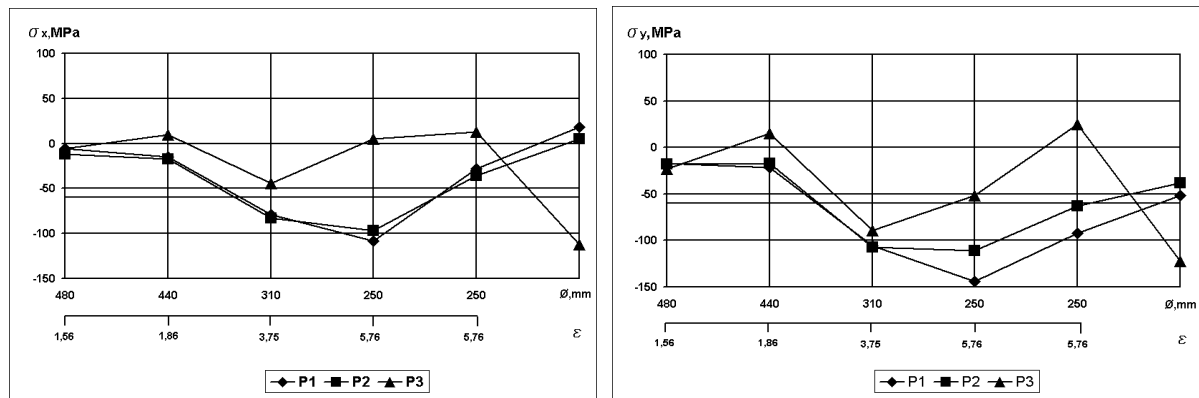


Fig. 6 Dependence of longitudinal (σ_x) and transverse (σ_y) stresses in a workpiece upon its cross-sectional size (deformation ratio) in case of forging technique No.3.2.

The maximum compressive stresses (-108 and -144 MPa) are achieved at the 3rd and 4th passes during a forging process with maximum reductions of 170 – 220 mm per pass (Technique No. 3.2). The greater is the degree of deformation in a forging process using **FDFDs**, more compressive stresses are generated in the core zone of the workpiece.

Quite a different situation is observed when it comes to forge workpieces of square cross-sections involving workpiece reductions along the ribs of a workpiece. The maximum compressive longitudinal and transverse stresses in the case of forging in **FDFD** with large reductions (with metal spreading between the dies) (Technique No. 3.4, Fig.6) are only 8-15% higher than the maximum compressive stresses occurring in the core zone of the workpiece when it is forged without metal spreading between the dies (Technique No. 3.3, Fig.5,6). In addition, the following results were recorded in forging the blanks of round and square cross-sections (with reductions along the ribs of the square shape):

- When forging workpieces of square cross-section without metal spreading between the dies (Technique No. 3.3), the maximum compressive stresses are much (1,8 – 2,4 times) higher than the maximum compressive stresses, which occur when forging round workpieces of identical cross-section area without metal spreading between the dies (Technique No. 3.1);
- When forging workpieces of square cross-section with metal spreading between the dies (Technique No. 3.4), the maximum compressive stresses are roughly equal to the maximum compressive stresses occurring when forging round workpieces of identical area with metal spreading between the dies (Technique No. 3.2).

When forging in **FDFD** according to Technique No. 4 (forging using the helical paths), stress distribution pattern in a workpiece appears to be different from those observed both when forging in RFMs and conventional forging in **FDFD** (Fig.7). During the first two passes, minor longitudinal tensile stresses are generated in the core zone of the workpiece (Fig.7,a), which are then transformed into compressive stresses at the third pass. In case of forging in FDFD using the helical paths, transverse stresses remain compressive throughout the entire process (Fig.7,b).

Evaluation of metal damage incurred during the forging process was performed by means of *Cockroft & Latham* [5] method, which is natively incorporated into the software package *DEFORM 3D* as a basic model of metal failure under a high plastic strain. The less is the value of the damage factor based on the *Cockroft & Latham* equation, the smaller portion of the material plasticity margin is used up, and hence the lower is the probability of cracking.

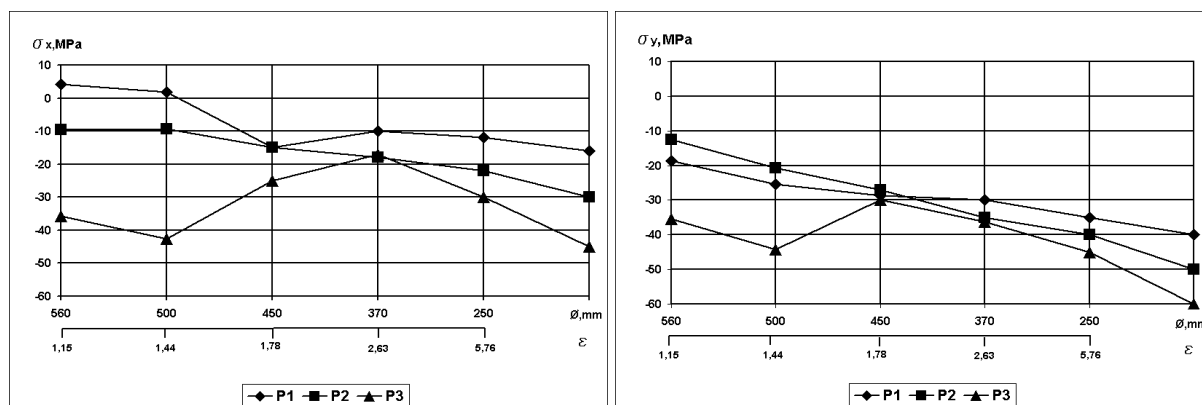


Fig. 7. Dependence of longitudinal (σ_x) and transverse (σ_y) stresses in a workpiece upon its cross-sectional dimensions (deformation ratio) in case of forging via Technique No.4.

The obtained results prove that Damage Factor ‘C’ in the core zone for all forging technologies remains roughly the same within the analyzed size range (deformation ratio) of forgings. However, the value of Damage Factor ‘C’ at Point P5 (close to the surface of the blank) when forged between two dies is higher than that observed during a four-die forging process in **DFD** under the most tough forging schedule (Technique No. 3.4), starting from a workpiece size of 400 mm (deformation ratio $\geq 30\%$). This factor in case of Technique No. 1 even exceeds “1,” which is indicative of the possibility of damage to the metal in the case of two-die forging.

The technologies studied in the paper were also analyzed in terms of maximum values of the main strains depending upon the workpiece cross-sectional size (deformation ratio) at each pass. Presented in Fig.8 are the graphs for maximum main strains in the core zone of the workpiece as a function of a pass number and the deformation ratio per pass for two-die forging process, when forging in RFM, and also for forging in **DFD** both with- and without metal spreading between the dies. The main strains in the core zone of the workpiece were found to be highest when forging in **DFD** with metal spreading between the dies, while the lowest main strains were observed for two-die forging operations. The maximum main strains in the core zone when forged using RFM were found to be also higher than the maximum main strains observed during a two-die forging process, but they did not exceed the values of the main strains in case of forging in **DFD**. Thus, the process of forging in **DFD** allows creating more favorable conditions for deformation treatment of metal, if compared to two-die forging.

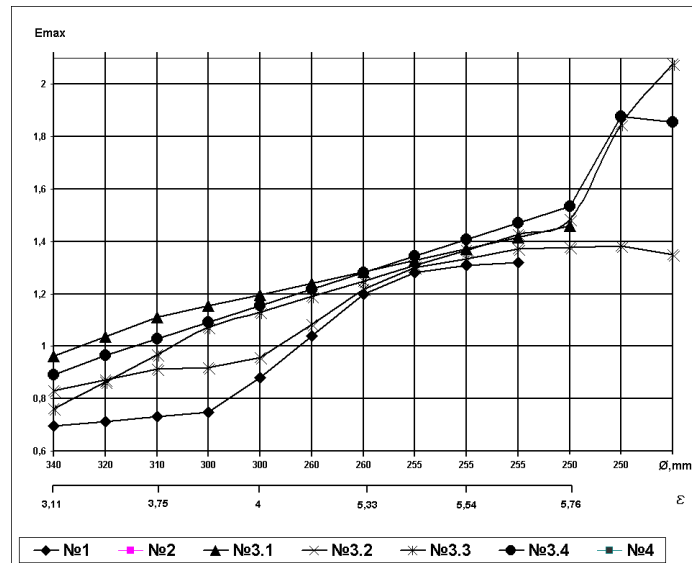


Fig.8. Dependence of the maximum main strains observed in the core zone and the surface layer of a workpiece upon its cross-sectional size (deformation ratio)

Large deformations in the core zone of the workpiece combined with additional shear strains when forged in **FDFD**s support a better voids closure, as well as more intensive crushing of non-metal inclusions, coarse carbides and carbide clusters in cast metal.

Temperature conditions of the forging processes were studied using similar initial ingots pre-heated up to 1260°C.

The forging temperature conditions were assessed for the two-die forging process (Technique No.1) and forging in **FDFD** (Technique No. 3.1). In case of two-die forging, the workpiece (with a cross-section area of 300x370 mm) was additionally re-heated after the ninth pass. The obtained data proves that in case of a two-die forging process, even with an additional re-heating, the surface of the workpiece cools down much faster than in case of forging in **FDFD**, while for the both forging techniques the temperature in the core zone remains the same and stays at the level of initial metal temperature. At the final stage of the forging process (finishing stage) the temperature of metal on the forged part surface for two-die forging process is much lower than metal temperature in the case of forging in **FDFD**. It proves that forging in **FDFD** generates considerable deformation heating of metal which results in significant reduction of the forging cycle duration.

Calculations of forging forces at each pass for all studied technologies were performed by means of DEFORM 3D software package. The calculations were based on the following parameters: feed rate, reduction time, pause time between reductions, actual temperature of metal at the time of reduction, deformation ratio and strain rate and also the temperature of the dies.

The obtained data proves that under above mentioned reductions per pass and feed rates within 200 – 250 mm the forging force generated during forging in **FDFD** are considerably (2 – 2,5 times) higher that those generated during two-die forging operations for the same feed rates. Service experience of **FDFD**s has shown that in some cases the press power may be not sufficient for such forging schedules. To overcome such limitations, various special techniques can be used for forging in **FDFD**.

Thus, for example, during the first forging passes when a workpiece is still rather of large cross-sectional dimensions and of a relatively small length, forging operation is performed with minimum feed rates and the same reductions. This approach makes it possible to significantly reduce the applied forging forces in such way that they approach those generated

during two-die forging operation. When the workpiece cross-sectional dimensions are sufficiently reduced using the described above method after the first passes, the feed and reductions rates can be increased.

Another technique which can be used to reduce forging force requirements is as follows: first a workpiece is forged between two dies, and then, without any re-heating it is finally forged in **FDFD** (Technique No. 5).

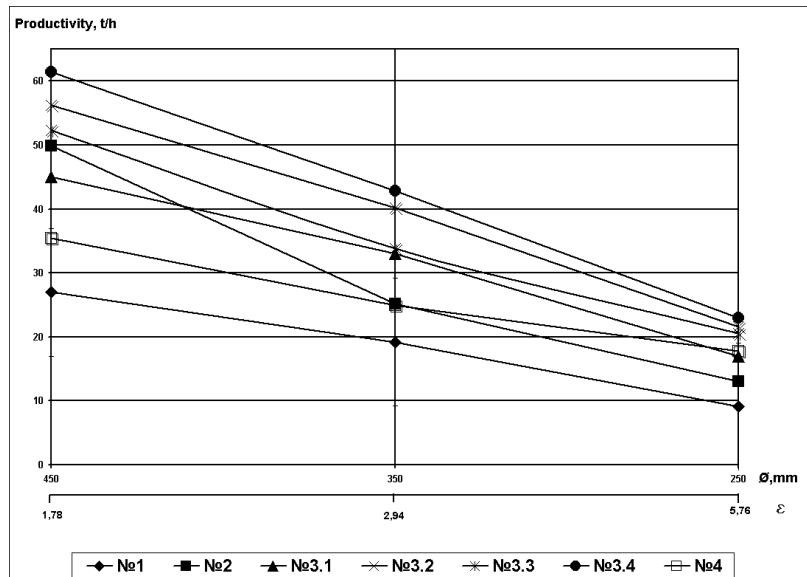


Fig. 9. Dependence of various forging techniques upon finish product size (deformation ratio).

All the forging process techniques studied herein were compared in terms of performance and output (Fig.9). The obtained data proves that the production output of the forging process performed in FDFDs is 1,6 – 3,0 times higher than the same parameter in case of two-die forging, and generally higher than in case of forging in RFM. Even in case of forging in FDFD with small feed rates (Technique No. 4, workpiece feed is 60 mm after each reduction), the process output is 1,3 – 2,2 times higher compared to the same parameter for the conventional two-die forging process.

3. Conclusions

A comparative FEM analysis of eight different forging techniques applied to initial ingots of equivalent size has been presented in this paper and the following results have been obtained:

1. In contrast to two-die forging technique, mainly compressive stresses are generated during the forging operation performed in FDFDs. Moreover, the stress distribution pattern when forged in FDFD is much more advantageous if compared not only to the two-die forging method, but also to the forging in radial forging machines.
2. It has been ascertained that the maximum longitudinal and transverse compressive stresses when forged in FDFD with metal spreading between the dies are significantly (2 – 2,8 times) higher than the maximum compressive stresses generated not only during the two-die

forging, but also when forging the equivalent initial ingots in FDFD without metal spreading between the dies.

3. Calculations of metal damage indices carried out according to the Cockroft & Latham method proved that metal fracture in the forging produced by means of two-die forging is going to happen much earlier than in the same component forged in FDFD.

4. It was demonstrated that the highest values of main strains were obtained if forged in FDFD with metal spreading between dies. It means that a forging process performed in FDFD generates more advantageous conditions for metal deformation treatment if compared to the two-die forging technique and forging technique used in radial forging machines.

5. Forging operations according to FDFD technologies ensure the significant deformation heating of metal which helps either to eliminate or, at least, to reduce the re-heating requirements.

6. Production output when forged in FDFD installed in a forging press depending upon particular forging technique and drawing ratio is 1,3 – 3,0 times higher in comparison to the two-die forging process.

7. Production output of a forging process performed in FDFD installed in 30MN forging press is approximately 40 to 45 percent higher than the same parameter of a forging process performed on 16 MN radial forging machine.

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