Metallurgist, Vol. 57, Nos. 7–8, November, 2013 (Russian Original Nos. 7–8, July–August, 2013)

STRUCTURE FORMATION OF COPPER WITH REVERSE EXTRUSION

N. A. Shestakov, V. N. Subich, and A. V. Shukshin

UDC 621.7.043:620.183.25

Data are provided for a new process achieving a greater degree of plastic deformation by reverse extrusion in bulky billets with the aim of forming a fine-grained structure. An algorithm is developed for loading stages of billets providing uniform accumulation of the degree of deformation throughout its volume. Data are provided for metal kinematic flow obtained by simulating reverse extrusion in Deform. New technology is proven by experiment using copper M1. Microstructure is studied after achieving a degree of deformation of 5.5–6. The possibility of obtaining a bulky billet with a grain size of 5–8 μm is demonstrated.

Keywords: *metal forming, multistage deformation, fine-grained structure.*

Thin-walled components of the copper facing type are used extensively in many branches of industry in components for different purposes, in particular, oil and gas recovery, for piercing casings, forming boreholes, preparation of holes in plates of different material, etc. The operating properties of linings are determined by the accuracy of their dimensions and installation in the body of equipment, and also material structure.

Some qualitative and quantitative properties of facings are provided in [1], affecting most markedly their operating properties. The relative contribution of aggregated imperfections of facing geometric shape and precision of its placement in the body of equipment to reducing operating properties, which in the majority of known recommendations play a dominant role, has been compared with the contribution of grain size. The main conclusion is that a predominant factor reducing the operating properties of facing is material grain size. It has been established that with a reduction in grain size from 0.3 to 0.1 mm facing efficiency increases by almost a factor of two, whereas overcoming the other errors mentioned above leads to an increase in effectiveness by about a factor of 1.5. Whence follows the importance of work aimed at obtaining a fine grained facing material structure.

One of the most important advantages of metal forming (MF) is the possibility of intentional formation of a prescribed structure and object material physicomechanical properties. Reserves of a whole set of material structure-sensitive properties with MF are connected with the creation and management of such forming properties as large plastic deformation (LPD, sometimes called intense plastic deformation, IPD), a stressed state scheme, deformation temperature and rate conditions, and deformation trajectory.

Among processes that make it possible to implement LPD, are mainly torsion in Bridgman anvils, equal-channel angular pressing (ECAP), forging with alternating operations of upsetting and drawing (all-round forging), and screw extrusion (SE). These methods of implementing LPD have a number of structural and production disadvantages, limiting their potential industrial application. Limitations connected with the use of torsion in Bridgman anvils are overcome in many cases in stamping with torsion, and these have been adequately substantiated theoretically, experimentally, and industrially [2]. However, use of stamping with torsion is limited to a class of comparatively moderate forgings with a diameter to thickness ratio of $d/h \ll 1$, and only in special presses with a rotary die-holder [2].

Moscow State Industrial University, Russia; e-mail: shes-v@mail.msiu.ru. Translated from Metallurg, No. 7, pp. 74–79, July, 2013. Original article submitted April 19, 2013.

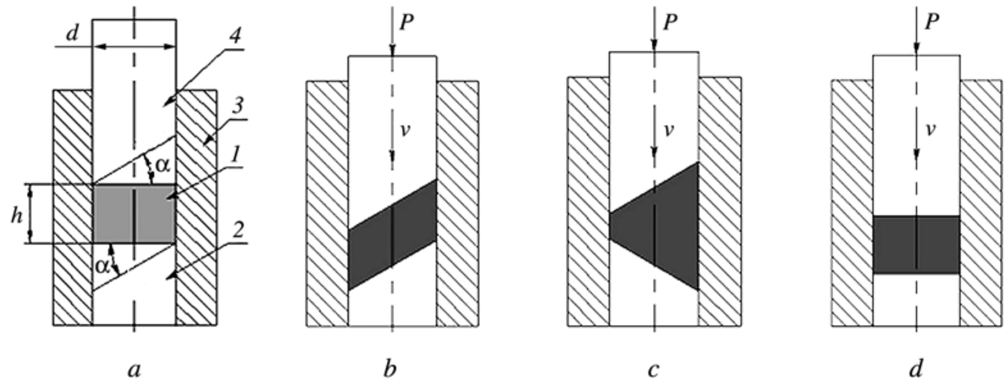

Fig. 1. Diagram of extrusion with angular punches: *a*) original condition; *b*) 1st method; *c*) 2nd method; *d*) sizing.

Use of ECAP [3] provides the possibility of obtaining a billet of extended round or rectangular cross section using a relatively simple die construction solely for ductile materials (copper, aluminum, nickel). In order to achieve considerable degrees of billet deformation after the first pressing, it is extracted from the receiving channel and given a second pressing. The number of pressing cycles is selected in relation to the required degree of deformation. A complication arises with billet extraction after each pressing cycle and its installation for the next pressing. As a rule machining is necessary in order to install a billet in a channel for the next pressing.

There is also a limitation with respect to length L of a billet being treated (L/d = 4–6, where d is diameter or typical size of a rectangular cross section billet) due to a requirement for overcoming friction forces. In addition, large undeformed end sections remain. In order to process materials with low ductility, there is a marked requirement for complication of production equipment due to use of devices for creating counterpressure. There are similar disadvantages for screw extrusion [4].

All-round forging is used for obtaining a high degree of deformation for heated billets of different metals, as a rule under isothermal conditions, and this limits considerably their field of application for forming ultrafine grained (UFG) and submicrocrystalline (SMC) structures. Achievement of LPD, corresponding to formation of UFG- and SMC-structures with cold deformation is limited by metallic material insufficient ductility.

The disadvantages of traditional treatment processes stimulate finding and developing new plastic deformation schemes, making it possible to implement the possibility of plastic deformation as one of the most effective means of forming metal and alloy structures.

The aim of this work is to study flow kinematics with reverse extrusion by angular punches and the effect of accumulated deformation on forming UFG- and SMC-structures in bulky billets of copper M1 used for facing production.

The substance of the new process includes the following. A starting billet *1* (Fig. 1*a*) is placed in channel *3*, on punch *2*. Punch *4* is installed on the billet, which accomplishes deformation with force P with parallel (Fig. 1*b*) or counter (Fig. 1*c*) direction of punch working surfaces. In order to reduce friction forces, the die may be floating. The die channel *3* may have a round or rectangular cross section. Accumulation of deformation, required for forming a required structure, proceeds in several stages by method 1, and in different combinations by method 2. Verification (Fig. 1*d*) may be provided between stages, which may also be the concluding stage. Two tasks were raised in studying flow kinetics:

1) exclusion of defects in the form of folds and pinches;

2) achievement of maximum uniform distribution of deformation throughout a billet volume required for forming a uniform structure.

An algorithm is presented in Fig. 2 demonstrating different combinations of deformation stages. Transfer to the next deformation stage is accomplished by withdrawal of punch *2* or *4*, or both simultaneously from the die channel *3*, turning them through 180°, and new loading. Extraction of a billet is only carried out after the required number of loading stages.

The potential of the method proposed was studied in a program complex Deform D. The initial simulation conditions were: the equipment is a press with a slide movement rate of 1 mm/sec; cross section dimensions: h = 24 mm; d = 36 mm

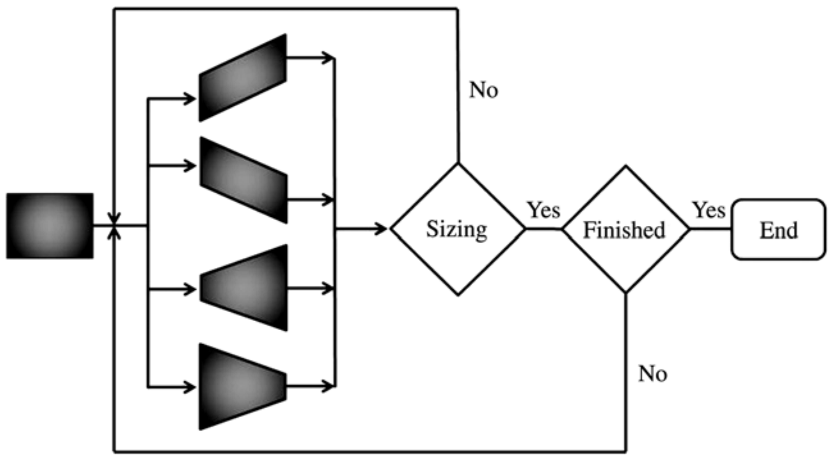

Fig. 2. Algorithm for extrusion with angular punches.

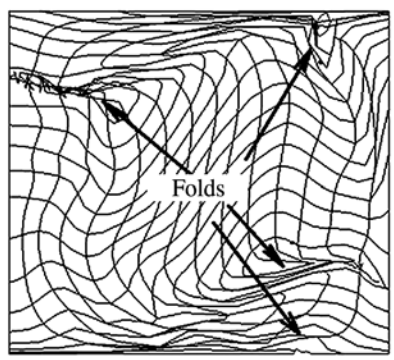

Fig. 3. Deformed billet defects in the form of folds.

(see Fig. 1); friction coefficient assumed to be zero; billet and tool temperature 20°C; punch angles a taken as 30, 35, 40, 45, and 50°. For a plane strained state, in Deform dimensions, perpendicular to the design plane, for default were assumed to equal one.

Copper M1 was chosen as the material for virtual and experimental studies. The M1 copper strengthening curve was approximated according to data in [5] for the relationship $\sigma_s = 435\varepsilon_0^{0.15}$, where σ_s is material flow stress, ε_0 is degree of deformation.

Experimental modelling showed that angle α has the main influence on defects in the form of pinches. A typical form of a model with folds is shown in Fig. 3. It was established that fold formation is not observed with a reduction in angle α to 30°. Subsequent studies were carried out using this value of the angle. Use of angles less than 30° is undesirable in view of the number of press working passes in order to achieve the required deformation.

Solution of the second problem was achieved on the basis of studying deformation state within the billet volume. A typical selection of material (tracking) points P1–P15 was taken for this purpose (Fig. 4). In view of deformation symmetry, the position of tracking points was only selected for the upper half of a billet.

During experimental modelling, the possibility was established of controlling deformation accumulation in different cross sectional areas of a billet being treated. With parallel arrangement of both punch surfaces, deformation increases in billet central layers, and with counter arrangement, in the corresponding boundary areas. A sequence of Lagrangian line distortion, obtained as a result of modelling in Deform, is shown in Fig. 5 for the combination of deformation stages adopted.

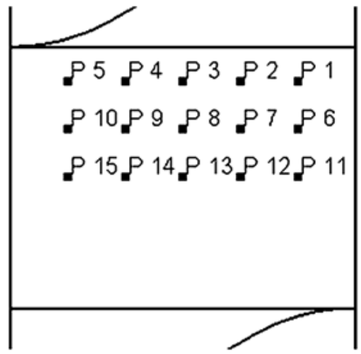

Fig. 4. Design layout and initial position of tracking points.

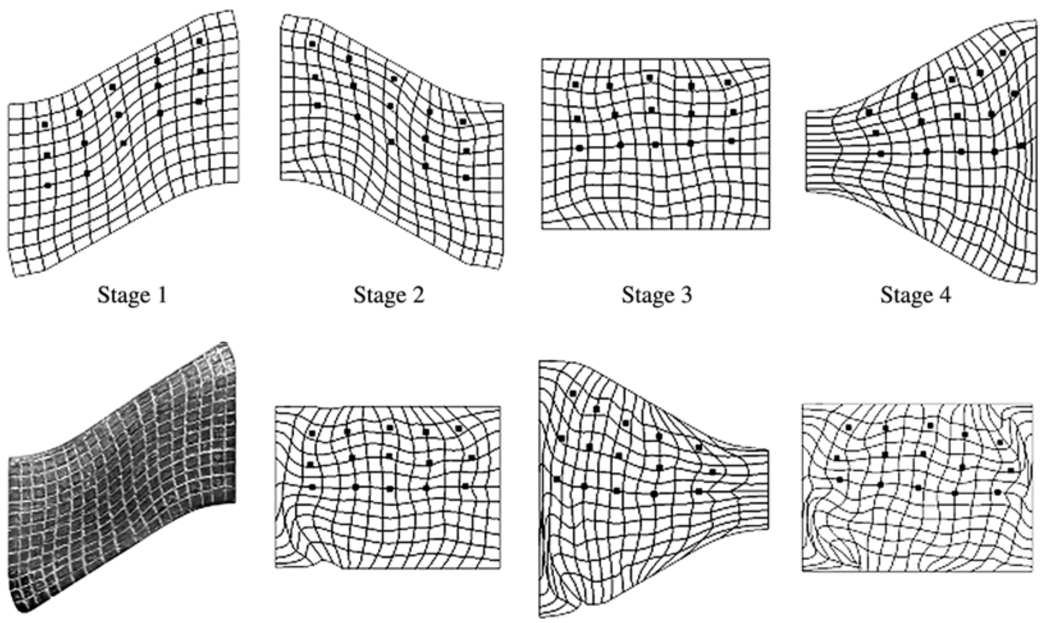

Fig. 5. Stagewise shape change of Lagrange lines obtained during simulation of reverse extrusion, and result of experimental verification with deformation of an actual billet in stage 1.

The adequacy of modelling was checked experimentally by a method of coordinate networks using lead billets. As seen from Fig. 5, the coordinate network in an actual billet is similar in form of Lagrangian lines obtained after the first deformation stage.

The nature of the dependence of degree of deformation ε_0 on slide path for tracking points P1, P3, P5, P6, P8, P10, P11, P13, P15 with seven deformation stages (see Fig. 5) is shown in Fig. 6. For degree of deformation here and subsequently, we recognize the value:

$$\varepsilon_0 = \int \dot{\varepsilon}_{\mathrm{i}} dt,$$

where

$$\dot{\varepsilon}_{\mathrm{i}} = \sqrt{2\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}/3}$$

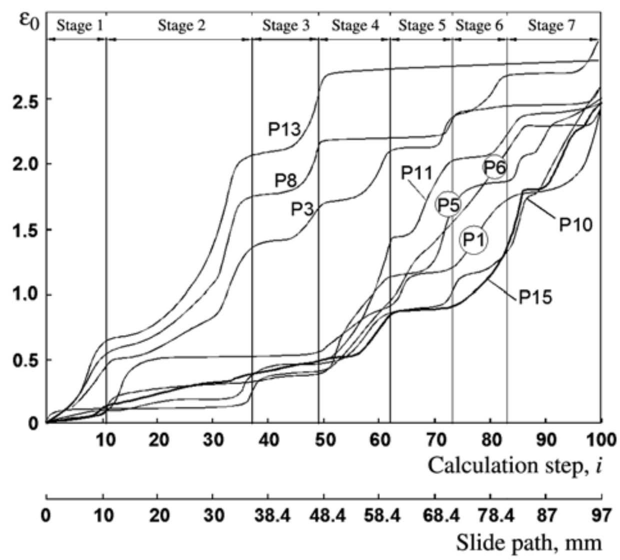

Fig. 6. Dependence of the degree of deformation ε_0 on slide path and loading scheme with seven-stage deformation with angular punches.

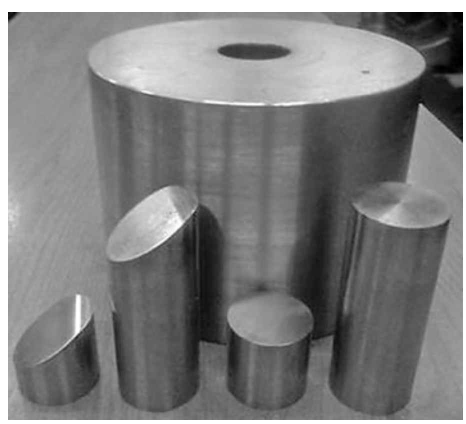

Fig. 7. Experimental press tool.

is the deformation rate intensity; $\dot{\varepsilon}_{ij}$ are deformation rate tensor components; $i, j = 1, 2, 3$ [6]. Comparison of the derived dependences shows that deformation in stages 1, 2, and 3 leads to a rapid increase in degree of deformation at points P3, P8, and P13, and an insignificant increase in degree of deformation at other points.

The picture changes markedly in stages 4–7. As a result, distribution of the degree of deformation over the billet cross section was levelled out to a considerable extent. At the end of stage 7, the most deformed area is the region in the vicinity of point P3 ($\varepsilon_0 = 2.8$), and the least deformed is in the vicinity of point P1 ($\varepsilon_0 = 2.4$), i.e., the difference between accumulated deformation in the most and least deformed areas of a billet cross section was ≈15%.

A significant conclusion from these comparisons is the fact that selection of subsequent stages with different loading schemes is a tool for controlling the amount of deformation accumulation in different areas of a billet in order to obtain the required degree of deformation in prescribed billet areas with a regulated grain size throughout the volume.

Finite element modelling of stagewise extrusion by angular punches made it possible to obtain complete information about the history of change in stress-strained state at tracking points P1–P15 and to establish an important process parame-

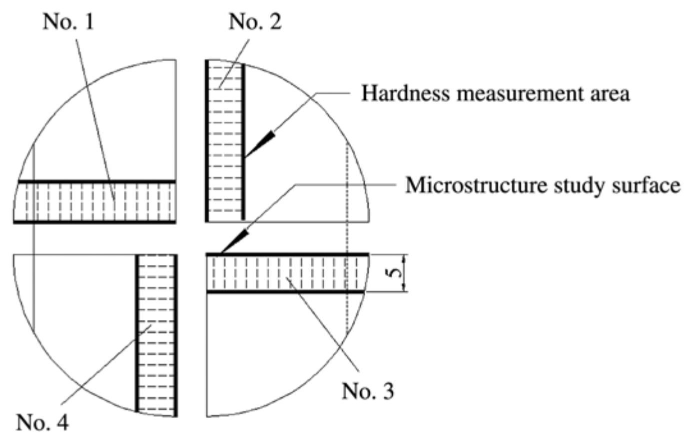

Fig. 8. Diagram of deformed billet section in specimens (Nos. 1–4) for studying microstructure.

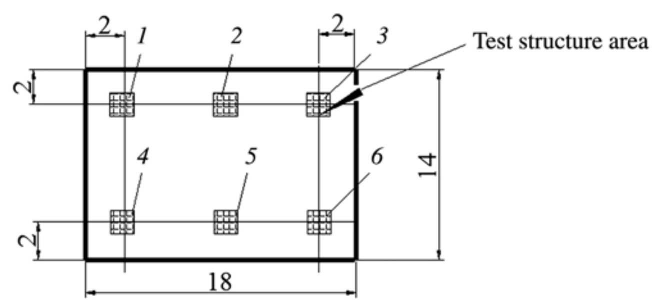

Fig. 9. Areas of test microstructure in specimens cut from deformed billet according to scheme in Fig. 8: 1–6 are numbers of test structure area in specimen surface.

TABLE 1. Hardness Measurement Results with Different Specimen Temperature

Specimen number (see Fig. 8)	Heat treatment (annealing for 40 min with water cooling)	Hardness HRF (Rockwell, 60 kgf, ball 1/16″), measured at six points of each specimen					
1	380°C	61	58	60	58	61	61
2	380°C	60	62	64	63	61	62
3	450°C	56	50	58	60	56	50
4	450°C	51	51	60	58	56	59
5	As-supplied condition	38	39	48	51	52	41

ter, governing deformed material failure resistance. Evaluation of the stressed state scheme, specified by stiffness coefficient $\eta = 3\sigma_{av}/\sigma_i$ (σ_{av} is average stress, σ_i is stress intensity), showed that the value of η in all deformation stages is within limits from –5 to –0.5. As a rule, with these stressed state schemes it is possible to deform even metals and alloys with low ductility properties up to high degrees of deformation.

Experimental study of deformed metal microstructure for copper M1 36 mm in diameter and 24 mm thick. The combination of metal deformation stages shown in Fig. 5 was used, and for final billet preparation for stamping a facing two more

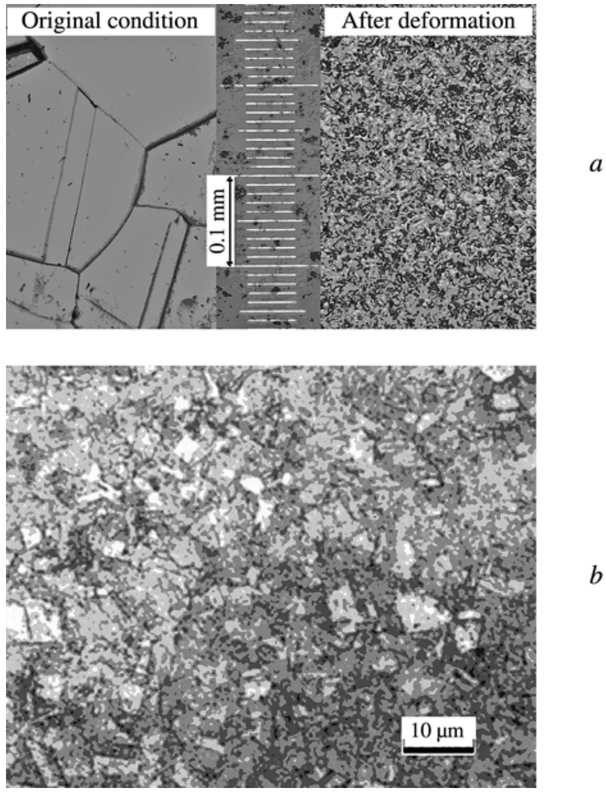

Fig. 10. Original microstructure (left) and deformed metal structure (right): *a*) ×200; *b*) ×1000.

deformation stages were added, shown in Fig. 1*a*. As a result, the calculated degree of deformation reached $\varepsilon_0 = 5.5–6$ (550–600%). A round container and two sets of punches were used for an experiment: a set with flat ends for performing the verification operation and a pair of punches with working surfaces arranged at an angle of 30° (Fig. 7).

The specimen cutting scheme and arrangement of areas for studying the microstructure are shown in Fig. 8. Revelation of the microstructure and hardness measurement were performed after annealing at 380 and 450°C. Copper hardness in the original condition was 50–52 HRF. Achievement of this hardness was a criterion for selecting annealing temperature. Achievement of the original hardness indicates the completeness of heat treatment by annealing. As follows from Table 1, total annealing is provided during 40 min annealing at 450°C. All together, there were 24 photographs of the microstructure (for six measurements in four specimens by the scheme shown in Fig. 9).

Grain size determination was performed according to scale III of GOST 21073.1–75. On average, the grain size corresponded to point 10–12, i.e., average grain diameter 5–8 μm (Fig. 10). The measured size for the original state corresponded to point 1–2 (0.25–0.17 mm).

Conclusions

1. A new production scheme has been developed for achieving high degrees of plastic deformation, which may be proposed as a basis for forming a fine-grained structure in billets for manufacturing facings and other copper objects.

2. The new production scheme has advantages compared with known schemes, and this includes simplification of working tool construction, exclusion of intermediate operations for extraction and installation of a billet between deformation stages, absence of undeformed end zones and nonuniformity of deformation over a billet length, and also the possibility of controlling deformation accumulation in different areas of a billet cross section, which also makes it possible to provide sufficiently uniform distribution of accumulated deformation over a billet cross section.

The work was carried out within the scope of state assignment on theme 7.714.2011.

REFERENCES

1. L. P. Orlenko (ed.), *Explosion Physics* [in Russian], 3rd edition, FIZMATLIT, Moscow (2004), Vol. 2.
2. V. N. Subich, V. A. Demin, N. A. Shestakov, and A. V. Vlasov, *Stamping with Torsion* [in Russian], MGIU, Moscow (2008).
3. V. M. Segal, V. I. Reznikov, V. I. Koplylov, et al., *Processes of Metal Plastic Structure Formation* [in Russian], Nauka i Tekhnika, Moscow (1994).
4. Ya. E. Beigelzimer, V. N. Baryukhin, D. V. Orlov, and S. G. Synkov, *Screw Extrusion – Process of Strain Accumulation* [in Russian], Firma TEAN, Donetsk (2003).
5. P. I. Polukhin, G. Ya. Gui, and A. M. Galkin, *Metal and Alloys Plastic Deformation Resistance: Handbook* [in Russian], Metallurgiya, Moscow (1976).
6. L. M. Kachanov, *Bases of Plasticity Theory: Textbook for Universities* [in Russian], Nauka, Moscow (1969).