NEW TECHNOLOGIES OF FORGING
OF INGOTS AND BLANKS BY FOUR DIES
IN OPEN-DIE FORGING PRESSES
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1. Summary
In recent time the technologies of forging by four dies are increasingly used in the industry as demand grows for more sophisticated and heavier long forgings. There are two technologies of forging of ingots by four dies that are developed independently from one another. The first one is a conventional technology where powerful radial forging machines (RFM) are employed. The second technology is based on the use of open-die forging presses and special four-die forging devices.

This paper considers the technology of forging by four dies using four-die forging devices in open-die forging presses. New technologies of forging in four-die forging devices mastered by Tyazhpressmash JSC (Russia) are shown, including those used to produce heavy hollow forgings.

On the basis of industrial studies it has been confirmed that the use of a four-die forging device ensures high process productivity, isothermal conditions of forging and intensive deformation working of metal structure due to additional shear strains.

It has been established that the forging of stainless, tool, die, high-speed, titanium, heat-resistant and high-temperature steels and alloys in the four-die forging device ensures at least a double increase in productivity, lower metal loss, better surface and in-depth metal quality in comparison with conventional technology of forging by two dies.

Industrial-scale production of four-die forging devices for 5 to 45 MN open-die forging presses has been mastered.

Prospects for the development of four-die forging with use of new forging devices have been outlined.

2. Introduction
Until recently the processes of forging by four dies included only the processes of radial forging in radial forging machines (RFM). By now the situation has changed, although the most of products forged by four dies are still made in RFMs.

In late 60s – early 70s of the recent century, when new powerful radial forging machines of 6.5 to 25 MN per die were built, they started to be used for radial forging of large ingots and continuously cast billets of various materials including high alloy steels and alloys. The world leading manufacturers of radial forging machines, such as GFM GmbH (Austria), SMS Meer GmbH (Germany), Danieli (Italy) achieved great success in developing state-of-the-art RFMs to forge ingots, both solid and hollow ones, of up to 850 mm in diameter ensuring not only high forging rate, but good quality of forgings as well [1].

The current level of engineering development demonstrates that there is an ongoing demand for large-size machines and units requiring long forgings, both solid and hollow ones, of increasingly large size and weight. However, since 30 MN RFMs were designed by GFM GmbH further manufacture of such and more powerful machines has slowed down. It seems that we are about to achieve the limit in the capacity of such machines and size of forgings made by them. Such machines cost
several times as much as comparable open-die forging presses. They are hardly cost-effective in the manufacture of unique heavy forgings required only in small quantities.

Therefore, many attempts were made in the second half of the twentieth century to adapt open-die forging presses to four-die forging. Though, first operable designs of industrial-type four-die forging devices intended for four-die forging of ingots in open-die forging presses appeared not long ago (Fig. 1 to 3) [2, 3].

Fig. 1 Four-die forging device for a 45 MN open-die forging press

Fig. 2 Forging a 10 t ingot of tool steel in the four-die forging device (25 MN press)

Fig. 3 Four-die forging device in operation with a 45 MN open-die forging press
3. Forging with use of four-die forging devices in open-die forging presses

When the four-die forging device was being designed, the objective was not simply copying the well-known technology of four-die forging used in RFMs, but making the utmost efficient technology by taking all the best from radial forging. When the workpiece is reduced from four sides in RFM, all dies travel the same way (radially), lateral spread is almost absent and all metal flows in longitudinal direction ensuring high forging rate. Compressive stresses are generated on the workpiece surface preventing any tears in the superficial layer of metal and surface defects present in the workpiece initially are decreased in depth as forging proceeds. However, this symmetrical four-side reduction with limited freedom of metal flowing into the spacing between dies does not produce any significant shear strains in the workpiece cross-section. It results in much higher forging reduction ratio required to be achieved by RFMs as compared to presses and hammers to obtain comparable quality of metal of forgings from equivalent initial stock.

In the four-die forging device design developed the lower die (1) always remains stationary, two lateral dies (2, 4) move to the workpiece (5) centre and to the lower die simultaneously, and the upper die (3) travels twice the distance covered by each lateral die in radial direction (Fig. 4). This forging scheme allows accomplishing two tasks at once: generate compressive stresses on the workpiece surface and induce shear strains in the workpiece cross-section.

Furthermore, an open-die forging press allows forging at any reductions limited only by the press capacity and working space. Therefore, when forging in the four-die forging device an ingot can be reduced so that part of metal is forced into the spacing between dies to intensify deformation working of cast metal structure. Additional shear strains are developed in the workpiece as a result of such reductions. Then, after turning the workpiece by 45°, metal projections so obtained are forced back in radial direction of the workpiece allowing for penetration of shear strains through its entire cross-section.

3.1 Productivity

The productivity of forging in the four-die forging device depends on the scheme of forging, ingot weight and reduction ratio necessary to obtain a forging with required dimensions from a given ingot (Fig. 5). Figure 5 provides data on the productivity of forging for three types of ingots – 5 t (scheme No. 1, 4), 7 t (scheme No. 2, 5) and 10 t (scheme No. 3, 6) of 40XH (analogue of AISI 3140) steel in a 25 MN open-die forging press. Forging schemes No. 1 to 3 are the schemes where metal is not forced into the spacing between dies, while forging schemes No. 4 to 6 feature metal forcing into the spacing between dies.

Forging scheme numbers correspond to curve numbers in Fig. 5.
Scheme No.1:
Ø750 mm → 750x670 mm
→ 670x670 mm → 670x640 mm
→ 640x610 mm → 610x560 mm
→ 560x490 mm → 490x400 mm
→ 400x300 mm → 300x300
→ Ø300 mm (10 passes).

Scheme No.2:
Ø850 mm → 850x780 mm
→ 780x740 mm → 740x700 mm
→ 700x630 mm → 630x540 mm
→ 540x420 mm → 420x350 mm
→ 350x350 mm → Ø350 mm
(9 passes).

Scheme No.3:
Ø1000 mm → 1000x900 mm
→ 900x900 mm → 900x850 mm
→ 850x800 mm → 800x700 mm
→ 700x600 mm → 600x440 mm
→ 440x400 mm → Ø400 mm
(9 passes).

Scheme No.4:
Ø750 mm → 760x550 mm → 550x540 mm → 540x440 mm → 440x380 mm → 380x310 mm → 310x240 mm → 240x240 mm → Ø240 mm (8 passes).

Scheme No.5:
Ø850 mm → 860x600 mm → 600x560 mm → 560x520 mm → 520x470 mm → 470x400 mm → 400x280 mm → 280x270 mm → Ø270 mm (8 passes).

Scheme No.6:
Ø1000 mm → 1005x750 mm → 750x720 mm → 720x700 mm → 700x530 mm
→ 530x430 mm → 430x320 mm → 320x320 mm → Ø320 mm (8 passes).

Figure 5 shows that forging with metal forcing into the spacing between dies (Schemes No. 4 to 6) features much higher process productivity than forging without it (Schemes No. 1 to 3). Besides, the productivity grows as ingot weight increases.

Curve 7 (Fig. 5) represents the relationship between the productivity of forging a 5 t ingot by two dies in 25 MN press and the reduction ratio. Comparison of two processes of ingot forging shows that the productivity of forging in the four-die forging device is at least by 4.5 times higher than that of conventional two-die forging process.

When selecting a forging scheme, forging force required for each operation shall be calculated. The forging force must not exceed the maximum permissible force of an open-die forging press to be used for forging. Calculation of forging force for the four-die forging device is much different from calculation of forces for other four-die forging processes. Based on the analysis of distribution of forces in the forging device and stress and strain state of metal, equilibrium equations were made, after solution of which the following formula was obtained to determine the force required on the press ram ($P$):
\[
P = 1.15 \cdot \sigma \cdot n_{\sigma}^{\prime} \cdot n_{\sigma}^{\prime\prime} \cdot b \cdot s \cdot \frac{1 + \mu + \tan \alpha \cdot (1 - \mu)}{1 - \mu \cdot \tan \alpha}
\]  
(1),

where
- \( n_{\sigma}^{\prime}, n_{\sigma}^{\prime\prime} \) – stressed state coefficients;
- \( s \) – average length of geometrical deformation zone (feed);
- \( b \) – average width of geometrical deformation zone;
- \( \sigma \) – resistance to plastic deformation;
- \( \alpha \) – angle of slope of lateral sliding surfaces of the forging device;
- \( \mu \) – friction factor for lateral sliding surfaces of the forging device.

Formula (1) has been proven by industrial practice of forging of many ingots and blanks from various steels and alloys at 5, 18, 20, 25 and 45 MN forging presses. Deviations of experimental data from calculated ones did not exceed 15% that is sufficiently good for engineering practice.

3.2 Isothermal conditions of forging

Forging in the four-die forging device enables maintaining the workpiece metal temperature in a narrow range due to deformation heating since four-side reduction generates much more heat than reduction by two dies. This advantage offered by the four-die forging device has been confirmed by successful forging of high-temperature nickel-based alloys. However, to forge high-alloy steels and alloys, it is recommended to integrate the four-die forging devices with automated forging plants featuring computer-aided control. Specified reductions, turns and feeds may be performed with use of a set forging programme so that conditions close to isothermal ones are fulfilled as well as necessary radial and shear strains. In this regard, the continuous monitoring of the workpiece metal temperature is required, e.g. with use of fixed pyrometers. These pyrometers shall continuously send data to the computer to processes these data and adjust forging parameters on a real time basis. Forging in isothermal conditions allows obtaining finished forgings exhibiting uniform properties both lengthwise and crosswise with minimum intermediate heating of the workpiece or without it. This results in lower energy consumption, lower metal loss in scale, lower time and labour required. Isothermal mode was used to forge 10 t ingots of 17Г1С, 18Г (analogue of AISI 5120) and 40ХМА low-alloy structural steels with use of the four-die forging device installed in a 20MN open-die forging press. The press was controlled manually. Nevertheless, even manual control allowed carrying out forging within 1010 to 1030°C. The ingots were forged in one heat (Fig. 6).
3.3 Quality of forgings from tool steels

Metal quality is the main criterion in selecting a forging process almost at all times. By the moment numerous studies of the quality of metal forged with use of four-die forging devices have been carried out showing high efficiency of four-die forging for wide range of steels and alloys [4].

It is known that mechanical properties of metal depend on the amount of its plastic deformation and final heat treatment. By varying four main process parameters (strain rate and degree, temperature and post-deformation pause) and chemical composition of alloy, one can obtain the full set of structural states, e.g. cold hardening substructure, polygonal substructure, fine grain recrystallized structure. In addition to the above mentioned parameters, metal structure can be efficiently controlled by selecting certain scheme of deformation leading to shear strains in the workpiece metal.

X12МФ (analogue of AISI D2) tool steel bars of the following chemical composition were forged to a reduction ratio of 2 in the four-die forging device installed in a 5MN forging press and in SXP-55 radial forging machine: C – 1.5%, Si – 0.4%, Mn – 0.4%, Cr – 12%, Mo – 0.5%, V – 0.3%.

Figure 7 shows the microstructure of metal in the core zone of 122 mm diameter forgings made in RFM (Fig. 7a) where many large-sized carbides and carbide clusters are observed, which is the evidence of poorly worked metal structure, and in the forging device (Fig. 7b) where metal microstructure features numerous small and medium-sized carbides uniformly distributed in the volume of metal.

![Fig. 7 Microstructure of metal in the core zone of 122 mm diameter forgings made in RFM (a) and four-die forging device (b), magnification 100x](image)

Figure 8 illustrates the distribution of area occupied by carbides of different sizes for metal forged in RFM (curve 1) and in the forging device (curve 2). Thus, the four-die forging device provides more uniform working of metal structure in the entire cross-section that is evidenced by breakdown of eutectic carbides not only in the surface zone, but in the core zone of the forging cross section as well and by destruction of large eutectic clusters.

Further studies demonstrated that intensive radial and shear forging of bars of B11M7K23-MOD and USP18K23-MOD-PM alloys in the four-die forging device ensures uniform distribution of fine intermetallic phases like (Fe, Co)7, (W, Mo)6 and Laves phases like Fe2W(Mo). Besides, the studies have shown that the four-side forging
in the forging device provides carbon inhomogeneity in forgings of 80 to 100 mm in diameter by 1.5 to 2 times lower than that obtained when forging by two dies.

Fig. 8 Distribution of area occupied by carbides of different sizes for metal forged in RFM (1) and in the four-die forging device (2)

3.4 Quality of forgings from special high-alloy steels and alloys

Using four-die forging devices to forge ingots of high-alloy steels and alloys featuring low plasticity is of great interest. Ingots of various steels and alloys were forged in the four-die forging device installed in a 20MN open-die forging press on orders from numerous customers in Russia (Table 1).

<table>
<thead>
<tr>
<th>Steel, alloy grade</th>
<th>Foreign analogue</th>
<th>Ingot weight (kg)</th>
<th>Average cross-sectional size of an ingot (mm)</th>
<th>Cross-sectional size of a forging (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08Х18H10Т</td>
<td>AISI 321</td>
<td>2,800</td>
<td>620</td>
<td>280</td>
</tr>
<tr>
<td>10Х11Н20Т3Р</td>
<td>-</td>
<td>2,750</td>
<td>600</td>
<td>330</td>
</tr>
<tr>
<td>XH38ВТ</td>
<td>Incoloy 825</td>
<td>2,750</td>
<td>600</td>
<td>330</td>
</tr>
<tr>
<td>XН73МБТЮ-ВД</td>
<td>Inconel 751</td>
<td>1,370</td>
<td>450</td>
<td>370</td>
</tr>
<tr>
<td>XН62БКТЮ-ИД</td>
<td>Inconel 751</td>
<td>915</td>
<td>370</td>
<td>300</td>
</tr>
<tr>
<td>2В</td>
<td>-</td>
<td>545</td>
<td>350</td>
<td>180</td>
</tr>
</tbody>
</table>

An ingot of 08Х18H10Т steel was heated in a gas chamber furnace to 1030°C and forged in the four-die forging device to a diameter of 280 mm in one heat. Forging finish temperature was 780°C. Reduction ratio: in the ingot’s head portion – 5.5 and in the ingot’s tail portion – 3.3. No defects were found on the forging surface.

Assessment of macrostructure of 08Х18H10Т steel samples showed that the macrostructure was compact and uniform. Mechanical test results are given in Table 2. The results show that the level of properties exceeds the requirements of normative documents. There is no considerable difference in the level of properties in the head portion and in the tail portion of the forging. Intergranular corrosion resistance tests also gave good results at different sample hardening temperatures.
Quality of forgings of 10X11H20T3P and XH38BT steels was also high and was equal to the quality of forgings made by two dies in an open-die forging press according to conventional process except for plasticity indicators ($\delta$, $\psi$). Relative elongation ($\delta$, %) and contraction ($\psi$, %) exceeded the same properties of forgings made by two dies by 20 - 30%.

Table 2

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Reduction ratio</th>
<th>T (°C)</th>
<th>$\sigma_B$ (N/mm$^2$)</th>
<th>$\sigma_{0.2}$ (N/mm$^2$)</th>
<th>$\delta$ (%)</th>
<th>$\psi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tail portion</td>
<td>3.3</td>
<td>20</td>
<td>519.8</td>
<td>275.0</td>
<td>50.6</td>
<td>76.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>565.8</td>
<td>255.6</td>
<td>55.7</td>
<td>74.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>532.3</td>
<td>252.1</td>
<td>56.1</td>
<td>76.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>555.0</td>
<td>259.1</td>
<td>54.4</td>
<td>77.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>555.7</td>
<td>242.4</td>
<td>58.9</td>
<td>74.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>553.3</td>
<td>243.1</td>
<td>56.9</td>
<td>74.6</td>
</tr>
<tr>
<td>Head portion</td>
<td>5.5</td>
<td>20</td>
<td>543.6</td>
<td>246.9</td>
<td>61.5</td>
<td>71.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>530.5</td>
<td>259.2</td>
<td>58.4</td>
<td>75.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>558.9</td>
<td>237.8</td>
<td>53.9</td>
<td>76.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>554.0</td>
<td>228.6</td>
<td>57.9</td>
<td>76.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>568.1</td>
<td>242.4</td>
<td>55.7</td>
<td>76.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>528.3</td>
<td>238.1</td>
<td>56.3</td>
<td>78.6</td>
</tr>
<tr>
<td>As per GOST (minimum)</td>
<td></td>
<td></td>
<td>490</td>
<td>196</td>
<td>40</td>
<td>55</td>
</tr>
</tbody>
</table>

Special radius dies were used to forge 2B titanium alloy. The dies were preheated to 320 to 340°C. Forging was accomplished in one heat of ingot. It took 17 to 18 minutes to forge one ingot. Forging finish temperature was 1000°C. Macrostructure of forged bar was studied using a cross-sectional test sample cut out from the central portion of forging. No internal defects in the form of cracks, delamination and other discontinuities were found. Recrystallized macrostructure did not contain any remains of as-cast grains and was sufficiently uniform. Grain size in the sample’s core zone was 3 to 4 mm and that in its periphery was 2 to 3 mm. Forged bar surface was smooth and without any tears.

XH62БКПЮ-ИД nickel-based alloy ingot was heated in a gas furnace to 1140°C. Ingot surface was covered with heat-insulating material before forging. Where the ingot surface was not covered with heat-insulating material, 3 to 5 mm deep cracks were observed. The rest of surface exhibited no cracks. The ingot was forged to a diameter of 300 mm in one heat. Macrostructure was studied at cross-sectional samples cut out from the forged bar’s tail portion and head portion. No internal defects in the form of cracks, delamination and other discontinuities were found. Grain size in the sample’s core zone was 2 to 4 mm and that in its periphery was 1 to 2 mm.

XH73МБПЮ-ВД nickel-based alloy ingot was heated in a gas furnace to 1180°C and fed into an open-die forging press fitted with the four-die forging device with use of an overhead travelling crane. The ingot temperature immediately before forging was 1130°C to 1140°C. The ingot was forged to a diameter of 370 mm in one heat. The ingot surface exhibited no cracks. Macrostructure was studied at cross-sectional samples cut out from the forging’s tail portion and head portion. No internal defects in the form of cracks, delamination and other discontinuities were found. Grain size in the sample’s core zone was up to 3 mm and that in its periphery was 1 to 2 mm.
Forgings quality studies carried out (see Table 1) have shown that their geometry, extreme diameter deviations and macrostructure fully comply with the requirements to such semi-finished products.

By now the processes of forging of ingots and blanks of various steels and alloys with use of four-die forging devices in open-die forging presses have been mastered by JSC Tyazhpresssmash, VSMPO AVISMA, JSC Bumsmash and OOO SSM Tyazhmas (Russia). Besides, JSC Tyazhpresssmash has designed, manufactured, delivered, installed and commissioned more than 10 four-die forging devices for 10, 16, 20, 30, and 45MN presses for customers in China and other countries.

### 3.5 Manufacture of hollow forgings

The industry sets more and more complex tasks before the manufacturers of forgings, which cannot be accomplished without mastering new technologies of forging of ingots by four dies in open-die forging presses. One of such tasks is the manufacture of heavy hollow forgings with external diameter of 450 to 1,500 mm, wall thickness of 60 to 250 mm and length of 5,000 to 12,000 mm.

A hollow forging can be made with use of the four-die forging device from an ordinary ingot, hollow ingot, blank with a hole made by machining or from a tubular blank. The stock to be used is the base for building a process for manufacture of hollow large-size products that shall be finalized with forging over a mandrel in the four-die forging device similarly to the process of forging hollow products in radial forging machines. This technology of radial forging is very promising and it is being elaborated now at Tyazhpressmash JSC. By the moment, Tyazhpressmash JSC has mastered the process of forging hollow products of 460 mm in diameter and 5,100 mm in length (wall thickness – 95 mm) over a mandrel with use of the four-die forging device in 25MN open-die forging press (Fig. 9).

![Fig. 9 Forging of hollow ingot over a mandrel in the four-die forging device](image_url)

4. Prospects of further development of processes of forging by four dies

By the moment four-die forging device designs and technologies of forging have been elaborated for the manufacture of solid and hollow forgings with an outside diameter of 1,000 to 3,000 mm from ingots of 1,300 to 4,000 mm in diameter in 60 to 150 MN forging presses. These technologies are about to be implemented in the industry.
In 2012 it is planned to master the technologies of forging of ingots from super alloys (high-temperature, heat resistant, precision, etc.) with use of four-die forging devices in 60 MN presses.

The experience of operation of four-die forging devices has shown that the device design, after its upgrading and forging press upgrading, enables the forging of ingots with intensive shear strains according to developed technology without any signs of ingots destruction. This allows achieving metal materials with ultra fine grain structure increasing metal strength, plasticity, wear resistance and other performance indicators.

5. Conclusions
1. New process of forging of ingots and blanks by four dies with use of new four-die forging devices in 5 to 45 MN open-die forging presses has been mastered in industrial conditions.
2. In contrast to four-die radial forging machines the four-die forging devices enable additional shear strains conditioned by complex travel of lateral dies and forging at any reductions limited only by the press capacity and working space.
3. Four-die forging ensures increase in productivity of forging in open-die forging presses by several times as compared to conventional processes of forging by two dies. Additional productivity gains are possible through reductions with metal forcing into the spacing between dies.
4. The effect of significant deformation heating observed when forging in the four-die forging device provides roughly isothermal conditions of forging making it possible to reduce the number of intermediate heating or remove it at all thereby saving time, power and labour, and decreasing metal loss in scale.
5. Results of industrial studies of forging of ingots from structural, tool steels and special high-alloy steels and alloys have shown that the four-die forging device ensures metal structure working through the entire cross-section of workpiece, superior mechanical properties of forged metal, high dimensional accuracy, good shape and surface finish of forgings.
6. The process of forging of hollow forgings over a mandrel with use of the four-die forging devices in open-die forging presses has been mastered.
7. In the nearest future it is planned to start manufacturing forgings with ultra fine grain structure, including those from special alloys, as well as using four-die forging devices in presses up to 150 MN in force to make heavy forgings, both solid and hollow ones.

6. References