Effect of cold work on the mechanical response of drawn ultra-fine gold wire

Sridhar, Idapalapati; Subbiah, Sathyan; Narayanan, Karthic R.

2010

Narayanan, K. R., Sridhar, I., & Subbiah, S. (2010). Effect of cold work on the mechanical response of drawn ultra-fine gold wire. Computational materials science, 49(1), S119-S125.

<https://hdl.handle.net/10356/93852>

<https://doi.org/10.1016/j.commatsci.2009.12.038>

© 2010 Elsevier. This is the author created version of a work that has been peer reviewed and accepted for publication by Computational Materials Science, Elsevier. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: <http://dx.doi.org/10.1016/j.commatsci.2009.12.038>.

Downloaded on 26 Apr 2023 12:02:51 SGT

Effect of Cold Work on the Mechanical Response of Drawn Ultra-Fine Gold Wire

Karthic. R. Narayanan, I. Sridhar*, S. Subbiah

School of Mechanical & Aerospace Engineering, Nanyang Technological University,
Singapore 639798, Singapore

Abstract

Effect of cold work on the mechanical response of drawn gold wire is studied using finite element (FE) simulations. The drawing simulations were conducted in a single stage as well as multistage *i.e.* two steps for the equivalent area reduction on a micrometer size gold wire. The effect of wire drawing process parameters such as die angle, coefficient of friction and area reduction were considered for the simulations. A clear variation in residual stresses from tensile to compressive is seen across the wire cross section. Mechanical properties are assessed via residual stress state and the hardness variation across the drawn wire cross-section; the hardness is determined using simulated micro-indentation tests. The effect of this stress is also observed in the indentation response. In the area of tensile residual stresses increasing pile up was seen at the indenter edges, while in the area of compressive stresses the opposite was observed. The results clearly show the dominating role played by the residual compressive and tensile stresses across the wire section in its mechanical response.

keywords: wire drawing, reduction ratio, finite element analysis, drawing stress, indentation, mechanical properties.

1 Introduction

Rapid development in the electronic packaging industry in the recent years has begun to witness the evolution of high power density and smaller size circuits. As the device dimensions are shrinking, the integrated chip has become smaller and its contact-pads are becoming closely spaced [1]. This fine-pitch necessitates the use of smaller diameter gold wires (few hundreds of micrometers or less) to provide the interconnects and this imposes a constraint on the mechanical properties of such thin gold wires [2]. The growing demand of such wires has led to a need to steadily increase the quality requirements of the processed wires which is measured by improved mechanical properties and geometrical tolerances. For fine pitch packaging applications, low wire loops that do not sag and long span wires that do not sway are required. The bond wire goes through many phases of mechanical deformation during loop bonding, die moulding and reliability tests

*Corresponding Author: msridhar@ntu.edu.sg

during operational stage of the device. This approach is time consuming and costly. So, mechanical property becomes important to understand for achieving better design during wire looping process which helps in optimizing the loop profile. Multi pass cold drawing is commonly used in the wire bonding industry to manufacture micrometer sized wires from cast gold bars. Understanding the effect of the process parameters on the properties of the cold drawn wire will help achieve improved process control.

Cold drawing involves plastic cold working in which material undergoes large plastic deformation at temperatures less than $0.3T_m$ (T_m is absolute melting temperature) in several stages with intermittent annealing steps to reduce the effect of work-hardening. During this severe deformation process several defects such as cracks and inhomogeneous stress distributions can occur [3, 4]. The work hardening also induces residual stresses in the multi drawn wire cross section that has a detrimental effect on the durability of the wire [5, 6]. Both stress inhomogeneity and residual stresses influence the mechanical properties and micro structures of the deformed materials [7, 8]. Stress inhomogeneity is strongly affected by the cold drawing process parameters such as die angle, coefficient of friction and area reduction (RA). One of the parameters used to detect inhomogeneity in flow stress is hardness variation, which gives a direct measure of the material strength. Hardness can be determined indirectly from strains induced in the work material or directly using indentation tests, which can be done via simulations or experiments. Experimental indentation tests have been reported on a drawn wire to study the transverse cross sectional strain variations [6]. The metal forming industry uses effective strains on a formed product and estimates hardness from this using analytical expressions [5]. However, an indentation test done by simulation can be comprehensive, since it can provide a better understanding of the indentation depth and work of indentation that can be used to analyze the inhomogeneous stress fields. Analysis of this type has also been found suitable for low strain hardening materials that exhibits significant pile up at the indenter edges [9, 10]. Spherical indentation simulations for residual stress effects is also found to be effective in elastic-plastic transition deformation regimes [11, 12]. In addition, indentation tests have other uses. The mechanical properties of bulk and small volume materials such as Young's modulus (E), hardness, plastic properties measured with instrumented and simulated indentation tests has gained prominence [13, 14, 15, 16, 17, 18]. Although, number of experimental and numerical studies have been carried to analyze the effect of die angles ' α ', coefficient of friction ' μ ' at the interface of the die - work piece and area reduction (RA) on the deformation behavior and strain variations [19, 20, 21, 22, 23, 24, 25], hardness variation across the cross section of a drawn wire and the effect of drawing process parameters on this variation based on simulated indentation tests has not been explored. Hence, this is the subject of this paper.

In this study, finite element (FE) simulations of wire drawing are performed, with process parameters similar to practical industry conditions, for analyzing the residual stress in the transverse cross section of cold multistage drawn wire. The required equivalent total plastic strain (ε_p) in the drawn wire was obtained in a single step reduction as well as in multiple steps. The multistage consisted of two consecutive deformation steps without intermediate relaxation as the deformation pattern tends to be similar in each step [26] and the ε_p subjected in the first pass of the multistage drawing is kept below 0.45 [27] for all the area reductions. The drawn wire obtained from both the single stage as well as multistage drawing for the same area reduction is further studied for the mechanical response by extracting load-displacement curves from spherical micro indentation simulations conducted on the transverse cross section of the wire. For the indentation tests,

only the residual axial stress distribution (σ_{22}) effects of the drawn wire are considered as the properties measured in the drawing direction are of interest.

2 Numerical modeling

2.1 Finite element implementation

A rigid conical die was used to reduce the cross sectional area of a gold wire 40 μm in diameter and 140 μm long by 10%, 20% and 30% in area using axi-symmetric finite element (FE) drawing simulations. Both single stage and two stage reduction processes are analysed. For the two stage process the area reduction is achieved as follows: 10% by two stages of 5% and 5%, 20% by two stages of 10% and 10%, and 30% in two stages of 20% and 10%. Semi-die angles of 4°, 5° and 6° were simulated. The die angles were kept the same within the two stages of a multistage drawing simulation. The coefficient of friction μ between the die and the gold wire was kept constant at a value of 0.05 for all the drawing simulations conducted. The constitutive behavior of the gold wire at the room temperature was obtained from the experimental work of Liu et al. [28]. The plastic stress - strain behavior of the wire is modeled in the power law form $\sigma = K\varepsilon^n$, where K (291.2 MPa) is the strength coefficient and n (0.0535) is the strain-hardening exponent. Figure 1 shows the comparison between the experimentally measured stress - strain response and the fitted power law. The Young's modulus (E) and Poisson's ratio (ν) of the wire are 80 GPa and 0.42 respectively. A finite strain version of the J₂ flow theory is used to simulate the drawing process. The FE simulations are carried out using the commercial software ABAQUS using the explicit formulation. The wire was modeled using axisymmetric boundary conditions such that the wire is allowed to deform in the axial direction and one end of the wire is fixed as shown in Figure 2a. Wire drawing is simulated by moving the die, which is given the drawing speed of 1 mm/sec causing it to traverse the wire from one end to the other.

The wire drawing simulation is conducted as the first analysis step followed by relaxation of the wire from all the external boundary conditions until the wire reaches steady state as shown in Figure 2b. The macroscopic stress-strain variations across the wire radial-section and over the longitudinal section were taken after this relaxation step. Therefore, the drawn wire is in a completely external load-free condition and the stresses considered for the microindentation simulation studies are all residual effects. Then, to analyse mechanical property variation across the wire cross-section, frictionless indentations are performed. Frictionless conditions were assumed since experimental evidence concluding no significant effects in spherical indentation is reported in the literature [29, 30]. The indentations are performed with a spherical indenter of 3 μm radius (R), with the load controlled at a value of 30mN $\pm$ 1 is conducted in the next step at three different points (P₁, P₂, P₃) across the wire cross-section as shown in Figure 2c. Two-dimensional axisymmetric model was used to conduct the indentations at the center (P₁) as shown in Figure 2d and three-dimensional wire model was used for the off-center points (P₂ and P₃) as seen in Figure 2e. At a time, only one point on the wire cross section was indented and the simulations utilised adaptive meshing with mass scaling to minimise element distortions and to speed up the simulations respectively. The boundary conditions of the three-dimensional model for all the simulations are same as the two-dimensional axisymmetric model. Owing to the radial symmetry of the spherical indenter, only one quarter of the three-dimensional model is simulated.

Figure 1: Power law approximation to the stress-strain response of gold wire at room temperature

Figure 2: Finite element modeling procedure a. Boundary condition for the drawing process, b. Boundary conditions relaxed after drawing, c. Spherical indentation simulations on the drawn wire, d. Indentation mesh used for center point P_1 and e. 3D model used for points P_2 and P_3 .

2.2 Dimensional analysis for mechanical response

Dimensional analysis based on the energy method proposed by Ni et al. [31] is used to analyze the indentation response of cold drawn gold wire. During the loading stage, the indentation force (F_l) and the total penetration depth by including material pile-up (h_c) as shown in Figure 3a are functions of the material properties: Young's modulus (E), Poisson's ratio (ν), yield strength (Y), strain hardening exponent (n), indenter displacement (h) and indenter radius (R). Implementing the Π theorem [32] in dimensional analysis yields

$$F_l = ER^2\Pi_\alpha\left(\frac{Y}{E}, \nu, n, \frac{h}{R}\right) \quad (1)$$

$$h_c = R\Pi_\beta\left(\frac{Y}{E}, \nu, n, \frac{h}{R}\right) \quad (2)$$

where $\Pi_\alpha = F_l/ER^2$ and $\Pi_\beta = h_c/R$ are the non-dimensional load and penetration depth, respectively. The unloading force (F_u), in addition to the above parameters, depends upon the actual indentation depth at maximum load (h_{max}). Applying the Π theorem for unloading stage, we have

$$F_u = ER^2\Pi_\gamma\left(\frac{Y}{E}, \nu, n, \frac{h}{R}, \frac{h_{max}}{R}\right) \quad (3)$$

Equations (1) and (3) can be integrated with respect to the displacement to obtain the total work (W_t) and reversible work (W_u) defined by the areas under the loading and unloading curves as shown in Figure 3b. Extensive FE simulations of spherical indentations was conducted on the drawn wire to analyse the residual axial stress effect by relating h_c/h_{max} (pile up or sink in), h_{max}/R (indentation depth) as a function of material properties (Y/E , n and ν). Similarly $(W_t - W_u)/W_t$ and h_f/h_{max} (elastic recovery parameter) were investigated and calculated.

At small indentation depths (where elastic regime prevails), the indentation response is governed by Hertzian elastic behavior and is not effected by the magnitude of residual stresses. Similarly, at large indentation depths, wherein, the fully-plastic state develops underneath the indenter, the indentation response is governed by the yield strength of the material. In the intermediate regime of indentation depths, the residual stresses control the indentation behavior by the parameters involving effective modulus $E_e = E/(1-\nu^2)$, Y , contact radius ($a = \sqrt{\text{contact area } (A)/\pi}$), mean contact pressure (p_m) and geometrical strain [33]. The indentation load-displacement curves as well as the contact area A are obtained directly from the FE simulations. The elastic recovery parameter is obtained from the load-displacement curve, and by integrating the area under the simulated loading-unloading curve the total work (W_t) and reversible work (W_u) are calculated.

Figure 3: a. Spherical indentation schematic and b. Definition of irreversible work (W_t - W_u) and reversible work (W_u)

3 Results and discussion

The drawing stress results and the axial residual stress distribution obtained from the simulations are presented followed by the results obtained from the micro indentation simulations to compare the mechanical response. The indentation simulations were conducted on the relaxed wire transverse cross section.

3.1 Validation of the model using slab analysis

In FE simulation, the drawing stress is calculated by dividing the maximum contact force on the reference point of the rigid-die with the wire cross-sectional area. Using an upper bound technique such as the slab method (SM) [34], the drawing stress σ_d can be expressed as

$$\text{drawing stress, } \sigma_d = \bar{\sigma}_y \left(1 + \frac{\tan \alpha}{\mu} \right) (1 - \exp^{-(\mu \tan \alpha \varepsilon_h)}) \quad (4)$$

$$\text{homogeneous strain, } \varepsilon_h = \ln\left(\frac{1}{1-r}\right) \quad (5)$$

where, $\bar{\sigma}_y$ is the mean yield stress of the gold wire, μ is the coefficient of friction between the die and wire interface, α is die semi angle, ε_h is the homogeneous plastic strain for the imposed reduction ratio r . The drawability limit was analyzed by plotting the normalized drawing stress with the area reduction as shown in Figure 4. The results indicate that the drawing stress increases with increasing reduction ratio and for a given RA the drawing stress value increases with decreasing die angle. The drawing stresses calculated from the FE are higher than that of the slab method and the difference between them increases with increasing RA.

It was also noted that for particular area reduction, the drawing stress values is not considerably affected by the die semi-angles as predicted by both FEM and SM. This difference is due to the simplified homogeneous deformation that has been assumed in

the slab method: the distortion energy is not considered. The FE method predicted normalised drawing stress values are in close agreement with the experimental investigations conducted on copper wires [35]. The experimental measurements are superimposed with filled markers in Figure 4.

Figure 4: Variation of normalised drawing stress with area reduction: FE predictions are compared with slab method values and published experimental measurements on a drawn copper wire [35].

3.2 Effect of area reduction (RA) and die angle (α) on the axial stresses

The axial stress (σ_{22}) variation across the cross-section of the drawn wire obtained from the FE simulations for different RA and die angle α are shown in Figures.5a, 5b and 5c. The figure shows that the central section is in compression and the outer section (closer to the surface of the wire) is in tension. The regimes marked as P_1 , P_2 , P_3 in Figure 5a indicate the nature of the stress in each region. With increasing RA, the residual compressive stresses increases at the centre of the wire and the residual tensile stresses decreases at the outer edge of the wire; this may be due to the effect of the frictional shear stresses rendering plastic strain homogeneity at higher reduction [36, 6]. For an equivalent area reduction, the single stage drawing process results in higher compressive stress at the centre of the wire and lower tensile stress at the outer surface of the wire than the multi stage process. The effect of work hardening induced in the first step has an effect on the following step during the multi stage drawing process. By way of an example for 10% reduction ratio, the difference in compressive stress between a single stage and a multi stage is approximately 20% and the tensile stress differed by 18% respectively. The stress variation between the single stage and multi stage drawing process decreases with increasing reduction ratio: in the particular case of 30% reduction the axial stress

determined from single stage drawing within numerical scatter matches to that of the multi-stage drawing process. This is due to the strain homogeneity at higher reductions.

The effect of die-angle is found to be insignificant on the drawn wire residual stress distribution obtained from both the single stage as well as multi stage process. Smaller die angles used in the drawing dies have been found to have negligible effect on the residual axial, radial and circumferential stress distribution [36].

Figure 5: Axial residual stress distribution on drawn wire for area reductions (RA) a. 10%, b. 20% and c. 30%

3.3 Influence of residual stress on $h_c/h_{\max}$, $(W_t - W_u)/W_t$ and p_m

The results from spherical indentation simulations performed at cross sectional points P_1 , P_2 and P_3 are analyzed. Only the area reduction effects are considered for the indentation simulations as it was shown earlier that the narrow die angle variations (*i.e.* 4° to 6°) considered in this study has negligible effect on the residual stress distribution. The

influence of residual stresses on $h_c/h_{\max}$ with respect to $h_{\max}/R$ is used to evaluate the degree of pile-up for the single stage and multi stage process as illustrated in Figures 6a and 6b respectively. The $h_c/h_{\max}$ values as a function of $h_{\max}/R$ are plotted for Y/E and n respectively. It is noted that for materials with small value of Y/E and n , such as the gold material used here, pile-up is expected at large indentation depths. The variation in $h_c/h_{\max}$ with respect to $h_{\max}/R$ clearly shows the influence of residual axial stress on the pile up at the different stress regions of compressive (P_1), transition from compression to tension region (P_2) and tensile region (P_3). In the compression region (P_1) low values of $h_c/h_{\max}$ are observed compared to that at points P_2 and P_3 . Higher area reduction (30%) results in higher compressive stress at P_1 and this leads to a lower $h_c/h_{\max}$ value. A small increase in $h_c/h_{\max}$ value is observed when the compressive stresses decrease with lower reduction ratios. In the transition region (P_2) an increase in $h_c/h_{\max}$ compared to P_1 was observed. However, in this region the variation in RA was not significant because the residual axial stresses were close to zero. In the tensile stress region (P_3) higher $h_c/h_{\max}$ values were seen especially at the lowest area reduction of 10% where $h_c/h_{\max}$ was the highest. Similar observations were seen for both single and multiple stage simulations. At all the stress regions lower values of $h_c/h_{\max}$ were observed for single stage drawing compared to multistage drawing. The trends in $h_c/h_{\max}$ can be explained as follows: indentation in a compressive stress region results in less plastic deformation, while indentation in a tensile stress region produces higher plastic flow. Also, as observed from Figure 5a-c multistage drawing resulted in lower compressive residual stresses and hence higher $h_c/h_{\max}$ values.

The representative load-displacement curve obtained from the finite element simulations were analyzed to obtain the relationship for $(W_t - W_u)/W_t$ and $h_f/h_{\max}$ as shown in Figures 6c and 6d. The variation in $(W_t - W_u)/W_t$ versus $h_f/h_{\max}$ is found to be increasing in the different stress regions of compressive (P_1), transition from compression to tension region (P_2) and tensile region (P_3). The 30% RA at compressive region (P_1) had the lowest $(W_t - W_u)/W_t$ value and the elastic recovery parameter ($h_f/h_{\max}$) at the same location was also observed to be the lowest. This is attributed to the higher compressive residual stresses in these regions which resists the plastic flow. The transition region (P_2) showed an increase in $(W_t - W_u)/W_t$ values compared to the compressive region (P_1) but the effect of area reduction was insignificant as seen during $h_c/h_{\max}$ variations. For the case of 10% RA, in the tensile region (P_3), highest $(W_t - W_u)/W_t$ and highest $h_f/h_{\max}$ values were observed, because of the higher tensile residual stresses. The values found for $(W_t - W_u)/W_t$ versus $h_f/h_{\max}$ from single stage drawing were found to be lower than the multistage process. A similar trend has been observed in these regions during $h_c/h_{\max}$ analysis. As discussed earlier, the reason is due to single stage drawing yielding higher compressive stress at the centre and lower tensile stresses at the edge compared to multistage. The variation of $(W_t - W_u)/W_t$ with respect to $h_f/h_{\max}$ for single stage and multi stage drawing was seen to be linear. In all the indentation simulations, the loading and unloading curve were seen to be almost linear. This linear trend has also been reported in experiments in several different materials [31].

Figures 6e and 6f show that the variation of normalized mean pressure (p_m/Y) with normalized strain (E_a/YR) is affected by the residual stress variation across the wire cross section. The mean contact pressure p_m for RA 30% at compressive region (P_1) was found to be the highest and for RA 10% at tensile region (P_3) was lowest. The mean contact pressure p_m at the transition region (P_2) was lower compared to the compressive region (P_1) but higher than the tensile region (P_3). Tensile stresses observed

at P_3 region are found to reduce the p_m as it promotes yielding and plastic flow by increasing the local mises stress, whereas the compressive stress observed at P_1 tend to have an opposite effect. Swadener et al. [11] have carried out spherical indentation tests on prestressed (tensile/compressive) 2024 aluminum substrate. Their measurement of normalised contact pressure at several strain values are superimposed in Figures 6e and 6f. The measurements compare well with the numerical analysis within the experimental scatter. Also, these effects of axial residual stress variation on the mechanical response, observed by the indentation simulations, agree well with the reported experimental nano indentation test results on a drawn steel wire as reported [6]. Due to higher compressive stress and lower tensile stress values for single stage, the mean contact pressure (p_m) was found to be higher compared to the multistage.

Figure 6: Influence of residual stress on $h_c/h_{\max}$ (pile-up) versus $h_{\max}/R$ (indentation depth) a. Single stage drawing, b. Multi stage drawing, $(W_t - W_u)/W_t$ versus $h_f/h_{\max}$ (elastic recovery parameter) c. Single stage drawing, d. Multi stage drawing and p_m/Y versus $E_e a/YR$ e. Single stage drawing, f. Multi stage drawing

4 Conclusions

The influence of process parameters in the cold drawn wire for the residual stress effects has been investigated and analyzed by finite element simulations. The major conclusions from this work are summarized below:

1. The residual axial stresses across the transverse section of the drawn wire were beneficially influenced by the area reduction while insignificant change was observed for the range of die angles used for this study. As area reduction increased the compressive stress increased in the centre of the wire while at the outer section the tensile stresses reduced. Single stage drawing of the equivalent area reduction had higher compressive stresses at the center and lower tensile stress at the edge compared to multi stage drawn wire.
2. The mechanical response analyzed on the drawn wire cross section showed the influence of residual stresses on the micro-hardness variation. The residual axial tensile stresses were found to promote yielding thereby leading to larger penetration depths while the compressive stresses resulted in smaller indentations indicating resistance to yielding which was also reflected in variation of the pile-up, indentation work and mean contact pressure distributions. The elastic recovery parameter $h_f / h_{\max}$ increased when the residual stress regions shifted from compression to tension and linear trend was observed between the indentation work and elastic recovery parameter relation. The mean contact pressure on the indenter was higher at compressive stress regions and decreased as it moved to the tensile regions of the drawn wire.
3. Both the single stage and multi stage simulations show the same effect of residual axial stress namely: that at a given indentation load, the total depth of penetration $h_{\max}$ is much greater for regions of residual stresses in tension (P_3) as compared to compression (P_1) and near zero residual stress (P_2).
4. There is stress inhomogeneity across the wire that can lead to non-uniform mechanical properties, which in turn will affect the wire's looping ability in integrated wire-bonding process. The looping characteristics demand high tensile strength, high modulus and controlled fracture strain without any residual stresses. This will be explored in future work.

Acknowledgment

Karthic R Narayanan acknowledges the financial support of Nanyang Technological University in the form of Graduate Assistantship. The authors acknowledge the assistance of undergraduate student Mr. Ang Boliang of NTU, with some of the simulations.

References

- [1] L.T. Nguyen. Wire bond behavior during molding operations of electronic packages. *Polymer Engineering and Science*, 28(14):926 – 943, 1988.
- [2] K. Busch, H.U. Kunzi, and B. Ilschner. Annealing and recrystallization kinetics of ultrathin gold wires: modulus and resistivity measurements. *Scripta Metallurgica*, 22(4):501 – 5, 1988.

- [3] P.F. Browning, C.L. Briant, K. Rajan, and B.A. Knudsen. Analysis of splitting failures during the drawing of tungsten wire. *Engineering Failure Analysis*, 2(2):105 – 115, 1995.
- [4] P. Schade. Wire drawing failures and tungsten fracture phenomena. *International Journal of Refractory Metals & Hard Materials*, 24(4):332 – 7, 2006.
- [5] R.B. Gifford, A.R. Bandar, J.P. Coulter, and W.Z. Misiolek. The analysis and control of micro-hardness distribution during wire drawing. *Transactions of the ASME. Journal of Manufacturing Science and Engineering*, 126(2):247 – 54, 2004.
- [6] D.C. Ko, S.K. Lee, W.H. Hwangb, B.M. Kim, and C.M. Bae. The evaluation of residual stress on the drawn wire using nano-indentation test. *Journal of Materials Processing Technology*, 191(1-3):64 – 67, 2007.
- [7] F.M. Haggag and G.E. Lucas. Determination of luders strains and flow properties in steels from hardness/microhardness tests. *Metallurgical Transactions A (Physical Metallurgy and Materials Science)*, 14A(8):1607 – 13, 1983.
- [8] A.R. Bandar, R.B. Gifford, W.Z. Misiolek, and J.P. Coulter. Impact of die geometry on microhardness and grain size of cold-drawn steel wire. *Materials and Manufacturing Processes*, 19(3):507 – 21, 2004.
- [9] A.L. Norbury and T. Samuel. Brinell test. *Journal of the Iron and Steel Institute*, 117:673 – 687, 1928.
- [10] M. M. Chaudhri and M. Winter. The load-bearing area of a hardness indentation. *Journal of Physics D: Applied Physics*, 21(2):370–374, 1988.
- [11] J.G. Swadener, B. Taljat, and G.M. Pharr. Measurement of residual stress by load and depth sensing indentation with spherical indenters. *Journal of Materials Research*, 16(7):2091 – 102, 2001.
- [12] N. Huber and J. Heerens. On the effect of a general residual stress state on indentation and hardness testing. *Acta Materialia*, 56(20):6205 – 13, 2008.
- [13] J.S. Field and M.V. Swain. Determining the mechanical properties of small volumes of material from submicrometer spherical indentations. *Journal of Materials Research*, 10(1):101 – 12, 1995.
- [14] J.S. Field and M.V. Swain. A simple predictive model for spherical indentation. *Journal of Materials Research*, 8(2):297 – 306, 1993.
- [15] E.G. Herbert, G.M. Pharr, W.C. Oliver, B.N. Lucas, and J.L. Hay. On the measurement of stress-strain curves by spherical indentation. *Thin Solid Films*, 398-399:331 – 335, 2001.
- [16] N. Huber and Ch. Tsakmakis. Determination of constitutive properties from spherical indentation data using neural networks. ii. plasticity with nonlinear isotropic and kinematic hardening. *Journal of the Mechanics and Physics of Solids*, 47(7):1589 – 607, 1999.

- [17] S. Kucharski and Z. Mroz. Identification of hardening parameters of metals from spherical indentation tests. *Journal of Engineering Materials and Technology, Transactions of the ASME*, 123(3):245 – 250, 2001.
- [18] B. Taljat, T. Zacharia, and F.M. Haggag. Analysis of ball-indentation load-depth data: Part i. determining elastic modulus. *Journal of Materials Research*, 12(4):965 – 974, 1997.
- [19] N.H. Loh and D.H. Sansome. Upper-bound solution for elevated temperature wire drawing. *Journal of mechanical working technology*, 18(1):33 – 51, 1989.
- [20] P. Phelan, J. Brandon, and M. Hillery. Numerical modelling of defect formation on copper wire surfaces during the wire drawing process. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 215(2):237 – 246, 2001.
- [21] A. Phelippeau, S. Pommier, T. Tsakalakos, M. Clavel, and C. Prioul. Cold drawn steel wires-processing, residual stresses and ductility-part i: metallography and finite element analyses. *Fatigue and Fracture of Engineering Material and Structures*, 29(3):243 – 53, 2006.
- [22] D.J. Celentano, M.A. Palacios, E.L. Rojas, M.A. Cruchaga, A.A. Artigas, and A.E. Monsalve. Simulation and experimental validation of multiple-step wire drawing processes. *Finite Elements in Analysis and Design*, 45(3):163 – 80, 2009.
- [23] S. He, A. Van Bael, S.Y. Li, P. Van Houtte, F. Mei, and A. Sarban. Residual stress determination in cold drawn steel wire by fem simulation and x-ray diffraction. *Materials Science & Engineering A (Structural Materials: Properties, Microstructure and Processing)*, A346(1-2):101 – 7, 2003.
- [24] S. He, P. Van Houtte, A. Van Bael, F. Mei, A. Sarban, P. Boesman, F. Galvez, and J.M. Atienza. Strain rate effect in high-speed wire drawing process. *Modelling and Simulation in Materials Science and Engineering*, 10(3):267 – 76, 2002.
- [25] L. Lazzarotto, L. Dubar, A. Dubois, P. Ravassard, and J. Oudin. Identification of coulomb’s friction coefficient in real contact conditions applied to a wire drawing process. *Wear*, 211(1):54 – 63, 1997.
- [26] K.H. Oh, J.H. Cho, A.D. Rollett, J.S. Cho, Y.J. Park, and S.H. Park. Investigation on cold-drawn gold bonding wire with serial and reverse-direction drawing. *Materials Science & Engineering A (Structural Materials: Properties, Microstructure and Processing)*, 432(1-2):202 – 15, 2006.
- [27] N.V. Reddy, P.M. Dixit, and G.K. Lal. Ductile fracture criteria and its prediction in axisymmetric drawing. *International Journal of Machine Tools and Manufacture*, 40(1):95 – 111, 2000.
- [28] D.S. Liu, Y.C. Chao, and C.H. Wang. Study of wire bonding looping formation in the electronic packaging process using the three-dimensional finite element method. *Finite Elements in Analysis and Design*, 40(3):263 – 86, 2004.
- [29] D.A. Spence. The hertz contact problem with finite friction. *Journal of Elasticity*, 5(3-4):297 – 319, 1975.

- [30] A.C. Fischer-Cripps and R.E. Collins. Probability of hertzian fracture. *Journal of Materials Science*, 29(8):2216 – 2230, 1994.
- [31] W. Ni, Y.T. Cheng, C.M. Cheng, and D. S. Grummon. An energy-based method for analyzing instrumented spherical indentation experiments. *Journal of Materials Research*, 19(1):149 – 157, 2004.
- [32] G.I. Barenblatt. *Scaling, Self-similarity, and intermediate Asymptotics*. Cambridge University Press, Cambridge, 1996.
- [33] K.L. Johnson. The correlation of indentation experiments. *Journal of the Mechanics and Physics of Solids*, 18(2):115 – 26, 1970.
- [34] R. H. Wagoner and J.L. Chenot. *Fundamentals of metal forming*. John Wiley and sons, Inc, 1996.
- [35] B. Vega, A. Haddi, and A. Imad. Investigation of process parameters effect on the copper-wire drawing. *Materials and Design*, 30(8):3308–3312, 2008.
- [36] H. Riedel, S.M. Weygand, B. Eberhard, and G. Wouters. Numerical simulation of the drawing process of tungsten wires. *International Journal of Refractory Metals & Hard Materials*, 24(4):338 – 42, 2006.