COMPUTER SIMULATION OF PRELIMINARY HEAT TREATMENT AND RADIAL-SHEAR ROLLING OF COPPER

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ABSTRACT

This paper presents the results of computer simulation by the cellular automata method of preliminary heat treatment and radial-shear rolling of M1 copper alloy. Quenching and annealing processes were modeled as pre-heat treatment modes. The radial-shear rolling stage consisted of three passes with a compression of 3 mm per pass. The variable parameters were the roll rotation speed (40 rpm, 70 rpm and 100 rpm) and the workpiece heating temperature before rolling (20°C and 200°C). It was found that the most effective mode of pre-heat treatment for M1 copper alloy is quenching at 700°C. The most rational value of the workpiece heating temperature before rolling is 20°C, since in this case, at all selected speeds, the recrystallization process does not start, which contributes to intensive grinding of grain in the surface layers and on the periphery. An increase in the roll rotation speed causes additional deformation heating, which contributes to the recrystallization and suppression of intensive grain grinding. Therefore, when heating the M1 copper alloy to 200°C, it is not recommended to increase the rolling speed above the nominal.

Keywords: simulation, pre-heat treatment, radial-shear rolling, microstructure, copper.

INTRODUCTION

Despite the current level of development of virtual computing technologies, the main investigation method of any technological process remains a physical experiment. Since only in full-scale experience, it is possible to take into account all the parameters that affect the process. At the same time, conducting only physical experiments is a very irrational task that requires a lot of effort, time and material resources.

The ideal compromise is the use of virtual simulation software packages allowing to simulate the studied process, take into account almost all the parameters that affect it, as well as optimize the process, i.e. determine the values of all dependent parameters at which the process will proceed most stably. After that, when conducting a physical experiment with optimal values, the result will be the most successful, without rejection of the workpiece or equipment failure.

During the development of many processes of severe plastic deformation (both discrete and combined), it was found that usually a large number of deformation cycles are necessary to achieve the UFG structure [1 - 5]. At the same time, it is possible to reduce the required number of cycles and achieve the same effect of grain refinement by implementing pre-heat treatment (PHT), which also allows to reduce the initial grain size to a certain extent. To determine the most effective type of PHT for a specific combination of the processed material and the deformation scheme, a rational way is to simulate the microstructure evolution. The purpose of this work was computer modeling of the microstructure evolution of the M1 copper alloy during the processes of pre-heat treatment (PHT) and subsequent radial-shear rolling (RSR).

EXPERIMENTAL

It was decided to use the cellular automata mechanism v.2.0, implemented in the Deform v.13 system, to carry out computer modeling of the processes of preliminary heat treatment (PHT) and subsequent radial-shear rolling (RSR) of M1 copper alloy [6]. This mechanism allows not only to simulate grain size changes, but also to predict their shape during deformation or heat treatment. At the same time, according to the reference manual for the Deform v.13, in the cellular automata mechanism v.2.0, algorithms for predicting the shape of grains during various types of processing were significantly improved [7].

Taking into account the fact that after the PHT, the blanks are planned to be subjected to several cycles of RSR at the SVP-08 mill of Rudny Industrial Institute, a rod of circular cross-section with a diameter of 30 mm and a length of 150 mm was set as the initial billet.

For the M1 copper alloy, the following modes of PHT were selected:
- heating up to 700°C, cooling in water (quenching);
- heating up to 700°C, cooling with a furnace (annealing).

The time interval during which the sample is warmed up from ambient temperature (20°C) to a predetermined temperature with a uniform distribution over the cross section was adopted as the heating stage during modeling. Accordingly, the time interval during which the sample is cooled from a given temperature to ambient temperature with a uniform distribution over the cross section was adopted as the cooling stage during modeling. These heating-cooling intervals were determined analytically using the classical calculation algorithm, which is based on the Newton-Richman law and on theoretical and practical studies of the regular thermal regime [8, 9]. For convenience, this algorithm was presented in the Microsoft Excel environment, its operation requires the input of both geometric parameters of the body and thermophysical constants determined using reference literature.

In accordance with the calculations in this program, the following values of time intervals were obtained:
- heating to 700°C in 6782 seconds (113 minutes), cooling in water in 17 seconds;
- heating to 700°C in 6782 seconds (113 minutes), cooling with an oven in 6782 seconds (113 minutes).

In all cases, the holding time at the set temperatures was 30 minutes.

To create a model of the microstructure evolution during preliminary heat treatment, it is necessary to use only static recrystallization. Dynamic recrystallization cannot be used, since at this stage there is no deformation and material flow direction.

The key parameters of the cellular automata algorithm are the input of model constants, the values of which depend on the nature of the material. For the M1 copper alloy, the constants of the model are considered in [10]. Table 1 shows the values of these constants.

The calculation essence of the microstructure evolution by this method is the use of a ready-made, calculated model. Calculation windows with a certain resolution are installed at the selected points, in which a change in both the grain size and their shape is observed. Taking into account the fact that the initial grain size was set to 80 microns for the M1 copper alloy, it was decided to choose a square window with a face size of 200 microns so that it could track the full dimensions of several grains before and after the PHT.

Taking into account the fact that at this stage the modeling of the PHT is carried out without deformation, the structure in the longitudinal and transverse directions will be the same. Therefore, the study of the microstructure evolution will be carried out only in one direction. At the deformation stage, the microstructure will be considered both longitudinally and transversely.

It should also be noted that when modeling the

Table 1. Constants of the Cellular Automata 2.0 model.

Material	G, N/m^2	b, m	γ, J/m^2	δD_{0b}, m^3/s	Q_b, kJ/mol	A_1	n_1	Q_{def}, kJ/mol
M1 copper	$4,21\times10^{10}$	$2,56\times10^{-10}$	0,625	$1,09\times10^{-11}$	162	$3,51\times10^{43}$	0,131	294

microstructure evolution of copper and its alloys, one serious assumption has to be introduced. At this stage of the development of the cellular automata algorithm, it is impossible to simulate a change in the structure by twinning. Therefore, it is assumed that a dislocation mechanism works in all materials when the microstructure changes.

RESULTS AND DISCUSSION

The initial structure of M1 copper alloy with an average grain size of 80 microns, as well as after two different PHT, is shown in Fig. 1.

After quenching the M1 copper alloy at 700°C the initial grain size of 80 microns decreased to 50 microns approximately, while after annealing at 700°C the initial grain size has increased to 130 microns approximately. Based on the results obtained, it can be concluded that the most effective PHT mode of the two selected for the purpose of the initial grain size refinement of M1 copper alloy is quenching at 700°C.

To determine the rational speed and temperature parameters of radial-shear rolling in order to obtain an ultrafine-grained structure in copper for a small number of passes, it was decided to conduct three passes with a compression of 3 mm per pass.

As a speed characteristic, which is easy to vary in real conditions, the roll rotation speed was chosen. The nominal speed was set to 40 rpm, and increased values of 70 rpm and 100 rpm were also adopted to assess the effect of this parameter when changing.

As a temperature characteristic, which is easy to vary in real conditions, the workpiece heating temperature before rolling was chosen. Temperatures of 20°C and 200°C were selected for the M1 copper alloy.

Taking into account the fact that at the stage of simulation of PHT it was found that the most effective mode is quenching, it was decided to use the appropriate heating-cooling modes before the deformation stage. It was also decided to examine the microstructure not only in two different directions (longitudinal and transverse), but also at three different points along the cross section: in the axial zone, in the surface zone (at a distance of 10 mm from the center) and in the peripheral zone (at a

Fig. 1. Structure of M1 copper alloy: a - initial structure; b - after quenching at 700°C; c - after annealing at 700°C.

distance of about 5 - 6 mm from the center). This is due to the fact that experimentally it has been repeatedly proved the presence of a gradient distribution of grain size in the cross section of the workpiece after RSR and a significant difference in the shape of the grains in different directions.

Figs. 2 - 7 present the results of microstructure modeling of the M1 copper alloy at various speed and temperature parameters.

At ambient temperature, copper deformation

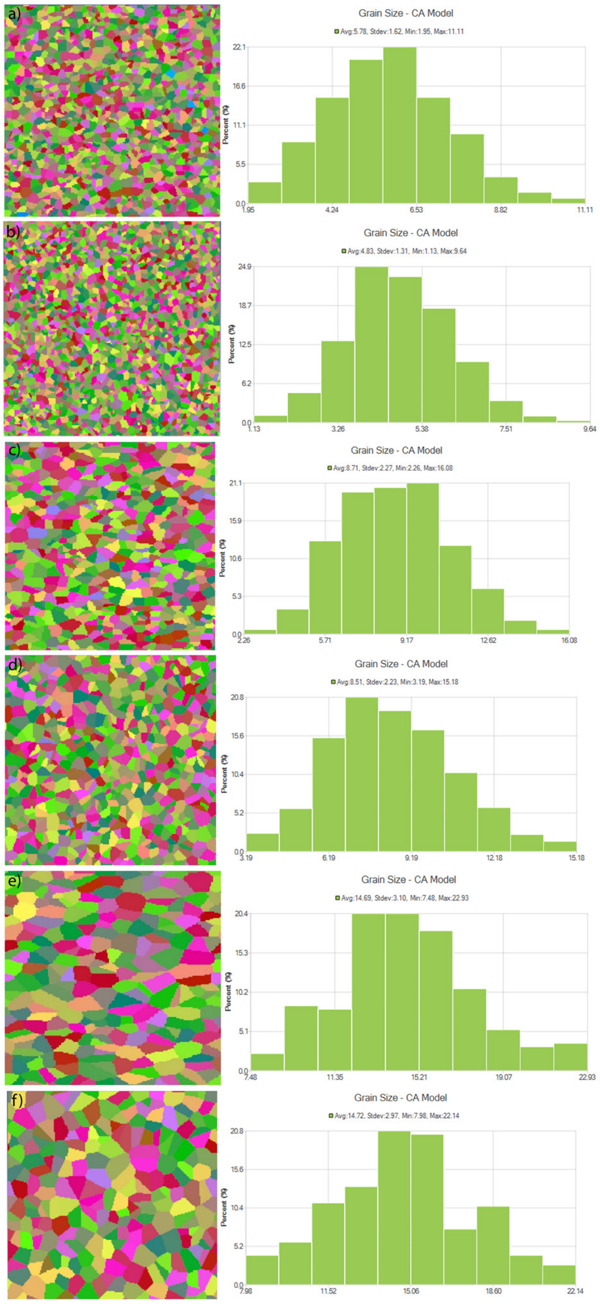

Fig. 2. Structure of M1 copper alloy after quenching, 3 cycles of RSR at a workpiece temperature of 20°C and a roll rotation speed of 40 rpm: a - surface, longitudinal direction; b - surface, transverse direction; c - periphery, longitudinal direction; d - periphery, transverse direction; e - center, longitudinal direction; f - center, transverse direction.

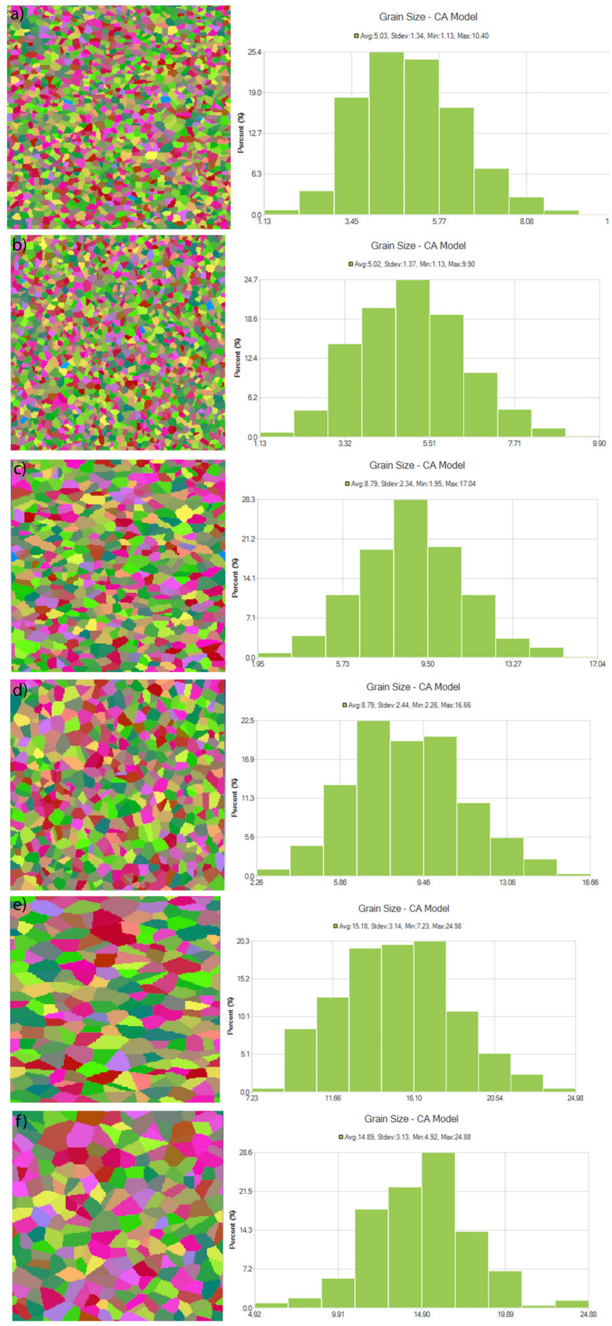

Fig. 3. Structure of M1 copper alloy after quenching, 3 cycles of RSR at a workpiece temperature of 20°C and a roll rotation speed of 70 rpm: a - surface, longitudinal direction; b - surface, transverse direction; c - periphery, longitudinal direction; d - periphery, transverse direction; e - center, longitudinal direction; f - center, transverse direction.

proceeds without recrystallization, since under these conditions the workpiece heats up to 40 - 45°C. As a result, here the initial grain size, equal to 50 microns after quenching, is refined most intensively. At the same time, the gradient distribution of grain size in the radial direction is clearly visible - the smallest grain size is observed in the surface layers (5 - 6 microns approximately), when moving to the center of the workpiece, the grain size increases to 15 microns. Also, the difference in the shape of the grains in different

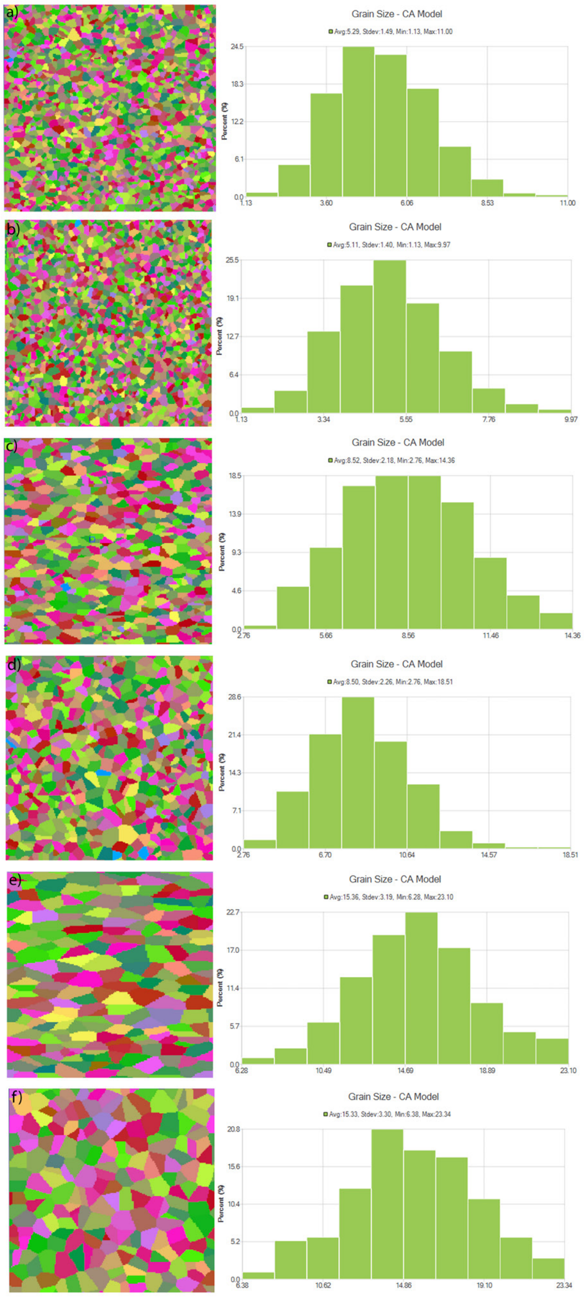

Fig. 4. Structure of M1 copper alloy after quenching, 3 cycles of RSR at a workpiece temperature of 20°C and a roll rotation speed of 100 rpm: a - surface, longitudinal direction; b - surface, transverse direction; c - periphery, longitudinal direction; d - periphery, transverse direction; e - center, longitudinal direction; f - center, transverse direction.

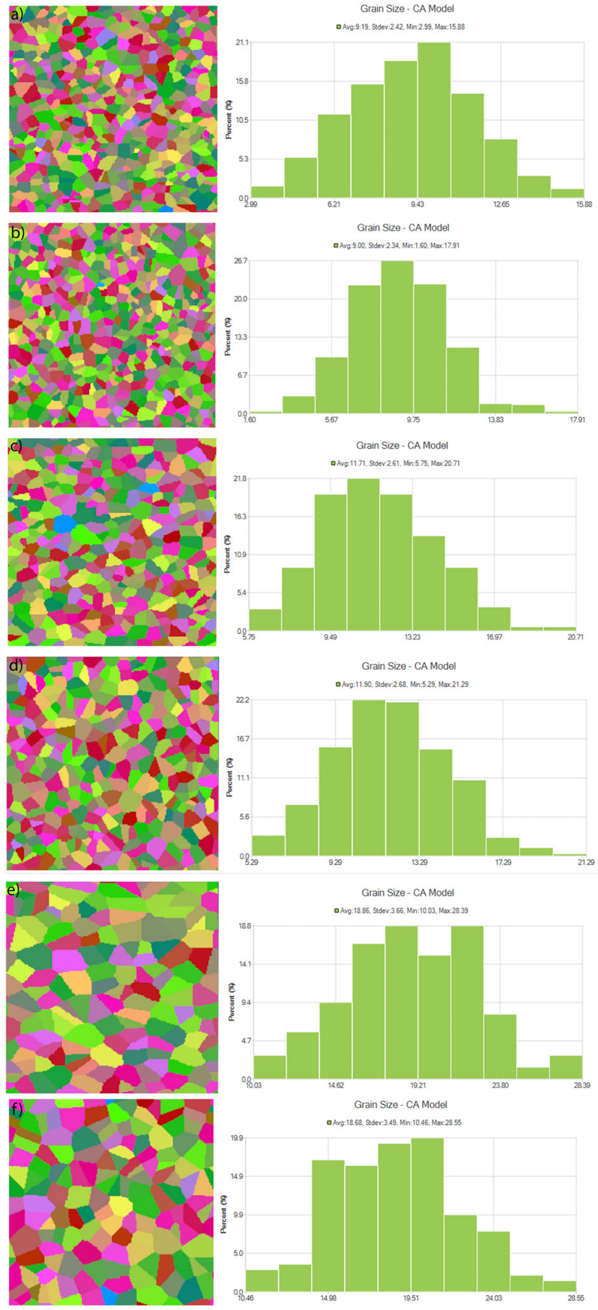

Fig. 5. Structure of M1 copper alloy after quenching, 3 cycles of RSR at a workpiece temperature of 200°C and the rotation speed of the rolls 40 rpm: a - surface, longitudinal direction; b - surface, transverse direction; c - periphery, longitudinal direction; d - periphery, transverse direction; e - center, longitudinal direction; f - center, transverse direction.

directions is clearly noticeable: in the longitudinal direction, the grains receive some elongation, the intensity of which is also gradiently distributed over the cross-section - in the center the elongation is most noticeable, on the surface it is practically absent.

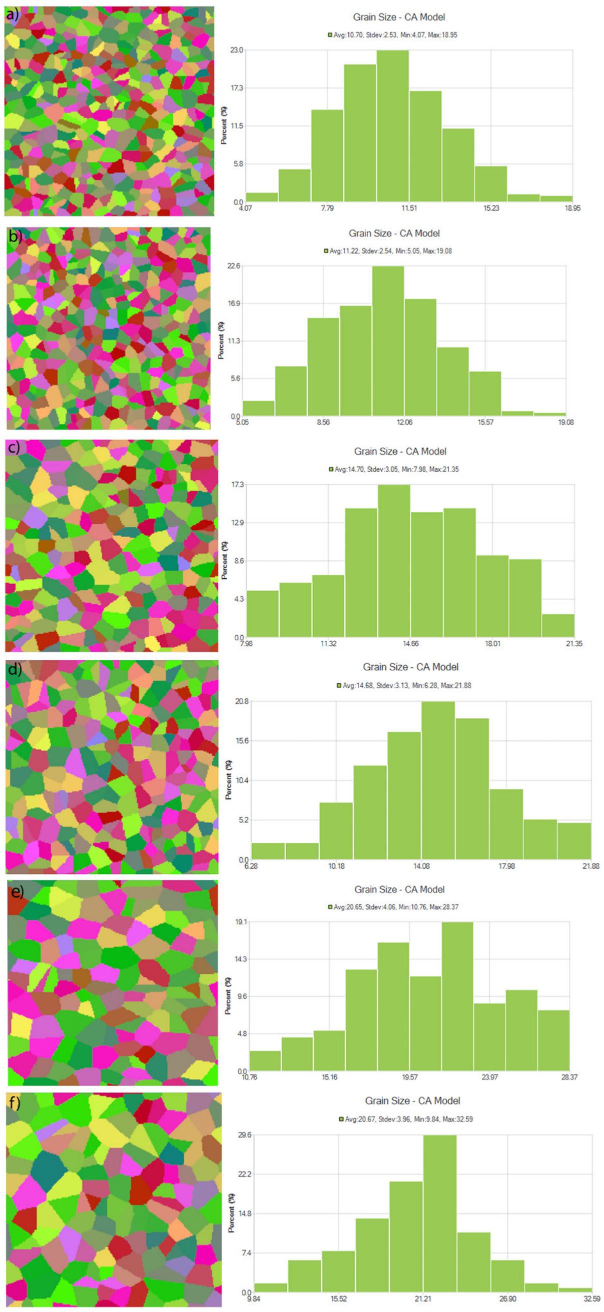

Fig. 6. Structure of M1 copper alloy after quenching, 3 RSR cycles at a workpiece temperature of 200°C and the rotation speed of the rolls 70 rpm: a - surface, longitudinal direction; b - surface, transverse direction; c - periphery, longitudinal direction; d - periphery, transverse direction; e - center, longitudinal direction; f - center, transverse direction.

With an increase in the rolls rotation speed to 70 rpm, copper deformation proceeds with a slight increase in the workpiece temperature to 55°C - 60°C due to the intensification of deformation heating in the rolls. Under these conditions, recrystallization does not begin, as a

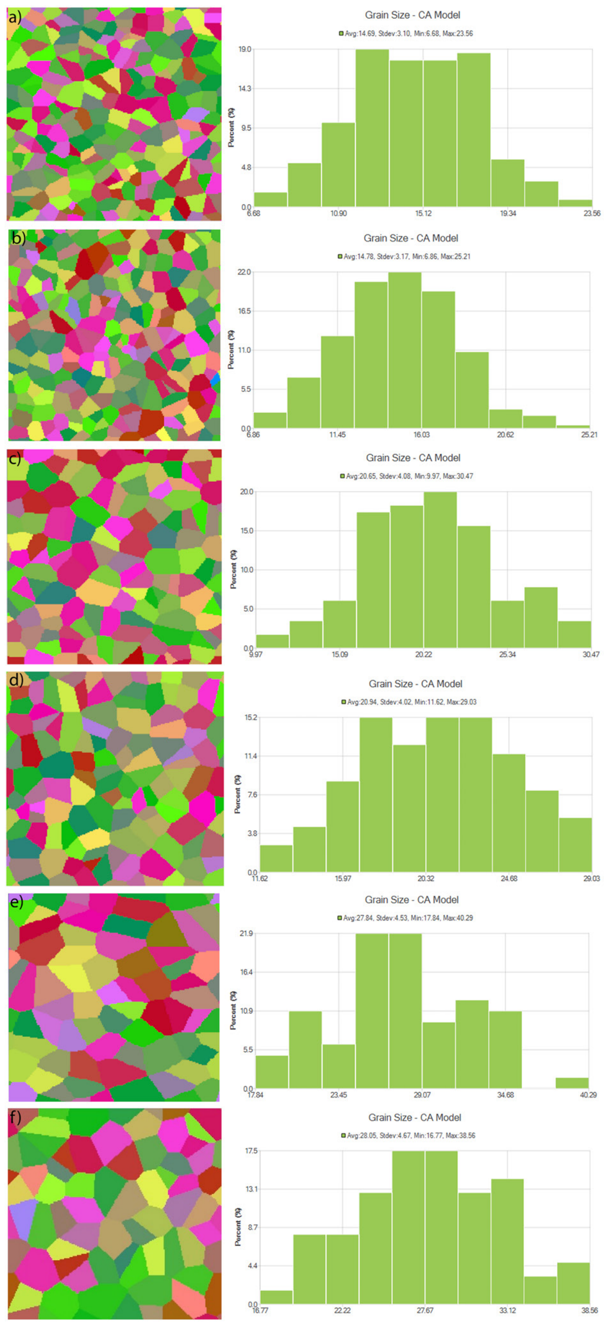

Fig. 7. Structure of M1 copper alloy after quenching, 3 cycles of RSR at a workpiece temperature of 200°C and the rotation speed of the rolls 100 rpm: a - surface, longitudinal direction; b - surface, transverse direction; c - periphery, longitudinal direction; d - periphery, transverse direction; e - center, longitudinal direction; f - center, transverse direction.

result of which the initial grain size, as in the previous case, is refined quite intensively (the level of grain grinding is similar here - from 5 microns on the surface to 15 microns in the center). However, due to an increase in the strain rate, a higher level of grain elongation is observed in the longitudinal directions at the periphery and in the center.

With an increase in the rolls rotation speed to 100 rpm, copper deformation proceeds with an increase in the workpiece temperature to 85°C - 90°C due to heating in the rolls and a general reduction in rolling time. This temperature is also insufficient to start the recrystallization process. The level of grain refinement by section here is similar to the two previous cases considered. Due to a further increase in the strain rate, an even higher level of grain elongation is observed in the longitudinal directions at the periphery and in the center.

When copper is heated to 200°C and then deformed, the workpiece has a temperature of about 195°C. At this temperature, recrystallization in copper is just beginning, as a result of which the initial grain size, equal to 50 microns after quenching, is refined quite intensively. The gradient distribution of grain size in the radial direction is preserved at the same time - the smallest grain size is observed in the surface layers (9 microns approximately), when moving to the center of the workpiece, the grain size increases to 19 microns. In the longitudinal direction, the grains also get some elongation, the intensity of which decreases due to the beginning of the recrystallization process.

Increasing the rolls rotation speed to 70 rpm leads to an increase in the temperature of the copper billet to 210°C. Under these conditions, recrystallization proceeds more intensively, as a result of which the initial grain size is crushed significantly weaker (from 11 microns on the surface to 21 microns in the center). This factor also causes a decrease in the level of elongation of grains in the longitudinal directions at the periphery and in the center.

An increase in the rolls rotation speed to 100 rpm leads to the fact that due to heating in the rolls and a general reduction in rolling time, the deformation of the copper billet proceeds at 230°C. Under these conditions, recrystallization proceeds more intensively, as a result of which the final grain size has the following dimensions - about 15 microns on the surface, increasing to 28 microns in the center. The level of elongation of the grains in the longitudinal directions at the periphery and in the center is insignificant under these conditions.

CONCLUSIONS

Based on the results obtained by the microstructure evolution modeling of M1 copper alloy, optimal parameters that allow to intensify the grain refinement process after PHT were determined: deformation at ambient temperature is the optimal option, since in this case, at all selected speeds, the recrystallization process does not start, which contributes to intensive grain refinement in the surface layers and on the periphery. Heating copper to 200°C leads to the boundary of the recrystallization beginning and only rolling at a speed of 40 rpm contributes to lowering the temperature below this boundary. An increase in the roll rotation speed causes additional deformation heating, which contributes to the recrystallization and suppression of intensive grain refinement. Therefore, when heating the M1 copper alloy to 200°C, it is not recommended to increase the rolling speed above the nominal.

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