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► **To cite this version:**

Alireza Dashti, Alain Guillet, Clément Keller, Benoît Vieille. Metal forming-induced residual stresses and rule of mixtures' prediction of tensile behavior of bimetallic wires. *Key Engineering Materials*, 2022, 926, pp.381-388. 10.4028/p-u71xzj . hal-04104810

HAL Id: hal-04104810

<https://hal.science/hal-04104810>

Submitted on 24 May 2024

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Metal Forming-Induced Residual Stresses and Rule of Mixtures' Prediction of Tensile Behavior of Bimetallic Wires

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Keywords: Wire drawing, Bimetallic composites, Copper, Iron, Aluminum, Finite element analysis

Abstract. The present study investigates the tensile behavior of the two bimetallic composite wires Cu-Al and Fe-Al. The purpose is to understand the deviation their tensile strengths show from the Rule of Mixtures' prediction. To that end, an experimental-numerical approach was adopted. Following tensile testing of the above cold-drawn composite wires, the manufacturing process (wire drawing) was simulated via finite element analysis. The prominent role of processing-induced residual stresses on the yield strength of cold-drawn products is known. Therefore, a discussion based on the axial tensile residual stress profile was developed. It was concluded that the higher-magnitude-near-surface tensile residual stresses in the Fe-Al wire causes its tensile curve to show a negative deviation from the Rule of Mixtures (RoM). The Cu-Al wire, on the contrary, exhibits a slight positive deviation.

1. Introduction

Cold drawing is the common technique for manufacturing wires and tubes of different sizes, for various applications. Cold-drawn wires and cables are used in a variety of different areas from electrical wires to suspension bridge cables [1]. It is sometimes beneficial to combine the diverse advantages of individual materials into composites. The purpose could be to reduce weight, cost or to improve the mechanical properties and so forth. A known example is the copper-clad aluminum wire (CCA) for power transfer [2, 3]. The wire drawing process is always associated with a residual stress profile in the product, resulting from the non-uniform plastic deformation involved. These residual stresses play an important role in determining the in-service mechanical properties such as the yield strength [4, 5]. Atienza and Elices [6] investigated the near-surface axial tensile residual stresses (ATRS) developing in cold-drawn steel wires. Having applied the finite element analysis and X-ray diffraction, to measure residual stresses, they conclude that those stresses are detrimental to the tensile strength of the wires. Undesirable ATRS are normally dealt with through optimizing the operational parameters (drawing die geometry for instance) or/and post-processing treatments (such as “skin pass” or the thermomechanical treatment “stabilizing”) [7-10]. The use of RoM to predict the mechanical behavior of bimetallic wires could be used as a simple tool for industrial applications. Nevertheless, due to the above-mentioned ATRS, one may wonder how accurately the RoM is able to predict the yield strength of different composite wires. The current investigation examines the effect of the differing mechanical properties of the fiber and matrix on the ATRS formation in bimetallic composite wires. This provides implications helping to understand the positive/negative deviations the stress-strain curves of composite wires show from the RoM prediction. There are several studies in the literature on the applicability of the RoM for approximating the mechanical behavior of bimetallic composites [11-13]. Therefore, a primarily numerical approach was adopted to simulate the wire drawing of Cu-Al and Fe-Al wires of the same Al volume fraction (50%) and diameter (3 mm). Having plotted their experimental stress-strain curves, their deviation from the RoM-predicted tensile curves is discussed based on their numerical ATRS profile. Finally, it is

concluded what the tensile strength deviation from the rule of mixtures could possibly imply about the residual stress profile in cold-drawn concentric cylindrical composites and vice versa.

2. Materials and Methods

2.1. Experimental Procedure

As mentioned above, the two bimetallic composite wires Cu-50%Al and Fe-50%Al were manufactured by wire drawing. Pure OFHC (Oxygen Free High Conductivity) copper, iron (low-carbon steel containing 0.05 weight percent carbon), and 99.50% pure Al (the 1000 series aluminum alloy “A5”) were the starting materials used for cold drawing. The Fe, Cu, and Al were annealed for 30 minutes at 900 °C, 3 hours at 500, and 3 hours at 300 °C before drawing. An 8.5 mm-Al rod was co-deformed with a Cu tube of an external diameter of 12 mm and an internal diameter of ≈ 8.5 mm to obtain a 3 mm-diameter copper-clad aluminum wire (CCA). A 3 mm-diameter iron-clad aluminum wire (FCA) was also obtained from the co-deformation of a 6 mm-diameter Al rod with an iron tube of an external diameter of 8.5 mm and an internal diameter of 6 mm. Figure 1 shows the corresponding micrographs. Both wires were drawn using the same set-up with the drawing die specifications illustrated in figure 2a. These composite wires were then tensile-tested using a 10 kN-universal testing machine ‘MTS Criterion Model 43’ with a conventional 25 mm-gage length extensometer to measure the axial strain. Specialized grips were used for tensile testing to minimize stress concentration. The wire samples were strained at an initial strain rate of 0.004 s^{-1} to avoid possible viscous effects (figure 2b). The displacement-controlled tensile tests were carried out at room temperature. Moreover, single Fe, Cu, and Al wires were manufactured from initial rods drawn down to the diameters ensuring the same amount of effective plastic strain experienced by the co-deformed materials (calculated using equation 1.). The single wires were also tensile-tested under the same conditions mentioned above. The purpose was to provide the finite element software with the constitutive equation for each material that is necessary for wire drawing simulations. Moreover, the single wire stress- curves were used for plotting the RoM curves for the Cu-Al and Fe-Al composite systems.

$$\varepsilon = 2 \ln \frac{D_0}{D} \quad (1)$$

D_0 and D represent the initial and final diameters of the rod respectively.

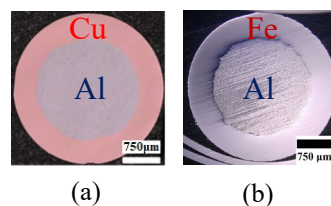


Fig 1. Micrographs of the cross-section of (a) CCA & (b) FCA wires

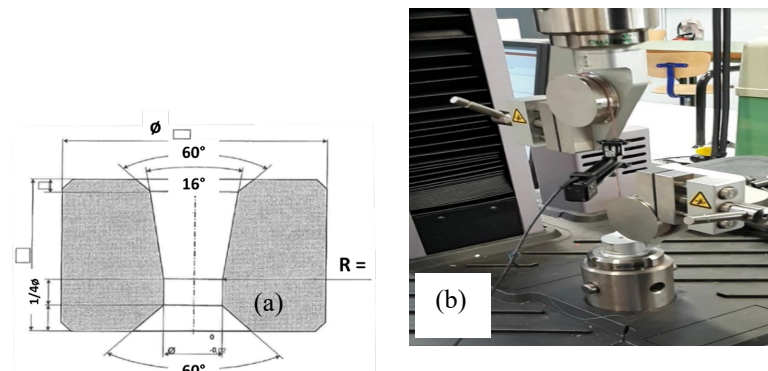


Fig 2. (a) Wire drawing die specifications (b) Tensile testing grips

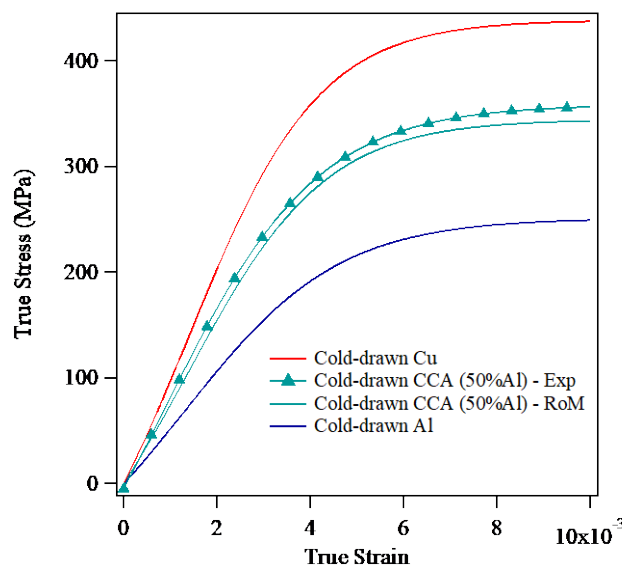
2.2. Numerical Procedure

The finite element software “Abaqus” was used to do the numerical analyses. 3D models of the CCA and FCA wires were created to simulate the last pass of the manufacture process (drawing), shown in figures 4a and 4c. The last pass was considered to compare the residual stress profiles of the 3 mm-diameter-drawing products (CCA and FCA). The wires were meshed by combining the full-integration linear elements (C3D8) and wedge elements (C3D6) to obtain an axisymmetric mesh. Elastic-plastic material behavior was used to define plasticity in Abaqus. A 3D implicit dynamic model was created to simulate cold drawing of CCA and FCA wires drawn from 3.4 mm down to 3 mm ($\approx 20\%$ area reduction). The model, consisted of deformable wires and an analytical rigid die, is designed according to the drawing die specifications (Fig. 2a). A drawing velocity of 35 m/s and a fixed die were chosen as the boundary conditions. The friction coefficient at the wire-die interface was set to zero for simplicity since powdered soap as the lubricant creates a small friction coefficient between 0.033 and 0.061 [14]. Furthermore, the simulations were run assuming a perfect fiber-matrix interface (Cu-Al & Fe-Al) and isotropic material behavior. Radial, circumferential, and tangential residual stresses form in numerically drawn CCA and FCA wires. The component of interest (ATRS as mentioned above) was profiled along the cross section of drawn wires. The ATRS profiles in CCA and FCA were plotted for comparison. They are presented in the ‘Results’ section in detail.

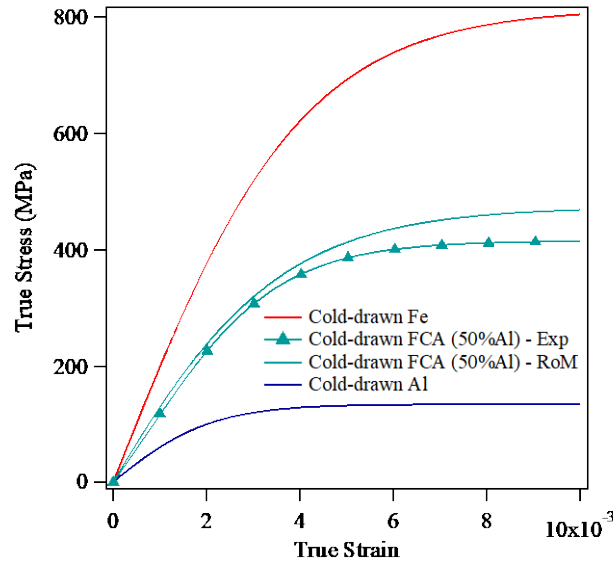
3. Results

As explained earlier in the ‘Experimental Procedure’ subsection, 3mm-CCA and FCA wires, containing 50% Al, were tensile-tested. Their experimental tensile curves along with the stress-strain curves of pure Cu, pure Fe, and pure Al are plotted in figures 3a and 3b. The corresponding RoM prediction (equation 2) is also included in each graph for comparison. σ and V stand for stress and volume fraction respectively. The subscripts c , f , and m also denote the composite, fiber (Al) and matrix (Cu/Fe) in the order given. It can be seen from the figure that the 0.2% yield stress of CCA (336 MPa) is higher than the corresponding RoM curve (326 MPa) by about 10 MPa. However, the 0.2% yield strength of FCA (387 MPa) is about 40 MPa less than the RoM-predicted value (427 MPa). Table 1 lists the yield strength and Young’s modulus of the wire samples in Fig. 3.

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \quad (2)$$



(a)



(b)

Fig 3. Experimental and RoM stress-strain curves of (a) 50%Al-CCA, pure Cu, pure Al and (b) 50%Al-FCA, pure Fe, and pure Al

Table 1. 0.2% Yield strength and Young's modulus of tensile-tested wires

Wire Sample	0.2% Yield Strength (MPa)	RoM 0.2% Yield Strength (MPa)	Young's Modulus (GPa)
Cu	420	-	≈ 129
Al (CCA)	230	-	≈ 66
Fe	728	-	≈ 200
Al (FCA)	130	-	≈ 72
CCA (50%Al)	336	326	≈ 97
FCA (50% Al)	387	427	≈ 136

Bearing in mind the important role of processing-induced residual stresses (ATRS), a numerical analysis was carried out to help understand the above deviations the composite wires show from the rule of mixtures. Therefore, wire drawing of CCA and FCA wires was modelled with the earlier-mentioned setup. Figure 4 shows the composite wires during (Figs. 4a and 4c) and after cold drawing (Figs. 4b and 4d).

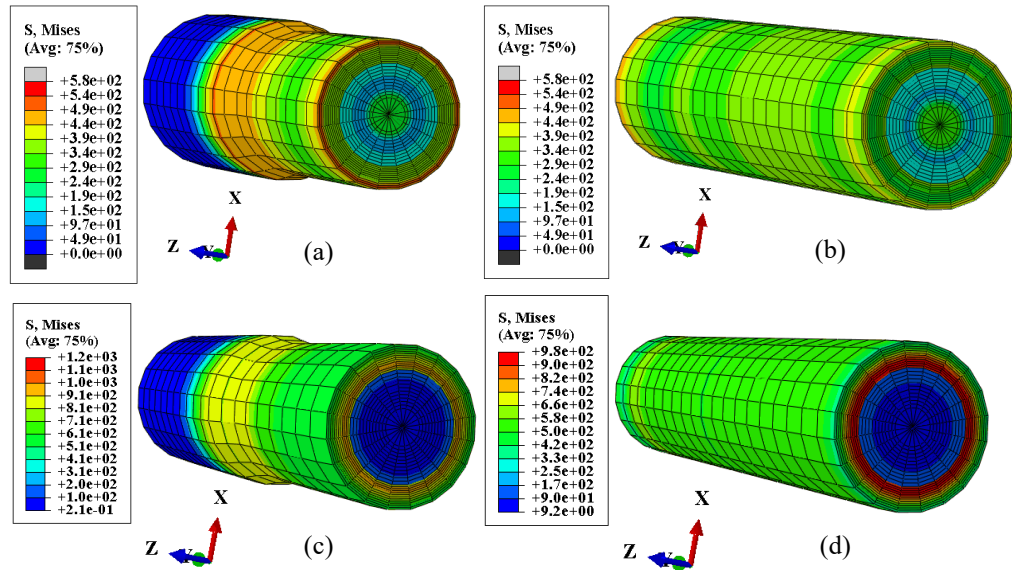


Fig 4. Cold drawing of Cu-Al (CCA) and Fe-Al (FCA) wires (stresses in MPa):
 (a) Cross-section reduction during drawing and (b) cold-drawing product (CCA)
 (c) Cross-section reduction during drawing and (d) cold-drawing product (FCA)

The development of the axial tensile residual stress (S22), ATRS, along the diameter of both CCA and FCA wires was extracted to be plotted. To that end, diameters from the middle section of the wires (shown in figure 5), away from the ends, were selected to avoid possible edge effects. Fig. 6 shows the ATRS profiles plotted versus the normalized distance along the diameter of CCA and FCA.

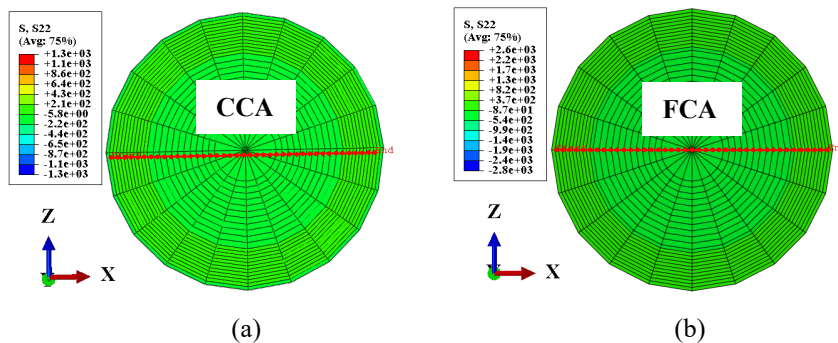


Fig 5. Paths of axial residual stress profile in (a) CCA and (b) FCA

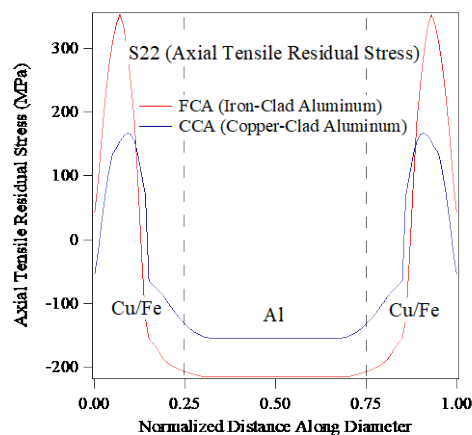


Fig 6. Axial tensile residual stress (S22) profile along the diameter (CCA vs FCA)

Figure 6 indicates that the ATRS variation from the wire surface to the interface, where the two phases meet, is less sharp in CCA relative to FCA. The maximum axial tensile and compressive residual stresses in CCA are about 167 and -154 MPa respectively while they are 353 and -215 MPa in the FCA wire. Furthermore, the residual stress curves are consistent with the appearance expected from Bullough's analytical model [15] predicting residual stresses through the cross-section of cylindrical concentric composite wires.

4. Discussion

As stated in the "Results" section, the CCA wire shows a slight positive deviation from the RoM prediction while FCA exhibit a relatively significant negative deviation. It was mentioned earlier that the inhomogeneous nature of plastic deformation during cold drawing gives rise to the formation of residual stresses. Being made up of different materials with differing mechanical properties, composite wires add to this inhomogeneity bringing about higher-magnitude residual stresses. Greater residual stresses form since the rates of increase of the lattice strain in multi-phase materials is significantly different during the drawing process [16]. In the current study, the Fe-Al composite system contains more contrasting phases than the Cu-Al system in terms of the yield strength and Young's modulus. The yield strength difference between the Fe and its Al core is 598 MPa while it is 190 MPa between the Cu and corresponding Al phase. It must be noted that because of the different diameters of the starting Al rods in each composite wire, the Al phase experiences different levels of plastic deformation and therefore has different tensile strengths in CCA and FCA. Additionally, the Young modulus difference in the Fe-Al and Cu-Al systems, between the two phases in each composite, is 128 and 63 GPa in the order given. Therefore, as could be expected, the Fe-Al wire, FCA, develops relatively large tensile residual stresses (≈ 353) near the wire surface. The near-surface ATRS are deleterious to the yield strength according to the literature presented in the "Introduction" section since they promote local yielding and premature deviation from the linear elastic behavior.

Therefore, to summarize, it can be argued that the rather significant negative deviation of the FCA stress-strain curve from the rule of mixtures, most probably, comes from its large ATRS lowering the tensile strength of the composite wire. The slight positive deviation of CCA from the RoM prediction, however, possibly originates from the fact that the pure Cu and pure Al wires themselves yield below the expected stress level under the influence of processing-induced ATRS. For that reason, their stress-strain curves (plotted in Fig. 3a) exhibit lower than expected yield and flow stresses (for the given effective plastic strain). Therefore, even though the maximum near-surface ATRS in the Cu phase deteriorates the yield strength of CCA, the combined adverse effect of ATRS on the yield and flow stress of pure Cu and Al wires (used for plotting the corresponding RoM curve) becomes dominant and brings about the observed positive deviation. This competing effect with regard to the detrimental effect of the ATRS on the yield strength of the composite and single wires exists in FCA as well. However, the ATRS forming near the wire surface in FCA is relatively so large that the Fe and Al tensile curves cannot compensate for its effect.

It should be noted that the current study only considers the effect of the differing mechanical properties of the phases constituting bimetallic composites. However, the volume fraction of the phases is another important factor that deserves an independent investigation.

5. Conclusions

The purpose of this work is to help better understand the deviation of the tensile behavior of bimetallic composite wires from the rule of mixtures prediction. To that end, two composite systems (Fe-Al and Cu-Al) were opted. 3 mm-diameter wires of the two composites were manufactured (via cold drawing) and then tensile tested. The manufacture process was then simulated to develop a residual stress-based analysis of the tensile behavior of the two composite wires. The conclusions are listed below:

- Tensile curves of bimetallic composite wires can exhibit either positive or negative deviation from the rule of mixtures' prediction

- The greater the difference between the mechanical properties of the constituting phases, more inhomogeneity will be involved in the manufacturing process giving rise to the formation of large near-surface axial tensile residual stresses
- Depending on how large the axial residual stresses developing near the wire surface are, positive or negative deviation could be expected for a given bimetallic composite wire
- For potential industrial applications, the RoM prediction of the tensile strength of the Cu-Al wire ($\approx 3\%$ difference) is more reliable than that of the Fe-Al wire ($\approx 10\%$) for the given volume fraction

Prospect

A separate study should be carried out to investigate the effect of volume fraction on the reliability of the rule of mixtures' approximation of the mechanical properties of bimetallic composite wires. Moreover, it is of paramount importance to develop a solid experimental method for measuring cold drawing-induced residual stresses.

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