Simulation of a copper micro-wire drawing for electronics

A V Volkov, I D Sokolova¹, A P Korzhavyi and L S Beckel
Kaluga Branch of Bauman Moscow State Technical University, Kaluga, Russia

¹E-mail: iren.d.sokolova-2013@ya.ru

Abstract. The paper discusses the application of the mathematical model of repeated drawing with the sliding of a micro-wire made of copper, intended for the installation of intracircuit electrical connections of microcircuits. Creating production methods and methods for producing microwires based on copper is a complex scientific and technical challenge: only individual firms can produce material that fully meets the needs of the microelectronic industry [1-3]. Therefore, it is necessary to work on the creation of a micro alloyed alloy with rational deformation parameters and providing protection against corrosion damage during micro welding, sealing and operation of devices. The algorithm of the mathematical model applied in the design of drawing transitions is presented. Based on the analysis of the model, recommendations were made for its further improvement in order to increase the reliability of the drawing process with the involvement of process stability criteria. In modelling the technological process of drawing copper, an algorithm developed by the authors for drawing aluminium microwire was used, taking into account the changes needed to make a different material [4–8].

1. Introduction
In this work, we used experimental data taken from a real serial technological process of drawing a microwire from an aluminium-silicon alloy. The process of deformation of the original billet by drawing with a slip consisted of twenty one transitions and was carried out on a SG5 drag machine made by Niehoff, Germany, with a given ratio of the speeds of the traction washers \( B_{i+1} / B_i = 1.05 \).

2. Mathematical model of the deformation process by drawing with a slip
To ensure that it is necessary to assess the effect of fluctuations in relative crimping on the stability of the drawing process, the explicit mathematical dependence of the relative crimping on the transition number, which takes discrete values, i.e., it is used as a so-called “trigger” actually "mathematical trigger":

\[
\Lambda_{i+1,j} = (\Lambda_{i,0} + 0.001 \cdot j) \cdot \left[ \frac{1 + (-1)^{i+1}}{2} \right] + (\Lambda_{i,0} - 0.001 \cdot j) \cdot \left[ \frac{1 - (-1)^{i+1}}{2} \right],
\]

where \( \Lambda_{i+1,j} \) – relative compression at \( \Lambda_{i,0} = 0.06 \) and the step of changing the relative compression of 0.001.

At the same time, for the simultaneous analysis of a symmetric (mirror) process, which ensures the presence of a field between the direct and inverse values of relative reductions, a mirror function was used that simulates a second (mirror-built) set of fibres at similar, but inverse, values of the reductions in the portages:
\[
\Lambda_{i+1,j} = (\Lambda_{1,0} + 0.001 \cdot j) \cdot \left[ \frac{1 + (1 - i)^{1.5}}{2} \right] + (\Lambda_{1,0} - 0.001 \cdot j) \cdot \left[ \frac{1 - (1 - i)^{1.5}}{2} \right].
\] (2)

Thus, the model presented earlier was corrected, which made it possible to automate the calculations and to obtain, as a result, the field of discrete values of the functions being studied in the range of variation \( \Lambda = 0.049 \ldots 0.071 \) across all drag transitions.

In addition, in this work, we used previously obtained by the authors the dependence of the hardening of the microwire from copper MB of oxygen-free melting according to TsMTU-3302-83 at the limiting degrees of deformation:

\[
x_{i+1,j} = x_{i,j} + 9.2 \ln \left( \frac{y_{i,j}}{y_{i,j}} \right)^{1.51},
\]

\[
x_{1i+1,j} = x_{1i,j} + 9.2 \ln \left( \frac{y_{1i,j}}{y_{1i,j}} \right)^{1.51},
\] (3)

where \( x_{ij} = S_{Ti} \) – average value of resistance to deformation within the deformation zone, MN/m²; \( y_i = F_i \) – current wire cross section, m².

The minimax system for calculating the parameters for transitions, characterized by periodic changes in reductions from minimum to maximum at each subsequent transition, was adopted as the basis for the model. Such a system, according to the authors, best describes the actual process of drawing microwires from non-ferrous metals, since allows us to take into account not only a significant variation in the tolerances on the diameters of the openings of diamond fibres in new transitions, but also changes in the dimensions of the fibres during wear, which are highly uneven.

Based on preliminary experiments, the following initial data were obtained for modelling the process of drawing copper microwire, and the calculations are given for the following initial conditions, according to the chosen technological process and equipment:

\( \Lambda_i \equiv \Lambda_{1i} \equiv \delta = 0.055 \ldots 0.06 \ldots 0.065 \) – relative compression, %;

\( x_{0,i} \equiv x_{1i,0} \equiv \sigma_{0i} = 439.920 \) – temporary resistance of the original wire drawing material with a diameter of \( d = 39 \) mkm, MPa;

\( y_{0i} \equiv y_{0j} = y_{10j} = F_{0j} = 0.1185 \times 10^{-8} \) – initial microwire section, m²;

\( \sigma_{0j} = \sigma_{10j} = 146.640 \) – dragging voltage on the first transition, MPa;

\( \sigma_{N,0} = \sigma_{N,10} = 54.000 \) – counter tension on the first transition, MPa;

\( \alpha = 0.14 \) – acting half angle forming die channel, rad;

\( t = 0.5 \) – die shape profile factor;

\( \xi = \tau = 0.08 \) – coefficient of friction of the wire material in the die;

\( \mu = 1 \) – the number of turns of wire on the drawing washer;

\( \varphi = 0.1 \) – coefficient of friction at normal pressure between the drawing washer and the wire;

\( \gamma_j = \gamma_{1j} = 2.0 \) – conversion factor, not less;

\( P_{21,0} = P_{121,0} = 3 \) m/c – microwire speeds at process exit, m/s;

\( B_{0,0} \) and \( B_{10,0} = 1.5 \) m/c – traction washer speeds, m/s.

For the simulation a system of equations was taken, including as follows:
- a simplified formula [8] for calculating the drawing voltage of simple round profiles;
- obtained by the authors the dependence of the hardening of the microwire from copper brand MB on the limiting degrees of deformation;
- the well-known relationship between drag tension;
- the above dependence of the hardening of the material, as well as the relationship of the theory of repeated drawing with slip and the characteristics of a particular drawing machine:

\[
y_{i+1,j} = (1 - \Lambda_{i,j}) \cdot y_{i,j},
\]
\[ \Lambda_{i+1,j} = (\Lambda_{1,0} + 0.001 \cdot j) \left[ \frac{1 + (\zeta_i-j)}{2} \right] + (\Lambda_{1,0} - 0.001 \cdot j) \left[ \frac{1 - (\zeta_i-j)}{2} \right]. \]

\[ y_{1+1,j}^{i} = (1 - \Lambda_{ij}) y_{1,j}^{i}, \]

\[ x_{i+1,j}^{i} = x_{ij}^{i} + 9.2 \ln \left( \frac{y_{ij}^{i}}{y_{i+1,j}^{i}} \right)^{1.5}, \]

\[ x_{1+1,j}^{i} = x_{1,j}^{i} + 9.2 \ln \left( \frac{y_{1,ij}^{i}}{y_{1,i+1,j}^{i}} \right)^{1.5}, \]

\[ \tan(\alpha) \frac{2 \tan(\alpha) y_{ij}^{i+1,j}}{1 + \left( \frac{y_{ij}^{i}}{y_{ij}^{i+1,j}} \right)^{1/2}}, \]

\[ Z_{i+1,j}^{i} = \frac{2 \tan(\alpha) y_{1,ij}^{i+1,j}}{1 + \left( \frac{y_{1,ij}^{i}}{y_{1,ij}^{i+1,j}} \right)^{1/2}}. \]

\[ z_{i+1,j}^{i} = \frac{2 \tan(\alpha) y_{1,ij}^{i+1,j}}{1 + \left( \frac{y_{1,ij}^{i}}{y_{1,ij}^{i+1,j}} \right)^{1/2}}. \]

\[ w_{ij}^{i} = \tan(\alpha) z_{ij}^{i}, \]

\[ w_{1,ij}^{i} = \tan(\alpha) z_{1,ij}^{i}, \]

\[ \sigma_{i+1,j} = x_{ij} \left( 1 + \frac{2 z_{i+1,j}}{\xi} \right) \left[ 1 - \left( \frac{y_{ij}^{i+1,j}}{y_{ij}^{i}} \right)^{2} \right] + \sigma_{ij} \left( \frac{y_{ij}^{i+1,j}}{y_{ij}^{i}} \right)^{\frac{\xi}{2} \phi}, \]

\[ \sigma_{1+1,j} = x_{1,ij} \left( 1 + \frac{2 z_{1+1,j}}{\xi} \right) \left[ 1 - \left( \frac{y_{1,ij}^{i+1,j}}{y_{1,ij}^{i}} \right)^{2} \right] + \sigma_{1,ij} \left( \frac{y_{1,ij}^{i+1,j}}{y_{1,ij}^{i}} \right)^{\frac{\xi}{2} \phi}, \]

\[ \sigma_{N_{i+1,j}} = x_{ij}^{i} \left( 1 + \frac{2 z_{i+1,j}}{\xi} \right) \left[ 1 - \left( \frac{y_{ij}^{i+1,j}}{y_{ij}^{i}} \right)^{2} \right], \]

\[ \sigma_{M_{i,ij}} = \frac{\sigma_{ij} \left( \frac{y_{ij}^{i+1,j}}{y_{ij}^{i}} \right)^{\frac{\xi}{2} \phi}, \]

\[ \sigma_{N_{1+1,j}} = x_{1,ij}^{i} \left( 1 + \frac{2 z_{1+1,j}}{\xi} \right) \left[ 1 - \left( \frac{y_{1,ij}^{i+1,j}}{y_{1,ij}^{i}} \right)^{2} \right], \]

\[ \sigma_{M_{1,ij}} = \frac{\sigma_{1,ij} \left( \frac{y_{1,ij}^{i+1,j}}{y_{1,ij}^{i}} \right)^{\frac{\xi}{2} \phi}. \]

\[ \gamma_{ij}^{i} = \frac{y_{ij}^{i}}{\sigma_{ij}}, \]

\[ \gamma_{1,ij}^{i} = \frac{y_{1,ij}^{i}}{\sigma_{1,ij}}, \]

\[ d_{ij}^{i} = 2 \left( \frac{y_{ij}^{i}}{\pi} \right)^{1/2}, \]

\[ d_{1,ij}^{i} = 2 \left( \frac{y_{1,ij}^{i}}{\pi} \right)^{1/2}, \]

\[ \Delta_{d_{ij}^{i}} = d_{i,0} - d_{ij}^{i}, \]

\[ \Delta d_{ij}^{i} = d_{1,0} - d_{ij}^{i}, \]

\[ P_{ij}^{i} = \frac{P_{21,j}^{21,j}}{y_{ij}}, \]

\[ P_{1,ij}^{i} = \frac{P_{121,j}^{21,j}}{y_{1,ij}}. \]
\[ B_{i+1,j} = 1.05 \cdot B_{i,j}, \]

\[ B_{1,i+1,j} = 1.05 \cdot B_{1,i,j}, \]

where \( \Lambda_i = \delta \) – relative compression, \( Z_{ij} = \tan \alpha \) – die reduced channel tangent, \( \alpha \) – acting half-angle forming a die channel, \( t \) – die channel form shape factor, \( \sigma_{ij} \) – drawing voltage across transitions, MN/m\(^2\), \( \varepsilon = f \) – coefficient of friction of the wire material in the die, \( \mu = m \) – the number of turns of wire on the drawing washer, \( \phi = f_l \) – normal pressure friction coefficient between the washer and wire, \( P_{ij} = B_{i,j} \) – the speed of the movement of the wind after it exits the die, m/s, \( B_{i,j} \) – traction washer speed, m/s.

3. Research results and discussion

According to the results of the automatic calculation of the specified system of equations, which provide a simulation of the process of multiple drawing of a copper microwire with a slip, three-dimensional graphical dependencies of the following functions were obtained:

- Current crimping at wire drawing, taking into account the process modelling by the mirror function of crimps in a symmetric fibre set (see above): \( \Lambda_{ij} \) and \( \Lambda_{1,ij} \), m\(^2\);
- Current sections of microwire transitions: \( y_{ij} \) and \( y_{1,ij} \), m\(^2\);
- Microwire strength at transitions: \( x_{ij} \) and \( x_{1,ij} \), MN/m\(^2\);
- Given die angles: \( z_{ij} \) and \( z_{1,ij} \), rad;
- Drawing voltage at transitions: \( \sigma_{ij} \) and \( \sigma_{1,ij} \), MN/m\(^2\);
- Coefficient of supply while drawing: \( \gamma_{ij} \) and \( \gamma_{1,ij} \);
- Speeds of microwire at die exit: \( P_{ij} \) and \( P_{1,ij} \), m/s;
- Traction washer speeds: \( B_{i,j} \) и \( B_{1,i,j} \), m/s.

From the analysis of dependences it follows that the tensile strength of the microwire during the drawing process increases slightly, and at the last transition it does not differ for two symmetric processes.

Figure 1 shows the voltage values of the drawing of copper wire in the process of drawing in the functions \( \sigma_{ij} \) and \( \sigma_{1,ij} \). The symmetry of the obtained values is well seen, their growth before practical stabilization at \( \sigma_{ij} \approx 198 \) MN/m\(^2\) (\( \Lambda = 0.07 \)) and \( \sigma_{1,ij} \approx 187 \) MN/m\(^2\) (\( \Lambda = 0.05 \)) from the sixth transition, when the low tension of the coiling device stops. Analysis of the contribution of the two components to the drawing voltage - hardening of the material and anti-tension showed that according to the model on the material under study, with minimal reductions, there is an approximately equal contribution of both components, and in the case of maximum reductions, the contribution of the first component increases to about 60% at \( \Lambda = 0.07 \) in transitions.

In the case of “ideal” drawing conditions, this process provides a safety factor of 2.4, i.e. somewhat higher than planned. With a maximum reduction \( \Lambda = 0.07 \), the safety factor decreases to a value of 2.3. This value may be sufficient for reliable implementation of a twenty-one-time process of drawing high-quality copper microwire, since production recommendations for microwires from copper, for example, of electrical quality, with a diameter of less than fifty micrometers, require providing \( \gamma \) within 2.3 - 3.0, or, practically, coincide with the obtained calculations.
Figure 1. Dependencies of the voltage of drawing the copper wire from the transition number \( i \) and the deviation of the drawing from the average \( j \) in the process of drawing in the functions \( \sigma_{ij} \) and \( \sigma_{1ij} \). The projections of the coordinates \( \sigma 1 - i - j \): • - function \( z_{ij} \); \( \times \) - function \( z_{1ij} \).

Thus, the presented model includes a number of process variants, which theoretically make it possible to ensure reliable (uninterrupted) drawing of copper microwire by deforming the original billet. This will allow, at the next stage of research, to model the main criteria for the reliability of the process of multiple drawing of copper microwire to make a decision on the choice of the optimal range of reductions in transitions in order to ensure the quality and reliability of the deformation process under study. Fulfilment of the criteria for the reliability of the deformation process by drawing a copper microwire with a slip will make it possible to manufacture high-quality material for microelectronics and to create the basis for designing transitions in the production of microwire from copper to meet the requirements for the assembly and operation of intra-circuit connections of integrated circuits, transistors and micro-assemblies.

4. Conclusions

The mathematical model of the process of deformation of the copper billet in the microwire by repeated drawing with a slip is improved. The model makes it possible to realize and significantly accelerate automatic calculations using symmetric cycles of the Mathcad environment, as well as to carry out adequate calculations of relative reduction, deformation resistance, drawing voltage, safety factor for drawing transitions, and circumferential speeds of copper microwire pulls to ensure selection as theoretically accepted, and actually given transitions of diamond fibres. The model was created in relation to the twenty-repeated SG5 “Niehoff” drawing machine (Germany) using graphic information, bypassing the stage of outputting the results in vector form.

References

[1] Perlin I L and Ermanok M Z 1971 Theory of drawing (Moscow: Mechanical engineering) pp 448
[2] Romanova M P 2008 The design and Assembly of integrated circuits: a tutorial (Ulyanovsk: UlSTU) pp 95
[3] Bartashevich S A 1983 Development of new methods and technologies of micro wire drawing (Minsk: BPI) pp 23
[4] Volkov A V 2002 Research, development of aluminum conductor materials and technologies of their serial production for automation of Assembly of integrated circuits (Moscow: MIET) pp 20
[5] Bondarenko G G and Volkov A V 2002 Development and implementation of the model of multiple drawing of Microfine Knowledge-based technologies 5 19-23
[6] Bondarenko G G and Volkov A V 2004 Improvement of the model of wire drawing Part I Knowl.-bas. Techn. 1 14-8
[7] Bondarenko G G and Volkov A V 2005 Improvement of the model of wire drawing Part II Knowl.-bas. Techn. 3(4) 34-8
[8] Volkov A V, Ustinov I K, Korzhavyi A P and Strel'chenko S S 2016 Modeling of physical process of obtaining micro wire for electronic products Elec. Wav. and Elect. Syst. 3 13-8