Criteria for the process of drawing copper microwire for electronics

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Abstract. The paper provides information on the use of the developed mathematical model of repeated drawing with the sliding of a microwire from copper, intended for the installation of intracircuit electrical connections of microcircuits. Creation of a microwire based on copper for internal electric contact connections is a complex task: in the world practice, only a few firms can produce such a material that fully meets the requirements of the microelectronic industry. To obtain the specified microwire, it is necessary to work on the creation of high quality microalloyed copper; make a serious adjustment of the process of obtaining microwires, taking into account the complex of physical and chemical properties of the material. The article defines the criteria for the stability of the process of drawing during modelling, suitable for designing transitions of diamond dies. An analysis of the slip drawing process criteria, the safety factor of the drawing transitions, and the peripheral speeds of the pulls and wires to ensure the selection of both theoretically accepted and actually specified transitions of diamond dies is given. Based on a preliminary analysis of the model, recommendations are presented for its further improvement with the use of the criteria for the stability of the drawing process in order to increase the reliability of the process of obtaining a copper microwire for electronics.

1. Introduction
The process of deformation of the original billet by drawing with a slip consisted of twenty one transitions for implementation on a SG5 drawing machine from Niehoff, Germany. The formulas are given for the simultaneous analysis of symmetric (mirror) processes, providing a complete analysis of the field between the direct and mirror values of the relative reductions in the portages. The possibility of automating the calculations and obtaining the fields of discrete values of the functions being studied for all transitions of the drawing made it possible to analyse simultaneously theoretically specified and practically real transitions of diamond dies.

2. Determining the criteria for the stability of the drawing process in modelling
According to the theory of repeated drawing [1-2], there are criteria for the process of drawing, the main factor of which is the safety factor in transitions - $\gamma_{\text{min}}$. Its value for this case was established in [4], while the minimum recommended value of the safety factor is limited to $\gamma_{\text{min}} = 2.0 - 2.3$. The safety factor for dragging on transitions is calculated by the formula (1), the results of the calculation are presented in figure 1:

$$\gamma_{ij} := \frac{x_{ij}}{\Delta_{ij}}$$
\[ \gamma_{1,ij} = \frac{x_{1,ij}}{\sigma_{1,ij}} \]  
(1)

where \( x_{1,ij} = x_{1,ij} \) is the average value of the strain resistance within the deformation zone, MN / m\(^2\); \( \sigma_{1,ij} \) - current cross-section of the wire, m\(^2\); \( \sigma_{1,ij} \) - pull voltage across transitions with a back tension, MN / m\(^2\), index \( i = 0..21 \) - for the implementation of processes in fifteen transitions, \( j = 0..11 \) – for setting the limits of change in relative reduction at each transition.

The peripheral speed of each intermediate puck \( B_{i,j} \) must always be slightly greater than the speed of the wire \( P_{i,j} \) on this washer:

\[ \left( \frac{B_{i,j} - P_{i,j}}{B_{i,j}} \right) > 0, \]  
(2)

or in the notation of the Mathcad environment under conditions of simultaneous analysis of symmetric processes:

\[ K_a(B, P, i,j) := \begin{cases} 1 \text{ if } \left( \frac{B_{i,j} - P_{i,j}}{B_{i,j}} \right) > 0, \\ 0 \text{ otherwise} \end{cases} \]  
(3)

\[ K_{1a}(B, P, i,j) := \begin{cases} 1 \text{ if } \left( \frac{B_{i,j} - P_{i,j}}{B_{i,j}} \right) > 0, \\ 0 \text{ otherwise} \end{cases} \]  
(4)

With correctly calculated transitions using formulas (3), (4), the relative slip of the wire is maximum on the first washer and gradually decreases to the last washer.
or in the notation of the Mathcad environment under conditions of simultaneous analysis of symmetric processes:

\[ \Lambda(B, P, i,j) := \begin{cases} 1 & \text{if } \left( \frac{B_{i+1,j} - P_{i+1,j}}{B_{i,j}} \right) > 0 \text{ otherwise} \\ 0 & \text{otherwise} \end{cases} \]

\[ \Lambda_1(B, P, i,j) := \begin{cases} 1 & \text{if } \left( \frac{B_{i+1,j} - P_{i+1,j}}{B_{i,j}} \right) > 0 \text{ otherwise} \\ 0 & \text{otherwise} \end{cases} \]

The total exhaust in all subsequent transitions must be greater than the ratio of the final speed \( P_{21,j} \) of drawing to the peripheral speed of this washer \( B_{i,j} \):

\[ \frac{y_{i,j}}{y_{21,j}} > \frac{P_{21,j}}{B_{i,j}} \]

(11)

or in the notation of the Mathcad environment under conditions of simultaneous analysis of symmetric processes:

\[ \Xi_a(y, B, i,j) := \begin{cases} 1 & \text{if } \frac{y_{i,j}}{y_{21,j}} > \frac{P_{21,j}}{B_{i,j}} \text{ otherwise} \\ 0 & \text{otherwise} \end{cases} \]

\[ \Xi_1(y_1, B, i,j) := \begin{cases} 1 & \text{if } \frac{y_{i,j}}{y_{21,j}} > \frac{P_{21,j}}{B_{i,j}} \text{ otherwise} \\ 0 & \text{otherwise} \end{cases} \]

In addition, it is known from the practice of multiple drawing that in high-quality die transitions it is desirable to ensure a reduction in the drag force during the process, which is especially important when drawing microwire, i.e.:

\[ \sigma_{i,j} y_{i,j} > \sigma_{i+1,j} y_{i+1,j} \]

or in the notation of the Mathcad environment under conditions of simultaneous analysis of symmetric processes:

\[ N_a(\sigma, y, i,j) := \begin{cases} 1 & \text{if } \sigma_{i,0} y_{i,0} > \sigma_{i+1,0} y_{i+1,0} \text{ otherwise} \\ 0 & \text{otherwise} \end{cases} \]
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\( N_1(a, y_1, i, j) := \begin{cases} 1 & \text{if } \sigma_1 y_1 > \sigma_{i+1} y_{i+1} \\ 0 & \text{otherwise} \end{cases} \) \hspace{1cm} (16)

This condition can be taken as the sixth criterion of the process.

The effectiveness of the process of repeated drawing of microwire is influenced by other factors, such as the number of turns of wire on the pulling puck; the ratio of the diameter of the wire wound on the washer to the diameter of the washer itself; method of applying coils of wire to intermediate pucks, etc. [one]. In this case, the number of turns of the wire is set during the implementation of the model [4], and the remaining factors are either constructive or technological, associated with a deeper process detail. The latter are not considered in connection with the use of a specific model, i.e. a twenty-one SG5 type drawing machine from Niehoff, Germany and the drawing conditions fixed by its design.

Thus, six variables were chosen as criteria for the process of drawing a microwire with sliding: the admissible value of the safety factor during drawing; the excess of the circumferential speed of the intermediate traction washers over the speed of the wire on these washers; a gradual decrease in the relative slip of the wire on the traction washers along the process; the excess of the total exhaust on subsequent transitions over the ratio of the final drawing speed to the peripheral speed of the puck; excess exhaust in each portage over the ratio of the speeds of the following and previous washers; reduction of dragging force during the process (formulas (1) - (16)).

3. Research results and discussion

The criterion of the excess of the peripheral speed of the intermediate traction washers over the speed of movement of the wire on these washers was evaluated by comparing conditions (3) and (4) in order to identify the same values using the formula:

\( K_2(a, K_1, i, j) := \begin{cases} 1 & \text{if } K_2(B, P, i, j) \land K_1(B_1, P_1, i, j) = 1 \\ 0 & \text{otherwise} \end{cases} \) \hspace{1cm} (17)

As a result of the comparison operation, with artificial separation of the comparison results by the amount of reductions in each transition, a matrix of fulfilment of conditions (3) and (4) of size 22 × 12 was obtained. From the data obtained, it follows that these conditions are fulfilled in the whole range of studied reductions.

The criterion of reducing the relative slip of the wire on the pulling washers along the process (criterion 3) was evaluated similarly to the previous one when comparing the conditions:

\( \Lambda_2(a, \Lambda_1, i, j) := \begin{cases} 1 & \text{if } \Lambda_2(B, P, i, j) \land \Lambda_1(B_1, P_1, i, j) = 1 \\ 0 & \text{otherwise} \end{cases} \) \hspace{1cm} (18)

As a result of the comparison, with artificial separation of the comparison results by the amount of reductions in each transition, as in the previous case, a matrix of conditions (6) and (7) of 22 × 12 was obtained. From the data obtained, it follows that these conditions are fulfilled in the whole range of studied values of reductions, except for the first transition, probably related to the tension force of the retractor. That is, failure to comply with conditions (6) and (7) on the first transitions (in calculations it was assumed that the force on the winding is equal to the tension force after leaving the die) is not critical to ensuring reliable drawing at the beginning of the process when the wire diameter is relatively large. Moreover, the tension force during winding can be adjusted by the braking device of the machine.

The criterion of exceeding the total exhaust in all subsequent transitions over the ratio of the final speed of drawing to the peripheral speed of this pull washer was evaluated by comparing conditions (9) and (10):

\( H_2(a, H_1, i, j) := \begin{cases} 1 & \text{if } H_2(y, B, P, i, j) \land H_1(y_1, B_1, P_1, i, j) = 1 \\ 0 & \text{otherwise} \end{cases} \) \hspace{1cm} (19)

The results of the analysis indicate that conditions (9) and (10) are satisfied over the entire range of the values studied.

The criterion of excess exhaust in each portage over the ratio of the speeds of the subsequent and the previous traction washers (formulas (12) and (13)) was evaluated similarly when comparing the conditions:
The resulting comparison matrix, calculated according to the given condition of intersection of the studied sets, shows that these conditions are satisfied for all studied values of reductions in transitions.

The criterion for reducing the dragging force along the process (formulas (15) and (16)) was evaluated similarly by the intersection condition:

$$N_2(\delta, \gamma, i, j) := \begin{cases} 1 & \text{if } \delta, \gamma, i, j \in A \text{ and } \delta, \gamma, i, j \in B, \text{ otherwise} \end{cases}.$$  \hfill (21)

From the data obtained, it follows that conditions (15) and (16) are not fulfilled at the first transition for all values of extracts, which may indicate the need to reduce the tension at the first transition. However, the failure to comply with this condition is not critical to ensuring the reliability of drawing, since it is not performed at the beginning of the process, when the wire diameter is relatively large, and it is possible to control the wire tension using a machine tension device. In addition, bearing in mind the non-fulfilment of these conditions on the first three transitions (j ≤ 3), with an increase in drawing in the walkways to the level of -0.05 and + 0.07, in order to stabilize the process, you should probably eliminate the increased range of reductions in the first three walkways (over -0.051 and + 0.069).

Failure to comply with conditions (15) and (16) with a significant increase in the range of compression in transitions may indicate both the need to improve the accuracy of manufacturing a set of dies, and the need to introduce control of the dies in the drawing process. This is due to the fact that when the die in the transitions is worn, these conditions will also be violated, which can serve as a criterion for choosing the sign of a defect if the set of dies is repaired. These conditions require the replacement of a set of dies or the performance of repair work with an acceptable range of private reductions in transitions $\Lambda = 0.06 \pm 0.009$.

Thus, the fulfillment of the complex conditions of the drawing process with the sliding of a microwire from a copper alloy on a twenty-one drawing machine of the SG5 type in accordance with this model is possible only if the relative reductions in the transitions $\Lambda = 0.06 \pm 0.009$ are provided, which is quite a rigid requirement. When translating this value into real tolerances of the diameters of the holes of diamond dies, we obtain $\Delta d_1 = \pm 0.27$ mkm for the diameter of the calibrating part of the die - 52.4 mkm and $\Delta d_2 = \pm 0.14$ mkm for the diameter of 27.8 mkm (here $\Delta d_1$ is tolerance on the diameter of the calibrating part of the die). This precision diamond performance is at the limit of the possibilities of modern technology and is available to a very limited number of manufacturers [5-8]. That is why the production of microwires from copper alloys using high-performance equipment is mastered only by units of domestic and foreign enterprises.

In connection with the tight tolerance for the diameters of the die holes in the kit, ensuring the fulfillment of the considered criteria for the drawing process, the question may arise about the possibility of implementing such a process in mass production. However, our more than ten-year experience of mass production of microwires shows that a once-formed high-quality set of diamond dies, for example, in the manufacture of copper microwires, can be relatively long-term operated in two-shift mode without significant wear and going beyond the requirements of the diameter of the holes in the die. The latter makes it possible in some cases related to the manufacture of microwires from copper alloys, not to lay the value of acceptable wear of the dies in the designed transitions.

We further clarify the values of the safety factors corresponding to the spread $\Delta \Lambda = \pm 0.01$, i.e. $\gamma_{1,2}$ and $\gamma_{1,2}$. To accurately determine $\gamma_{1,2}$, $\gamma_{1,2}$ within the framework of the Mathcad model and environment, we printed the values of the safety factors after scrolling the spreadsheet engines of the corresponding functions. The following results were obtained: $\gamma_{1,2} = \gamma_{1,2} = 2.2985 \pm 0.0545$, starting from the thirteenth transition. The minimum allowable value of the safety factor was - 2.244, or after rounding to practical accuracy - 2.2. This value is within the limits of known requirements and does not contradict practical data.

Thus, as a result of the work, it has been shown that the implemented model takes into account all the main criteria for repeated drawing with sliding and adequately describes the process of drawing.
copper microwire. It was previously shown that the model was formed on the basis of the basic equations of the theory of multiple drawing [1], and a particular case in it is only the use of the dependence of hardening of a microwire from a copper alloy on the limiting degrees of deformation [4]. In connection with the above, the developed model should be recommended for analysing the processes of drawing similar materials with appropriate adjustment of the “trigger of relative reductions” [4], the dependencies of hardening, initial conditions and constants.

4. Conclusions
The model presented in [4–8] is largely supplemented, which allowed to automate the calculations and to obtain, as a result, the field of discrete values of the studied functions of the technological process of drawing with sliding microwire from high-purity copper to assemble electrical connections of microelectronic devices in the range of reduction of compression \( \Lambda = 0.06 \pm 0.001 \ldots 0.009 \) for all transitions of the set of twenty-one diamond die.

At the same time, the developed algorithm allows the use of a drawing model for obtaining microwires with a diameter of up to ten to fifteen micrometers, i.e. extreme possibilities of manufacturing high-quality transitions of diamond dies.

It is advisable to recommend the model for the analysis of processes of repeated drawing with microwire sliding both from high-purity copper and similar materials, with appropriate adjustment of parameters.

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