Advantages of drawing and rolling metals with pulse current

O A Troitsky and V I Stashenko

Federal State Budget Office of Science
Institute of Mechanical Engineering. A.A. Blagonravova RAS
Russia, 101990, Moscow, M. Kharitonevsky per., 4
E-mail: oatroitsky@mail.ru and vis20-11@rambler.ru

Abstract. The results of studies on the drawing of copper and steel wires using pulsed current in the deformation zone are presented. The analysis of their structure and physicomechanical properties is given. As a result, the drawing forces of copper and steel wires are reduced by 30-35%, the electrical resistance is reduced by 18-20%, a more perfect axial texture appears, the ductility of the wires increases compared to warm drawing. In the steel wire, the \( \alpha \)-phase content sharply decreases, which is predominantly released in the surface layer by several microns. We propose methods for the modernization of rolling equipment for technology using pulsed current. The efficiency of using a high-density pulsed current on a rolling mill for producing stainless steel from an initial billet of 2 mm thick and 100 mm wide 0.3 mm thick tape without intermediate annealing and oxide film is shown.

Keywords: wire drawing, pulsed electric current, structure, properties, modernization of mills

1. Introduction
The most important property of plastically deformed materials is used to obtain blanks and products. Form-changes of the blanks while obtaining the product are accompanied by complex structural changes, which requires the improvement of metal forming under pressure processes (MFP).

Many materials used in mechanical engineering have low technological ductility. Therefore, the urgent task is to extend the ductility interval, a targeted effect on the metal structure, on the value of internal stresses. Decisive in the formation of a particular structure and, therefore, the necessary properties of the metal is the rate of heating and cooling [1]. Great opportunities in solving these problems in MFP technologies are provided by the use of electric current in the zone of metal deformation. The action of an electric current provides fast and uniform heating of the workpiece in a wide temperature range, which allows combining the heating of the workpiece and its deformation, creating conditions for continuous, rational and high-performance production of products [2,3]. An increase in the heating rate significantly accelerates the diffusion movement of carbon atoms, improves the purification of ferrite and delays the coagulation process, preserving the lamellar form of cementite, which is a must condition for large total compressions, for example, for steel [1,3].

An additional reserve for increasing the ductility of deformable structural materials is the use of high-density pulsed current. The plasticizing effect of the pulsed current on the deformation of the metal (electroplastic effect - EPE) was established during tension and compression of zinc single crystals in liquid nitrogen [4]. The effect manifested itself in the form of jumps in plastic deformation under pulses of current [5]. It was confirmed by the work of [6,7] American scientists on polycrystalline titanium.

The force action of the current on the plastic deformation of the metal occurs mainly through two channels - through the electronic subsystem through the action of the "electronic wind" on the
dislocation [8], and also through the lattice subsystem of the metal by creating vibration of the conductor due to the pinch action of the pulse current (pulsed current interaction with its own magnetic current field) [9] Recent studies have shown that under the action of current pulses, at the moments of the beginning of the leading and trailing edges of the pulse, significant jumps in acceleration (more than 1000 $\text{m/s}^2$) and surface displacements in the direction of the radius of the conductor occur [10], causing vibrations of the lattice sites similar to the effect caused by ultrasound on plastic deformation of metal.

For the implementation of EPE for any type of metal forming under pressure processes (MFP), the following conditions must be met:

- the workpiece must be under mechanical stresses above the yield strength $\sigma_t$;
- pulsed current of low voltage (20-25 V) and high density $J_m$ must be supplied directly to the deformation zone;
- the shape of the pulses must be rectangular or trapezoidal;
- pulse duration $\tau$ should have values $\tau$ of about $10^4$ seconds, do not exceed the $10^3$ second time of normal deformation jumps so that significant concomitant heating does not occur;
- the amplitude current density $J_m$ must be large, at least $10^5 \div 10^6 \text{A/cm}^2$ so that conduction electrons acquire significant drift velocities $v_e$ of the order of one meter per second (“electron wind” speed) in accordance with the formula $v_e = J_m/e \ n$, where $e$ and $n$ is the charge and concentration of free electrons and could transmit momenta of force and energy to dislocations and other mobile structural defects;
- pulse repetition rate $F$, defined by the formula $F = k \ v_{\text{mov}}/\Delta l$ where $v_{\text{mov}}$ - is the speed of movement of the workpiece, $\Delta l$ - the length of the deformation zone and $k$ is a factor of the order of two (two pulses per $\Delta l$) should be several hundred Hz to ensure that all sections of the workpiece are processed by the pulse current.
- The action of EPE during MFP gives the following results:
  - metal resistance to deformation is reduced by 25-30%;
  - increases the ductility of the metal during processing, as well as in the appearance of residual ductility by tens of percent;
  - the degree of perfection of the axial texture of the wire during drawing increases, its electrical resistance decreases by 15-20%. The phase composition of the metal and structure are improved;
  - during rolling, drawing and drawing of stainless steels, the austenitic-martensitic phase $\gamma - \alpha$ - transformation is almost completely suppressed, which makes the operations of expensive and energy-intensive austenizing annealing of workpieces unnecessary;
  - reduces the likelihood of brittle fracture of the workpiece material during processing.

The aim of the work is the application of technology for electroplastic wire drawing and strip rolling, as well as ways to modernize machine tools for electroplastic deformation of metal are given.

2. Technology of electroplastic drawing of wire

The technology of electroplastic drawing (EPD) allows you to: increase the residual ductility of the wires and the work of their destruction, reduce the electrical resistance of the original wires by increasing the degree of perfection of the axial texture, reduce and ordering the number of remaining defects, including dislocations.

This allows you to get stronger, lighter, more flexible and reliable current-carrying wires with improved surface and contact properties. In addition, a large technical and economic effect is achieved by the abolition of intermediate annealing operations, which increases the productivity of mills.

The EPD technology is based on the supply of electric current (constant or pulsed) directly to the deformation zone of a metal wire during drawing, Figure 1 Schemes , Figure 1a) and Figure 1b) allow
drawing with the passage of electric current through a section of wire, including a deformation zone, using carbide and diamond fibers, respectively.

Current is supplied to the drawing zone immediately before and after the die by means of rotating rollers or by means of sliding contacts. The entire EPD assembly is placed in a bath with a flowing emulsion, which guarantees the absence of thermal heating of the wire necessary for the effective action of EPE. A water-soap emulsion for copper, a triethanolamine emulsion and chlorine paraffin CP-70 for steels with unstable austenite were used as a cutting fluid. These lubricants cooled the die and the wire section subjected to current. The current supply to the moving wire was carried out using roller and brush contacts. A powder contacting device was also used [2].

For most metals (copper, tungsten and molybdenum), the effect of reducing the drawing force is maximum when connecting the plus of the current source to the deformation zone, when the direction of the conduction electron current coincides with the direction of movement of the deformation zone. The current effect is maximum at small wire drawing speeds \( u_s \leq 0.1 \) m/c, and it has a smaller value at average drawing speeds \( u_s = 0.3-0.5 \) m/c, with a further increase \( u_s \), the electron drift velocity \( u_e \) exceeds the metal deformation rate \( u_s \).

The maximum allowable current density in copper wires is \( J_m = 10^3 \) A/cm². This corresponds to the electron drift velocity of 0.1 cm/s. Concomitant heating of billets, as a rule, does not exceed 100-200 °C [7].

In semi-industrial experiments, pulsed current densities of \((0.35-0.5) \times 10^6 \) A/cm² corresponded to electron drift velocities \( u_e = 0.35-0.5 \) m/c. Thus, the applicability of EPE to intensify the process of metal drawing is undeniable.

The magnitude of the effect of the action of the current during EPD increases with increasing frequency, duration of current pulses, amplitude and average current density. During EPD on thin wires, the current power allocated in the drawing zone does not exceed 100 watts.

As a result of EPD of the stainless steel wire there is a sharp decrease in the content of the martensitic a-phase after 8-10 transitions on a wire with a diameter of 0.3 mm does not exceed 6-8%, and after the usual drawing 60-70%. The a-phase remaining after EPD the electron-hole emission is predominantly released at the surface of the wire, forming a jacket several microns thick.

The ductility of wire d (relative elongation) of metastable austenitic steel (MAS) as a result of EPD increases by 40%, which is more than the test results of samples after warm drawing (20-25%), and even more so after cold drawing (5-6%). The trip effect on the wire from the MAS, passed EPV, increases by more than two times at the pulsed current and one and a half times at constant current compared with warm drawing.

Improving the quality of the wire, reducing its cost is an urgent task. It becomes important to manufacture lightweight cables through the use of heavy copper substitutes with lighter and enough conductive materials, for example, aluminum and bimetals, which is primarily interested in the
aerospace field of technology. In the case of cables, the ultimate goal should be to reduce the number of conductors and the weight of the cables. The technology of electroplastic wire drawing was applied in the manufacture of cable. Compared to a standard cable, the new cable is almost twice as light, and in the future, the weight of the cable can be further reduced significantly (Figure 2).

![Figure 2. Typical existing cable a), new cable b) and prospective cable.](image)

3. Methods of modernizing existing rolling mills for EPD technology

As an example, let’s consider two main ways of applying current. The first method is to tear off one of the deformable shafts - the lower or upper part of the rolling stand from the mass of the mill, so that it is possible to supply the working current across the direction of movement of the workpiece according to the “from shaft to roll through the workpiece” scheme (Figure 3a) such a supply circuit current is most effective as an EPD method; it can be used when rolling sheet material and strips, as well as when flattening wire into tape on flattening mills; the accompanying thermal effect is minimal, not more than 100 °C, and unit allowable reductions reach values of tens of percent. The method is not limited with respect to the resulting thickness of the rolled sheet or strip. Provided that the portion of the workpiece under current is minimized, the possibility of overheating is completely eliminated. If necessary, when dosed thermal preparation of the workpiece material is required, this method can combine electrical contact heating (ECH) and EPD, which as a result makes it possible to reduce the workpiece’s resistance to deformation by more than 30-35%. The disadvantage of this method is the isolation of the deforming shafts from each other and from the rolling mill, i.e. modernization of the mill for EPD technology is not easy. However, this method is used to study EPD in laboratory conditions and on thin blanks.
Figure 3. a)- is a method of supplying current from a roll to a roll: \( v_n \) is the rolling speed; \( b_i, b_f \) - the initial and final thickness of the strip; \( J \) - is the current density vector; \( R \) - is the radius of the deforming shaft; \( B \) is the width of the deformation zone; b)- is the method of supplying current with two sliding contacts before and after the ZD (1 and 2 sliding contacts).

The second method of supplying current using the contacts before and after the rolling zone has its advantages and disadvantages (Figure 3b). This method is the simplest, does not require major modernization of the mill, saves deforming shafts from destruction by electroerosion and allows you to combine EPD and ECH. It has no restrictions on the thickness of the workpieces compared to the first method. It is advisable to supply current from both sides of the working zone of the mill using sliding or roller contacts.

It is advisable to use this current supply circuit when introducing EPD technology into production for the following reasons. Deformation shafts are not included in the electrical circuit. At the same time, they process the section of the workpiece through which the working current passes and in which the EPD is realised. The resistance to deformation from the side of the workpiece is reduced by 30-35%. This leads to a decrease in wear of the deforming shafts and reduces the likelihood of a tack phenomenon in the operation of the mill. In this case, upgrading the mill to EPD technology is a low-cost and long-term operation of the mill.

For operation, it is necessary to provide a device for powerfully connecting current-carrying coaxial cables to the rolling contacts at the inlet and outlet of the mill, as well as to the part of the rolling stand isolated from the mass of the mill.

4. Rolling mill for stainless steel tape
It is advisable to use EPD technology only at low and medium rolling speeds (not more than 0.5 m/c), or high-speed EPD on very thin workpieces.

In the work, the pulse current modes for rolling stainless steel are established: the amplitude current density \( J_m=10^4-10^5 \) A/cm², the pulse duration of \( 150-200\cdot10^{-6} \) c, the pulse repetition rate of 500-800 Hz. The method of supplying current with two sliding contacts was used (Figure 3 b).

During the testing of the mill, multiple strip rolling was performed from stainless steels of the 12X18H9 and 12X18H10T type from an initial thickness of 2 mm to a final thickness of 0.3 mm without intermediate annealing. At the same time, due to the rational choice of the pulsed current parameters, the appearance of an oxide film was prevented. The rolling speed was maintained in the range \( (0.3-0.5) \) m / s. The total electric power at maximum consumption was approximately 150 kW. The maximum amplitude value of the pulse current was 45 kA. Current density \( J_m \) in the steel strip in the deformation zone amounted to 300-800A/smm² depending on the current strip thickness.
In Figure 4, 5 show a view of a mill for producing stainless steel tape. In Figure 6 shows the results of measurements of physical and mechanical properties. The mill provided rolling of stainless steel tape 100 mm wide, from an initial thickness of 2.0 m to a final thickness of 0.3 mm with a rolling error of not more than 0.01.

The use of EPD technology in modern pulsed current mills opens up new possibilities for automatic regulation of the rolling process. By changing the amplitude and frequency of the pulses following the signals of the pressure sensors on the rolls, it is possible to strengthen or, on the contrary, weaken the electroplastic effect of the current. In this case, the gap between the rolls will remain unchanged and it will be possible to avoid an undesirable increase in the thickness of the workpiece (rolled) during the elastic squeezing of the rolls.

Figure 4. a) general view of the EPP mill; b) rolling of a steel strip
Figure 5. a) circuit current to the deformation zone: 1-sliding contacts, 2-working rolls, 3-tape, 4-current source; b) type of sliding contacts

Figure 6. a) change of yield strength $\sigma_t$ for different relative deformation $\varepsilon$: 1-cold rolling; 2-electroplastic rolling; b) change of thickness $b$ of steel strip on transitions $N$

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