Hydraulic Press Open Die Forging of 21CrMoV5-7 Steel CCM Roller with Flat Upper and Concave Semi-round Lower Cogging Dies

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Abstract. The cogging schedules were investigated with reduction and rotation joint effect around the workpiece's longitudinal axis, making it possible to improve the shaft forgings quality indices in geometry and distribution of strength properties in cross-sections. The forging for the rollers of continuous casting machine (CCM) of 21XMoV5-7 steel was produced according to the improved process in the forging shop with the hydraulic press combined dies (the upper die is flat, the lower die is semi-round cut-out, U-shaped). The advantage of the developed shaft forging schedules is the significant plastic deformation achievement in the forging cross-section using only one combined dies set. Manufacture of the CCM roller forging according to the new process made it possible to improve by 8.9% in the average yield strength and by 11.9% in the average ultimate tensile strength. It was possible to reduce the forging the data spread for the yield strength from 33% to 17% and the data dispersion for the ultimate tensile strength from 26% to 11%. The minimal ultimate tensile strength was increased by 14.7%.

Keywords: Shafts forging · Cogging · Combined flat-shaped dies · Reduction · Rotation angle · Strength · Grainflow · Grain size

1 Introduction

Several requirements exist for single and multi-diameter shafts forgings, depending upon the parts exploitation conditions to be manufactured. These requirements stipulate the forgings technological groups, the number, and the material mechanical testing [1]. Because of this, it is necessary to obtain of directional orientation grainflow not only in the ingot [2] and in the forging [3], as well as fine-grain micro-structure with maximum uniformity in cross-section is ensuring the best combination of the metal's mechanical properties.

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2 Literature Review

Innovative methods of severe plastic deformation are currently being developed [4], mainly based on various types of extrusion [5]. Most of them related to the realization of macroshifts at the cold, severe plastic material deformation in moving dies [6] or at the dieless forming with workpiece local heating [7]. One of the ways to control the formation of the metal's macro- and microstructure (as quality indicators [8]) is to varying the open die forging thermomechanical modes in the cogging operation, which takes up the bulk of the forging time when shafts are manufactured [9]. This solution makes it possible to intensify plastic deformation and obtain the macro-shifts effect at the application of a standard universal tool – flat rhombic and semi-round or combined dies (the upper being flat, the lower of V-shaped or ∪-shaped configuration) of a forging press [10]. Specific requirements for operating conditions of such shaft forgings like continuous casting machine (CCM) rollers stipulate application of steel, containing chromium, molybdenum, and vanadium, as well as intense forging modes and development of alternative designs of such parts [11]. For the wastes minimization at further forgings machining, it will be necessary to observe the requirements of geometric precision for the round cross-section forgings. Thus, forging schedules development for CCM rollers manufacturing seems to be expedient, with the objective of the geometric precision increasing and improving the indices of shafts forgings mechanical properties, as applied to the forging shop standard conditions, equipped with a hydraulic forging press with universal combined dies (the upper – flat, the lower – semi-round cut-out, ∪-shaped).

Realization of macro-shifts in material bulk allows refining of ingot cast structure without sufficient alternations in the area of its cross-section. It promotes to close of inner defects [12–18] (like cracks [12], inner voids [13–15], or cast axial non-density [16–18]), even for forging of big ingots with minimal forging ratio. It is convincingly indicated by the results of both modeling [14, 15, 17] and experiments [16, 18]. The macroshift deformations effect is achieved by radial reduction with complicated shape dies [17], the use of a special cast [18], or preformed [19] workpiece. The special four-die devices are applied for these purposes also [20]. Such technological solutions are related to the application of specialized metal-consuming forging devices, their assembling with press, requiring additional labor consumption, and reducing the production range of forgings in weight. In paper [21], theoretically and in work [22], experimentally was proposed to carry out the forging of heavy shafts with shaped dies that allow reducing an ingot into a three-beam or four-beam workpiece. Further cogging from a shaped ingot accompanied by the formation of a round cross-section through macroshift deformations requires the substitution of dies, and it may cause subcooling and the necessity to perform additional heating of ingots. Besides, different assemblies of tools for open die forging are used for obtaining three- and four-beam workpieces. Investigations of forging workpieces with specially shaped dies are described early in [17–19]. As well as the use of dies with a complex curved parting line [23], radial [24], spherical [25] dies, and four-beam workpiece [26] indicates the dimensions controlling possibility and macroshift metal flow initiating.

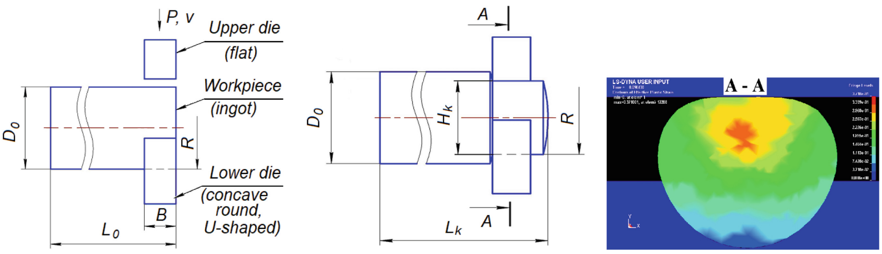
Material's uniformity improvement and increase at the treatment using increasing or complicating the tools set can be justified economically only for forging ingots made of high alloy steels or rare metals [27]. To equal the mechanical properties over the product cross-section, deformation schedules are combined directly [28] or stepped [29] heat treatment. However, investigations described in [30] deserve attention. According to the results obtained there, macro-shifts achievement revealed at the shafts open die forging with a round or polygonal cross-section combined (flat + shaped) dies using varying cogging modes. In our case, it is necessary to carry out rational forging modes for shafts with the application of combined dies of the type: the upper – flat, the lower – ∪-shaped [30], i.e., as they are used at the enterprise's shop.

The objective of our research is to develop forging schedules in combined dies (the upper die being flat, the lower – with round cut-out, ∪-shaped), in the form of rational alternation and determination of optimal reductions strokes, intermittent work feeds, and rotation angles of the ingot around its longitudinal axis, that leads to a satisfactory geometric precision of forged products and closure of core-defects (porosities, blowholes, etc.) utilizing realization of macroshift-effect in the deformation zone.

3 Research Methodology

The investigation was carried out with due regard to the manufacturing of shafts by forging at a forging shop of one of the industrial enterprises of Mariupol (Ukraine). The computer and physical simulation methods were used to investigate the strain state and shape deformation of workpieces with different reduction, supports, and rotation angles. The computer simulation was carried out in a universal package of the finite-elements analysis (LS-Dyna). The isothermal problem was solved with some assumptions. Other initial parameters were taken according to the processes of shafts forging at the forging shop: the dies were of combined type (the upper die was flat, the lower was ∪-shaped with the cut-out radius 300 mm, Fig. 1), the ingot's diameter D_0 was 550 mm, ingot's length L_0 = 1300 mm, the 21CrMoV5–7 ingot steels was made, the treatment temperature was t = 1,100 °C, the upper die stroke velocity – 50 mm/s. The dies were supposed to be absolutely rigid bodies. The deformed workpiece was divided into the finite elements of tetrahedral shape; the length of the middle element's side was equal to 10 mm. To carry out experimental investigations on a 1:10 scale, a laboratory assembly of combined dies were manufactured of C45 (1045) steel. Then they were installed on a hydraulic press with a nominal force of 0.63 MN. Experimental specimens were manufactured of antimony lead of SSu grade (Pb = 99.38… 99.6%, Sb = 0.4…0.6%, Bi $\leq$ 0.05%).

At computer simulation, the following was specified as varying parameters, Influencing the kinematic characteristics of the process of deformation of the ingot: (i) reduction: Δh_0 = 50 mm, 66 mm and 100 mm, i.e., relative reduction (reduction ratio) being $\varepsilon_{h\%} = (\Delta h \, / \, D_0) \times 100\%$ = 9.09%, 12%, and 18.18%; (ii) die width (the feed value): B = 180 mm, 240 mm and 300 mm, i.e., relative feeds (die width to diameter ratio) B/D_0 = 0.327, 0.436 and 0.545; (iii) rotation angles: φ = 30°, 60° and 90°.



(a) (b) (c)

Fig. 1. Position of a workpiece in combined dies before (a), and after (b) reduction and the process simulation by finite elements method (c): *B*, *R* – dies geometric parameters; L_0, L_k, D_0, H_k – geometric parameters of the ingot; *P*, *v* – kinematic parameters of cogging.

The varied parameters range was enlarged for experimental investigations. The analysis of the received data made it possible to determine that the distribution of the average strain from the workpiece's center towards the periphery corresponds to a linear equation at all simulated schedules of forging with a correlation coefficient (*R*) close to 1.0. Thus, the effective strain (e_i) distribution in the cross-section obeys the regularity:

$$e_i = e_{i.max} - a \cdot \rho, \tag{1}$$

where $e_{i.max}$ is the highest effective strain, observed on the axis; *a* is an angular coefficient of strain reduction towards the periphery; ρ is the radius vector from the center of the workpiece to the investigated point. The determined values of angular coefficients for the relative feed B/D_0 = 1.0 are summarized in Table 1.

Table 1. The calculated values of angular coefficients (B/D_0 = 1.0).

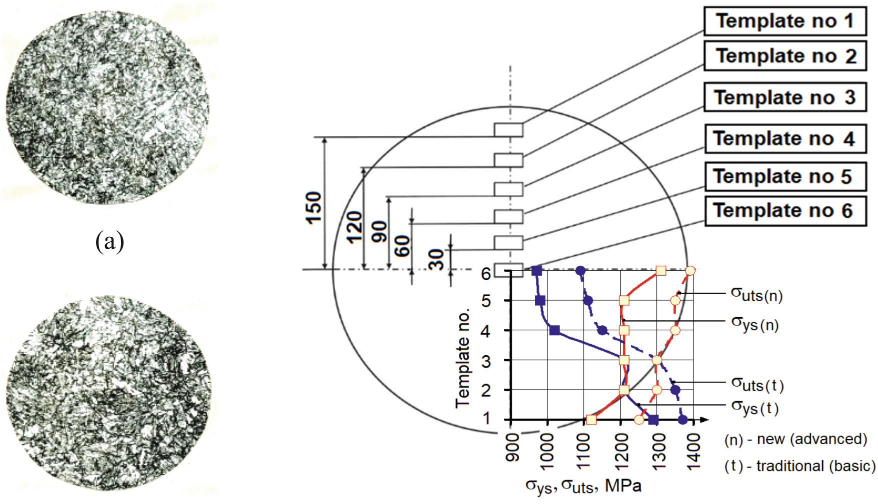
Reduction, mm × rotation angle (forging schedule)	*ei.max*	*a*	Correlation (χ^2)
50 × 30°	6.44 ± 0.053	0.01357 ± 0.000505	0.99
50 × 60°	8.04 ± 0.055	0.02099 ± 0.000541	0.99
50 × 90°	7.03 ± 0.073	0.02367 ± 0.000693	0.99
66 × 30°	6.08 ± 0.063	0.01452 ± 0.000599	0.99
66 × 60°	7.10 ± 0.05	0.02083 ± 0.000481	0.99
66 × 90°	7.54 ± 0.05	0.02084 ± 0.000482	0.99
100 × 30°	5.17 ± 0.052	0.01262 ± 0.000495	0.99
100 × 60°	6.46 ± 0.02	0.01967 ± 0.000192	0.99
100 × 90°	6.39 ± 0.12	0.1881 ± 0.0011	0.99

The workpiece cross-section was evaluated to a round shape approximation degree also. The evaluation was made by the relation of the forging perimeter to an equivalent circle perimeter, calculated through the forging cross-section area. Accordingly, the closer this ratio is to 1.0, the more accurately the geometry requirements for forging are met. The results of the analysis of the obtained theoretical and experimental data allowed us to propose manufacturing forgings of shafts by open die forging in combined dies of the analyzed design. One of the tasks was to reduce the number of processes passes at the application of one dies set and improve workpieces inner metal (closure of internal void defects, refining of grains), which makes it possible to reduce the total energy costs, increase the productivity of open die forging and improve the performance indices of parts. According to this method, a workpiece is forged in combined dies in several passes with rotation and subsequent cogging. Reductions at cogging are made with relative feed $B/D_0 = 0.55\ldots0.7$ to engineering strain $\varepsilon_{h\%} = 5\ldots18\%$ with rotation after each stroke for the angle $\varphi = 60\ldots90°$, the bigger rotation angle being ensured at smaller strain.

Industrial implementation of the methods was performed for the process of rollers forging for CCM of the oxygen-converter shop. There both rollers, imported from Romania and domestic, manufactured in Ukraine, are employed. The parts chemical composition is summarized in Table 2; their microstructure is shown in Fig. 2(a, b).

Table 2. Chemical composition, hardness of metal of investigated forgings intended for CCM rollers (21CrMoV5-7 steels).

Manufacturer	wt., %								Hardness, HRC
	C	Mn	Si	Cr	Mo	V	S	P	
Romania	0.26	0.57	0.40	1.51	0.61	0.24	0.023	0.036	34
Ukraine	0.24	0.46	0.45	1.72	0.86	0.26	0.019	0.012	31



(a)

(b)

(c)

Fig. 2. Microstructure (×500) of rollers manufactured in Romania (a) and Ukrainian (b); sketch of sampling to determine the metal structure of a workpiece ∅360 mm (c).

According to the base process for CCM rollers manufacturing hexahedral forge ingots, 5,000 kg in weight were used as original blanks. Smelting was carried out in electric-arc furnaces. Ingots were cast by the bottom pouring method. Heating was performed in gas chamber ovens with carriage-type bottom and setting up to 30 t in mass. Forging was performed on a hydraulic forging press, 12.5 MN in nominal force, with flat dies, 300 mm wide in "circle-square-circle" schedule with rotate reducing to the round shape of the cross-section at the final pass. The overall forging ratio was 2.7.

4 Results

Templates were chosen following the diagram pictured in Fig. 2c from the forgings cross-section, which eventually underwent subsequent quenching and tempering. After that, the chemical composition, mechanical properties as the yield strength σ_{ys}, ultimate tensile strength σ_{uts}, percent elongation δ_5, percent reduction in area (necking) ψ and hardness, according to Brinelle (*HB*) were determined (Table 3 and Table 4). Forging according to the new technology, combined dies with preservation of overall forging ratio, equal to 2.7. Templates were chosen from similar spots in the forgings cross-section to determine properties after additional heat treatment (quenching and tempering) (Table 4).

Table 3. Mechanical properties of templates (basic process).

Template no	σ_{ys}, MPa	σ_{uts}, MPa	δ_5, %	ψ, %	*HB*
1	1290	1370	12.5	44.0	415
2	1210	1350	12.5	48.0	415
3	1210	1300	9.0	55.0	415
4	1020	1150	11.5	53.0	302
5	980	1110	10.5	60.0	302
6	970	1090	13.5	62.0	341

Table 4. Mechanical properties of templates (advanced process).

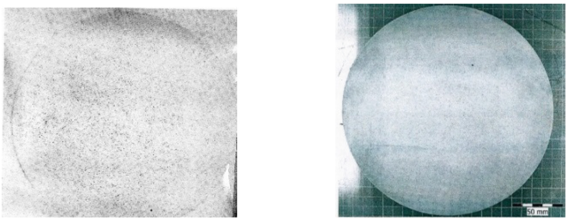
Template no	σ_{ys}, MPa	σ_{uts}, MPa	δ_5, %	ψ, %	*HB*
1	1120	1250	11.5	53.0	382
2	1210	1300	11.5	50.0	400
3	1210	1300	9.0	55.0	415
4	1210	1350	12.5	48.0	415
5	1210	1350	12.5	48.0	415
6	1310	1390	12.5	44.0	415

Table 5 summarizes the analysis of maximal, minimal, and average values of yield strength and ultimate tensile strength in forgings cross-section, forged according to the basic and new (advanced) processes. The data indicated in Tables 3 and 4 were used. The improvement index (I) is evaluated modulo as $I = (|A_t - A_n|/A_t) \times 100\%$, where A_t and A_n are values from Table 5 for the basic and new processes. Improvement in strength indices and their more uniform distribution in cross-section is observed as relative indices become closer to 1.0.

Table 5. Strength characteristics of 21CrMoV5-7 steel.

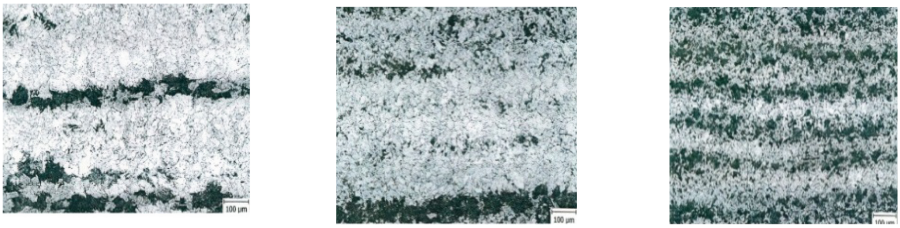
Forging schedule	$\sigma_{uts.max}$, MPa	$\sigma_{uts.av}$, MPa	$\sigma_{uts.min}$, MPa	$\sigma_{uts.max}/\sigma_{uts.min}$	$\sigma_{uts.max}/\sigma_{uts.av}$	$\sigma_{uts.min}/\sigma_{uts.av}$
Basic (A_t)	1370	1228	1090	1.26	1.12	0.89
Advanced (A_n)	1390	1323	1250	1.11	1.05	0.94
Improvement, %	1.5	7.7	14.7	11.9	6.3	5.6
Forging schedule	$\sigma_{ys.max}$, MPa	$\sigma_{ys.av}$, MPa	$\sigma_{ys.min}$, MPa	$\sigma_{ys.max}/\sigma_{ys.min}$	$\sigma_{ys.max}/\sigma_{ys.av}$	$\sigma_{ys.min}/\sigma_{ys.av}$
Basic (A_t)	1290	1113	970	1.33	1.16	0.87
Advanced (A_n)	1310	1212	1120	1.17	1.08	0.92
Improvement, %	1.6	8.9	15.5	12	6.9	5.7

Macrostructures and microstructure of forgings, forged according to the advanced process, are shown in Fig. 3 and Fig. 4. Table 6 reflects the results of grain size point's analysis for finished forgings.



(a) (b)

Fig. 3. Sulfur print (a) and macrostructure after pickling (b) of template from 21CrMoV5–7 steel forging.



(a) (b) (c)

Fig. 4. Microstructure (×100) of the 21CrMoV5-7 steel forging: (a) near the lateral surface (no 1); (b) at a distance $0.5R$ (no 3); (c) in the axis zone (no 6).

Table 6. Distribution of grain size points in cross-section of 21CrMoV5-7 steel workpiece.

Forging schedule	Grain size, points (GOST 5639)				G_{max}/G_{min}
	$G0$	$G0.5$	$G0.8$	G_{av}	
Basic	5–3	2–3	1–3	2.7	2
Advanced	8–9	8–9	8–7	8.2	1.13

According to the advanced process, manufacturing of forgings resulted in improvement by 8.9% in average yield strength and by 11.9% in average ultimate tensile strength. It was also possible to reduce by 12% (from 33% to 17%) range of yield strength data and by 11.9% (from 26% to 11%) dispersion for ultimate tensile strength data in cross-section, i.e., it was possible to reach more uniform grain structure and distribution of mechanical properties. The value of minimal ultimate tensile strength σ_{uts}, as one of the most limiting index, was increased by 14.7% (Fig. 2c).

5 Conclusions

It is shown that advanced open die forging schedules implementation in combined dies (the upper die is flat, the lower die is ∪-shaped) is a promising direction for quality improvement for the shafts forgings and the parts operation characteristics improvement. Process methods for the shafts forgings manufacture by cogging with combined dies were developed that allow reaching the severe deformations at the application of just one die tools set, i.e., by selecting rational forging schedules: rotation angles feeds and reduction. At the same time, the ranges of their values for achieving quality indices in terms of the forgings' mechanical properties and cross-section shape are sufficiently close, which allows optimizing the open die forging schedules for shafts manufacturing. A method of open die forging in combined dies has been developed, according to which reductions at cogging are made with relative feed B/D_0 = 0.55–0.7 to engineering strain $\varepsilon_{h\%}$ = 5–18% with rotation after each stroke to the angle φ = 60–90°, the bigger rotation angle being ensured at smaller $\varepsilon_{h\%}$ value. It was found out that the regularity of deformations distribution in the cross-section from the center to the periphery in a shaft forging, forged in combined dies, according to the new schedules, is linear. It was revealed that the proposed process allows increasing by 1.5…15.5% the principal strength properties of forgings, specifically $\sigma_{uts.max}$ from 1370 MPa to 1390 MPa and $\sigma_{ys.min}$ from 970 MPa to 1120 MPa. It has also allowed significantly (from 33% to 17%) reducing the hereditary structural and chemical heterogeneity of forged products.

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