Analysis of Hot Isothermal Copper Extrusion for Multi-Channel Profiles

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Master of Science

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This thesis titled
Analysis of Hot Isothermal Copper Extrusion for Multi-Channel Profiles

by

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ABSTRACT

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Analysis of Hot Isothermal Copper Extrusion for Multi-Channel Profiles

Director of Thesis: Frank F. Kraft

The primary focus of this thesis was to further development efforts on a process to produce copper multi-channel heat exchanger tube for high efficiency heat exchangers (such tube is not currently available commercially). The scope of the work involved experimental determination of parameters for an analytical extrusion model using UNS C12200 copper, the grade of copper typically used for these applications. Friction and redundant-work parameters for the extrusion model were determined from lab extrusion trials, which included two tube designs and an array of process conditions. The apparatus for the extrusion trials was also redesigned for this study. Flow stress of UNS C12200 copper was experimentally determined for process conditions involving strain rates of 1, 0.1, and 0.01 s\(^{-1}\) and temperatures of 700 and 750°C. These data were obtained via hot compression testing with an MTS® 810 test machine and Ameritherm 5kW induction heater. These data were used to determine material parameters for the classical Zener-Hollomon flow stress equation, and they were used in the extrusion model. Extrusion pressures calculated from the model were generally within 7% of the experimental data.
ACKNOWLEDGEMENTS

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CHAPTER 1

1.0 Copper Extrusion Products

Copper extrusion processes are capable of producing many profiles that can range from simple shapes to simple hollow profiles. The temperature range associated with the extrusion of copper alloys is 550 to 1000°C [1]. This range is significantly higher than that for the extrusion of aluminum alloys, another widely extruded material [1]. Simple extruded copper shapes include bar, rod, and other non-hollow profiles. Examples of simple shape copper extrusion products are shown below in Figure 1.

![Figure 1: Simple Shape Copper Products](image)

The coppers associated with these types of shapes generally consist of UNS C10100 or UNS C11000, and are generally extruded in a direct extrusion process. These copper classifications are essentially pure, electrical grade, coppers. UNS C10100 OFHC (oxygen free high conductivity) is commonly used in the automotive industry for rectifiers, radiators, and sensors. UNS C11000 ETP (electrolytic tough pitch) is widely
used in electrical conductors such as switches, bus bars, and transformers, but can also be used for household and automotive applications such as gaskets, radiators, and plumbing. Direct hot extrusion involves forcing a heated billet through a die with a ram. Figure 2 illustrates a basic direct extrusion process.

![Direct Extrusion](image)

**Figure 2: Simple Direct Extrusion Process [3]**

Hollow copper profiles are not extruded in the same manner in which hollow aluminum profiles are extruded with “port-hole” or “hollow” dies. The relatively high flow stresses and temperatures encountered in copper extrusion preclude the use of typical direct hot extrusion with “hollow” dies. However, simple, seamless, single cavity hollow profiles (of low reductions) are generally extruded by using hollow billets, or with a piercer press. A piercer-press is a press in which a piercer is forced into a billet to create the hollow billet prior to extrusion. Copper tube is generally produced in this manner from UNS C12200 copper for use in waterline and refrigeration applications. Additional drawing processes are required after tube extrusion in order to achieve a
desired diameter and wall thickness (from this low reduction process). Tube drawing is a process of pulling the tube through a series of die and mandrel sequences to achieve smaller diameter and wall thickness. Figure 3 shows some basic hollow copper profiles.

Figure 3: Copper Tube [2]

1.1 Process Parameters for the Extrusion of Copper in Industry

Hot extrusion of copper profiles is governed by several parameters including ram speed, billet/tooling temperature, and the extrusion ratio. The ram speed is important because copper is strain rate sensitive at copper extrusion temperatures. It is also important to extrude the billet as fast as reasonably possible in this temperature range. This is done to prevent or minimize overheating the tooling material. Extrusion speeds for copper extrusion range from 30 to 300 m/min, depending on the extrusion ratio and billet temperature specific to the process [1]. Generally, in copper extrusion, a billet is initially heated to a temperature of 800 to 1000°C. It is then transferred to the press for extrusion. The (steel) tooling temperature is maintained anywhere under 600°C [1]. The
tooling temperature is kept cooler, than the billet temperatures, allowing the use of hot-work tool steels for process tooling such as the container, dies, etc.

Copper extrusion tooling is typically made from hot work tool steels such as H10, H11, H12, and H13 [1]. The most common is H13 tool steel. Since hot work tool steel loses considerable strength above 600°C, it is imperative in copper extrusion processes to keep the tooling material under 600°C [1]. Due to the wide range of temperatures associated with copper extrusion, the process can be classified as non-isothermal. It is important for ram extrusion speed to be fast enough to minimize heat transfer to the tooling and prevent overheating of the tool material.

The extrusion ratio is defined as the ratio of cross-sectional area of the container to the final profile area. It is related to the deformation strain and is an indication of the work required for extrusion. The extrusion ratio in copper extrusion is typically low. Ratios generally range from 50 to 300 in the copper industry, and they are associated with high extrusion force ranging from 10 - 50 MN [1]. The extrusion ratio is typically low, mainly due to the relatively high extrusion temperature and flow stress of copper. Increase in extrusion ratio increases force required. Lower temperature would increase flow stress and hence could increase extrusion force beyond what is available from the press. Higher extrusion ratios are associated with lower ram speeds and tooling overheating concern. These ratios are relatively low when compared to aluminum extrusion which can have extrusion ratios ranging from 75 to 500 for similar force capabilities [1], and it can be in excess of 1000 for small refrigeration tubes.
1.2 Process Parameters for the Extrusion of Aluminum Alloys in Industry

Typical multi-channel profile extrusion with aluminum alloys use hollow dies made from tool steels. Process temperatures for aluminum extrusion range from 300-600°C [1]. This is due to aluminum’s significantly lower melting point and its low flow stress compared to copper at similar temperatures. Due to the lower process temperature, for aluminum extrusion, hot work tool steels are ideal because there is still considerable strength in the temperature range of 300-600°C. Hot work tool steels such as H10, H11, H12, and H13 would not sustain the temperatures and stresses to produce hollow copper profiles in the same manner in which aluminum hollow profiles are extruded.
CHAPTER 2

2.0 Development of Apparatus Design

As a departure from typical copper extrusion, a unique patented process for the extrusion of copper multi-channel tubing is under development [4,5,6,7]. The tubing produced with this process is for use in high efficiency heat exchangers, as an alternative to similar aluminum tubing profiles. Copper exhibits higher thermal conductivity and strength compared to similar aluminum alloy profiles. Furthermore, copper is antimicrobial and resistant to corrosion, which allows for its use in a variety of high-end, specialty applications.

Extrusion development efforts were undertaken with a special apparatus with a 250kN (56,000lbf) MTS® 810 test machine. The apparatus uses dual ram stems to simultaneously extrude two rectangular shaped billets through a hollow die. In this manner adverse stresses on the mandrel bridge are virtually eliminated. A basic schematic of the apparatus is shown in Figure 4.

Figure 4: Extrusion Apparatus Integration [7]
Research focused on extrusion of two multi-channel tube profiles of different extrusion ratios. One tube is an 11-channel profile and the other a 2-channel design. The 11-channel profile is given in Figure 5, and the 2-channel design in Figure 6. These are profiles that would be indicative of those used for special high efficiency heat exchangers.

![Figure 5: 11-Channel Profile [4]](image)

Dimensions are in mm.

![Figure 6: 2-Channel Design [4]](image)

Dimensions are in mm.
For the container size of the apparatus, the extrusion ratios associated with the profiles in Figures 5 and 6 are 27.5 and 49.1, respectively. This “type” of copper extrusion does not commercially exist. With this process, these tubes are produced essentially net shape and do not require any additional drawing processes. Figure 7 shows photos of these tubes.

![Figure 7: Currently Produced Tubing [Kraft, unpublished photos]](image)

### 2.1 Process Specifications and Tooling Materials

Comparable profiles can be extruded from aluminum alloys, which have an extrusion temperature of 450 - 500°C. However, due to the higher processing temperatures for copper, new tooling materials had to be considered. In the current experimental process, the billets are loaded into the container and the entirety of the apparatus is heated to approximately 750°C. Due to the uniqueness of this procedure, hot work tool steels could not be considered because they do not exhibit sufficient strength above 600°C (and this process is not fast enough to sufficiently limit heat transfer to the tooling). For many
aluminum extrusion processes, H13 tool steel and other hot work tool steels are used due to aluminum’s lower hot working temperature and lower flow stress. Super alloys such as Rene 41, Inconel 718, and ATI 720 are used here due to their higher strengths at elevated temperature. Figure 8 shows strength - temperature comparison for these super alloys and H13 tool steel.

![Figure 8: Comparison of Tooling Materials in Relation to Strength and Temperature](image)

For this process the tooling temperature is held at essentially the same temperature as the work piece, namely about 750°C. The apparatus is slowly heated to 750°C, from room temperature, and held there until thermal readings throughout the apparatus reach equilibrium. Due to the nature of the heating process, the process can be classified as near isothermal. Isothermal extrusion refers to the billet and extrudate material being at nearly the same temperature throughout the extrusion cycle. It is
inferred (with some data support) that this takes place, even though there are thermal gradients measured within the tooling. The billet and tooling are essentially the same temperature prior to extrusion so that there is no cooling due to heat transfer from an overheated billet to a cooler container and extrusion die. Also, extrusion is slow enough so deformation heating is readily dissipated, also resulting in negligible temperature change.

2.2 Product Material

Previous (published [6] and unpublished [11]) research used electrical grade, oxygen free, high conductivity (OFHC) UNS C10100 copper, because it was readily available and because the high purity should correlate to the lowest flow stress. Flow stress testing was conducted by Vaitkus [6] and Rogers [12]. These tests were performed for a temperature range of 600–750°C at strain rates of 3, 1, 0.1, and 0.01 s\(^{-1}\). Through the work of Vaitkus and Rogers an average flow stress of about 43 MPa at 750°C was determined for a strain rate of 1 s\(^{-1}\) for UNS C10100. Flow stress data from Rogers [12] supporting this are shown in Figure 9.
Nevertheless, copper tube used in refrigeration and heat-exchanger applications is DHP (deoxidized high phosphorus) copper, designated UNS C12200. The copper is deoxidized with phosphorus and thus has relatively high residual phosphorus content. Therefore, objectives of this research are to determine flow properties of UNS C12200 copper alloy and to determine the extrusion parameters for this process using this alloy. A comparison of the compositions of UNS C12200 and UNS C10100 is given in Table 1.

Table 1: Composition of Copper Alloys [13, 14]

<table>
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<th></th>
<th>Cu (%)</th>
<th>P (%)</th>
<th>Other (%)</th>
</tr>
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<tr>
<td>UNS C12200</td>
<td>99.98</td>
<td>0.02</td>
<td>0.001</td>
</tr>
<tr>
<td>UNS C10100</td>
<td>99.99</td>
<td>0.0003</td>
<td>0.01</td>
</tr>
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</table>

Figure 9: Flow Stress Data of UNSC10100 at 750°C [12]
2.3 Basic Analytical Modeling

For metals at a constant hot working temperature, flow stress can be characterized using the power expression shown in Equation 1 [15]. This equation relates flow stress ($\sigma$) to strain rate ($\dot{\varepsilon}$) and strain rate sensitivity ($m$).

$$\sigma = C \dot{\varepsilon}^m$$  \hspace{1cm} (1)

It is important to note that the material parameters $C$ and $m$ change with temperature.

For copper, strain rate dependence is closely related to temperature. Therefore a model that incorporates both the strain rate and temperature dependence is very useful. Zener and Hollomon [16] developed a flow model using the Arrhenius rate law. They argue that plastic straining at elevated temperatures can be quantified as a rate process [16]. Equation 2 gives the Arrhenius equation, where $K$ is a rate constant, $R_u$ is the universal gas constant, $T$ is absolute temperature, $Q$ is the activation energy, and $C$ is the pre-exponential factor.

$$K = C \exp \left( \frac{-Q}{R_u T} \right)$$  \hspace{1cm} (2)

Zener and Hollomon used the Arrhenius rate equation to develop their flow stress model. In Equation 3, $Z$ is called the temperature compensated strain rate or Zener-Hollomon parameter. This parameter encompasses both strain rate and temperature and is given in Equation 4. Equation 3 is the flow stress equation that is analogous to Equation 1, where $Z$ takes the place of $\dot{\varepsilon}$.

$$\sigma = CZ^m$$  \hspace{1cm} (3)

$$Z = \dot{\varepsilon} \exp \left( \frac{Q}{R_u T} \right)$$  \hspace{1cm} (4)
$Q$ is the activation energy, $T$ is absolute temperature, and $R_a$ is the gas constant, $\sigma$ is the flow stress of the material.
3.0 Analytical Model

An analytical model for the determination of ram pressure, based on process parameters of temperature and ram speed, has been under development for this overall research effort for several years. This model allows for the prediction of extrusion pressure and ram speed based on the dimensions of the billet, final dimensions of the extruded tubing, temperature at which deformation is occurring, and the strain rate at which it is occurring. The development of a functional analytical model is important for future work, particularly to scale-up the process.

The total work per unit volume of extruded material is equivalent to ram pressure. For this work, extrusion (ram) pressure, $P_e$, can be divided into the work that occurs in the die and work that occurs in the container, and this is expressed in Equation 5.

$$P_e = w_d + w_c$$  \hspace{1cm} (5)

$w_d$ is the total work per unit volume in the die. $w_c$ is the friction work per unit volume in the container. $w_d$ is defined by Equation 6, and $w_c$ is defined by Equation 7.

$$w_d = \frac{\sigma \ln R_e}{\eta}$$  \hspace{1cm} (6)

$$w_c = \frac{m_f \sigma P_e \ell_b}{\sqrt{3} A_e}$$  \hspace{1cm} (7)

In Equation 6, $\sigma$ is the flow stress of the material, and $R_e$ is the extrusion ratio. The efficiency term, $\eta$, takes into account non-uniform deformation and frictional work in the die and it is determined experimentally [15]. In Equation 7, $m_f$ is the friction factor (for a constant interfacial shear stress), and this is also determined experimentally. $A_e$ is
the cross sectional area of the container bore, $\ell_b$ is the billet length in contact with the container, and $p_c$ is the billet perimeter normal to its axial length [15].

For UNS C10100 alloy, and for Equations 3 and 4, $C$ is constant at 0.571 MPa, $Q$ is the activation energy 234 kJ, $R_u$ is the gas constant 8.314 J/mol-K, $m$ is the strain rate sensitivity 0.16, and $T$ is the absolute temperature [12]. $C$, $Q$, and $m_f$ are determined for UNS C12200 as a part of this work. Strain rate is estimated as a time averaged strain rate. This is presented in Equations 8 and 9, where $\dot{\varepsilon}$ is the mean strain rate, $R_e$ is the extrusion ratio, $V$ is the volume of material in the deformation zone, $t$ is the time in which deformation is occurring, $A_c$ is the area of the container, and $v_r$ is the velocity of the ram.

$$\dot{\varepsilon} = \frac{\ln R_e}{t}$$  \hspace{1cm} (8)

$$t = \frac{V}{v_r A_c}$$  \hspace{1cm} (9)

Extrusion pressure ($P_e$) is predicted by combining Equations 5 through 9, and this is given in Equation 10. In the situation in which there is constant ram pressure (such as in experimental work) the strain rate can be determined using Equation 11. By applying Equations 8 and 9, ram velocity can be expressed as a function of the constant ram pressure (the constant force divided by the container area) and this is given in Equation 12. Equation 12 is used to determine $\eta$ from experimental data.

$$P_e = C \left[ \dot{\varepsilon} \exp \left( \frac{Q}{R_u T} \right) \right]^m \left[ \frac{\ln R_e}{\eta} + \frac{m_f p_c \ell_b}{\sqrt{3} A_c} \right]$$  \hspace{1cm} (10)

$$\dot{\varepsilon} = \exp \left( \frac{-Q}{R_u T} \left[ \frac{C}{P_e} \left( \frac{\ln R_e}{\eta} + \frac{m_f p_c \ell_b}{\sqrt{3} A_c} \right) \right]^{1/m} \right)$$  \hspace{1cm} (11)
\[ v_r = \frac{V}{A_c \ln R_c} \exp \left( \frac{-Q}{R_a T + C \left( \frac{\ln R_c}{\eta} + \frac{m_f p_c \ell_b}{\sqrt{3} A_c} \right)} \right)^{-\frac{1}{m_f}} \]  \hspace{1cm} (12)

\( \eta \) and \( m_f \) will be determined for the extrusion model from experimental test data.

3.1 Objectives

The objectives for this work are:

- To refine and evaluate the analytical model to predict extrusion pressure and force using UNS C12200 copper.
- To experimentally determine flow stress of UNS C12200 at strain rates of 0.01, 0.1, 1s\(^{-1}\) at 700 and 750\(^{\circ}\)C and to develop Zener-Hollomon model parameters for use in the extrusion model.
- To redesign the extrusion apparatus and implement these changes in order to perform extrusion trials for experimental determination of the parameters for the extrusion model.
CHAPTER 4

4.0 Apparatus Design Modifications

To complete the experimental work, redesign of the apparatus and implementation of these changes was required. Due to the high extrusion forces, buckling failure of the ram stems and upper and lower mounts became a problem in previous work. An objective of this work was to redesign these components.

4.1 Apparatus Design

The extrusion apparatus is shown in Figure 10. The main components of the redesign are labeled in Figure 10.

Figure 10: Extrusion Apparatus Assembly

Not shown is the anti-rotation device for the lower assembly.
The upper and lower rams were redesigned to rigidly mount directly onto the MTS crosshead and ram, respectively. This was done to reduce or eliminate the possibility of ram-stem buckling by establishing more rigid mounts. The free-length of the ram stems was also shortened. The ram stem holder was also modified so that contact between the base of the holder and the top of the container could occur without interfering with the tops of the cartridge heaters, which are inserted into the top of the container. Ram stem and holder lengths were calculated so that their combined length would not extend past the bottom of the extrusion container with the dummy blocks.

Due to the increased diameter of the upper and lower main rams, new cooling blocks had to be constructed. These cooling blocks are important in the design of the apparatus because they remove heat from areas in which heat could be detrimental to the machine and hydraulic components. These cooling blocks have an increased water volume which aids in the dissipation of heat. A 3D model of the newly designed cooling block is shown in Figure 11.
Figure 12 shows the anti-rotation device which is bolted to the bottom ram. A “horseshoe” bracket with nylon bolts prevents rotation of the main MTS machine ram during extrusion trials. By adjusting the nylon bolts, the ram is constrained to follow the main upright of the MTS machine. This system was needed to prevent misalignment between the ram stems and container.

Figure 12: Anti-Rotation System
CHAPTER 5

5.0 Experimental Plan

The experimental approach to meet the objectives of this work is as follows:

- To perform compression flow stress testing on UNS C12200 copper and to compare results to UNS C10100 copper
- To redesign and incorporate apparatus modifications
- To perform extrusion trials with UNS C12200 to determine the friction factor and deformation efficiency for the extrusion modeling

5.1 Compression Testing

Table 2 shows the plan for hot compression testing of UNS C12200 copper specimens. Trials 7 - 9 are for UNS C10100 copper and were used to compare materials as well as to establish uncertainty for UNS C12200 compression tests (by comparing results to previous testing).

<table>
<thead>
<tr>
<th>Trial #</th>
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<th>Strain Rate (s⁻¹)</th>
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<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>0.01</td>
<td>UNS C12200</td>
</tr>
<tr>
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<td>0.1</td>
<td>UNS C12200</td>
</tr>
<tr>
<td>6</td>
<td>700</td>
<td>1</td>
<td>UNS C12200</td>
</tr>
<tr>
<td>7</td>
<td>750</td>
<td>0.01</td>
<td>UNS C10100</td>
</tr>
<tr>
<td>8</td>
<td>750</td>
<td>0.01</td>
<td>UNS C10100</td>
</tr>
<tr>
<td>9</td>
<td>750</td>
<td>0.01</td>
<td>UNS C10100</td>
</tr>
</tbody>
</table>
This testing was performed with the MTS machine and an Ameritherm 5kW induction heater [17]. As a specimen is compressed, its length decreases and area increases. Therefore the machine’s ram speed was accordingly decreased (via programming) to provide a constant strain rate for the test. Equation 13 was used to determine the appropriate ram velocity to maintain a constant strain rate. A constant strain rate \( \dot{\varepsilon} \) was achievable by dividing a MTS Teststar IIs program into steps. For every 1.27 mm (.050 inches) of compression the ram velocity was recalculated via equation 13.

\[
\dot{\varepsilon}_t = \frac{v_r}{l_0 + \Delta l}
\]

In Equation 13, \( v_r \) is the velocity of the ram, \( l_0 \) is the original billet length, \( \Delta l \) is the change in billet length. The tests were performed by placing the thermocouple end under the specimen and loading the specimen between the boron nitride lubricated compression anvils within the induction heater coils. Then the specimen was brought to temperature with the induction heater. The thermocouple provided temperature control feedback, and once the temperature was steady (within 5°C) the compression test commenced. Flow stress was calculated with Equation 14.

\[
Y = 2P_a \left\{ \left( \frac{h}{\mu R_s} \right)^2 \left[ \exp \left( \frac{2\mu R_s}{h} \right) - \frac{2\mu R_s}{h} - 1 \right] \right\}^{-1}
\]

In Equation 14 \( Y \) is the flow stress, \( P_a \) is the pressure along the axial area of the specimen, \( h \) is the instantaneous sample height, \( R_s \) is the instantaneous radius, and \( \mu \) is the friction coefficient. \( \mu \) has been determined experimentally, and the values associated with different temperatures are shown in Table 3 [6]. Boron nitride was used as a
lubricant in the determination of $\mu$ because boron nitride reduced the effects of friction the greatest [6] and was used in the compression testing. Table 3 [6] is representative of friction values using this lubricant.

Table 3: Coefficient of Friction for Essentially Pure Copper at Various Temperatures with Boron Nitride Lubricant [6]

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.14</td>
</tr>
<tr>
<td>650</td>
<td>0.15</td>
</tr>
<tr>
<td>700</td>
<td>0.2</td>
</tr>
<tr>
<td>750</td>
<td>0.2</td>
</tr>
</tbody>
</table>

5.2 Extrusion Trials

Table 4 lists the extrusion test trials for UNS C12200 copper. The results from these trials will be compared to UNS C10100 copper, and extrusion data attained by Vaitkus [6] and Kochis [11].

Table 4: Extrusion Trial Schedule

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Die/Profile</th>
<th>Billet Length</th>
<th>Ram Speed or Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>11 Channel</td>
<td>3 inch (76.2 mm)</td>
<td>.006 in/s (.152 mm/s)</td>
</tr>
<tr>
<td>Trial 2</td>
<td>2 Channel</td>
<td>3 inch (76.2 mm)</td>
<td>.006 in/s (.152 mm/s)</td>
</tr>
<tr>
<td>Trial 3</td>
<td>11 Channel</td>
<td>3.75 inch (95.25 mm)</td>
<td>45,000 lbf (200 kN)</td>
</tr>
<tr>
<td>Trial 4</td>
<td>2 Channel</td>
<td>3.75 inch (95.25 mm)</td>
<td>45,000 lbf (200 kN)</td>
</tr>
</tbody>
</table>
These trials have been chosen to determine the parameters of $\eta$ and $m_f$ and to assess the application of Equations 10 and 12. By varying the die, billet length, ram speed and force, comparisons between materials and testing conditions were able to be made.
6.0 Compression Test Results

The test results and analysis for hot compression testing of UNS C12200 copper are given in Figures 13 and 14 for temperatures of 750°C and 700°C, respectively and strain rates of 0.01, 0.1, and 1 s\(^{-1}\). True strain (\(\varepsilon_t\)) was calculated for Figures 13 - 15 via Equation 15.

\[
\varepsilon_t = \ln \frac{h_o}{h_I}
\]  

(15)

In Equation 15, \(h_o\) is the original sample height and \(h_I\) is the instantaneous sample height. Equation 14 was used to calculate flow stress.

Figure 13: Flow Stress Data as a Function of True Strain for UNS C12200 at 750°C and 1, 0.1, and 0.01 s\(^{-1}\) Strain Rates
Figure 14: Flow Stress Data as a Function of True Strain for UNS C12200 at 700°C and 1, 0.1, and 0.01 s\(^{-1}\) Strain Rates

Flow stress values representative of the varying strain rates and temperatures are given in Table 5 below. Since there is a slight slope in Figures 13 and 14 the values of constant flow stress were determined from the data at points where the slope of the line was as close to zero as possible. Steady state constant flow stress conditions exist when the slope of the line is as close to zero as possible.

<table>
<thead>
<tr>
<th>Table 5: Flow Stress Values for Specific Temperatures and Flow Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
</tr>
<tr>
<td>Strain Rate (s(^{-1}))</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>
Compression test data for trials 7 to 9 (identified in Table 2) for UNS C10100 copper are presented in Figure 15. These tests were performed to establish experimental accuracy and consistency.

![Flow Stress as a Function of True Strain for UNS C10100 at 750°C and 0.01s⁻¹ Strain Rate](image)

Figure 15: Flow Stress as a Function of True Strain for UNS C10100 at 750°C and 0.01s⁻¹ Strain Rate

To determine experimental accuracy (and consistency) of compression testing, the compression test results for UNS C10100 copper were compared to previously attained data points. The values of flow stress were determined near a true strain of 1.1 from Figure 15. After a statistical analysis of the data presented in Table 6 for UNS C10100 copper, a 95% confidence interval was achieved. This means there is a 95% likelihood repeat experiments, under the same conditions, will produce similar results. This confidence interval was based on the assumptions of a normal distribution of data points.
and 4 degrees of freedom. The uncertainty that corresponds to the confidence interval is 1.54 MPa. It is to be assumed that this confidence level is also applicable to UNS C12200 copper hot compression data points because they were gathered in the same manner, over the same sample period, and they did not show deviating characteristics.

Table 6: Flow Stress Data Points for UNS C10100 at 750°C and 0.01 s⁻¹ Strain Rate

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Flow Stress (MPa)</th>
<th>Flow Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>23</td>
<td>3300</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>3300</td>
</tr>
<tr>
<td>9</td>
<td>23</td>
<td>3300</td>
</tr>
<tr>
<td>Vaitkus</td>
<td>23</td>
<td>3300</td>
</tr>
<tr>
<td>Rogers</td>
<td>23</td>
<td>3300</td>
</tr>
</tbody>
</table>

6.1 Traditional Model Analysis

Equation 1 can be rewritten as Equation 16. Plotting \( \ln(\sigma) \) as a function of \( \ln(\dot{\varepsilon}) \) gives Figure 16. In Figure 16, the slope of the line gives strain rate sensitivity. The y-intercept can be calculated from a linear regression and is used to determine the strength constant \( C \). Table 7 lists a comparison of strain rate sensitivities and strength constants for UNS C12200 at 700°C and 750°C. Table 7 shows that as temperature increases the strength constant \( C \) decreases and strain rate sensitivity \( m \) increases. This behavior is expected and typical for copper.

\[
\ln(\sigma) = m\ln(\dot{\varepsilon}) + \ln(C)
\]  

(16)
Table 7: Strain Rate Sensitivity and Strength Constants for UNS C12200 at 700°C and 750°C

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Strength Constant C (MPa)</th>
<th>Strain Rate Sensitivity (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>51.5</td>
<td>0.180</td>
</tr>
<tr>
<td>750</td>
<td>40.0</td>
<td>0.187</td>
</tr>
</tbody>
</table>

6.2 Zener-Hollomon Model Analysis

Equation 17 is derived from Equation 3 for the determination of the values $C$ and $m$. Plotting $\ln(\sigma)$ as a function of $\ln(\dot{\varepsilon})$ allows for the strain rate sensitivity and the strength constant to be determined for the Zener-Hollomon model.
\[
\ln(\sigma) = m\ln(Z) + \ln(C) \quad (17)
\]

However, solving for \(\ln(Z)\) requires the activation energy. Strain rate can be expressed as a function of temperature for a constant stress. Equation 18 represents the relationship between strain rate and temperature and allows for the determination of the activation energy \(Q\). Figure 17 shows flow stress as a function of the strain rate.

\[
\ln(\dot{\varepsilon}) = -\frac{Q}{R_u} \frac{1}{T} + \ln(Z) \quad (18)
\]

![Figure 17: Plot of Flow Stress as a Function of Strain Rate](image)

Figure 17 identifies lines of constant flow stress, specifically 25, 30, 35, and 40 MPa. From these values of constant flow stress, the natural log of the strain rate is graphed as a function of the reciprocal of the absolute temperature. This is shown in
Figure 18. The average of these slopes was used to determine a mean value of $-Q/R_u$ by Equation 18. A average activation energy for UNS C12200 copper was determined to be 176 kJ/mol.

Figure 18: Plot of Constant Flow Stress for the Natural Log of the Strain Rate as the Reciprocal of Absolute Temperature

Figure 19 show the compression test data with a linear fit applied to it (by taking the natural log of the flow stress and Z-parameter). The parameters for Equation 17 are determined by this linear relationship. The slope of the line is the strain rate sensitivity
and the y-intercept is $\ln(C)$. From the data in Figure 19 the strength constant $C$ is
determined to be 0.986 MPa, and the strain rate sensitivity $m$ is 0.18 with a coefficient of
determination $R^2=0.995$ for the linear fit.

![Figure 19: Plot of $\ln(\sigma)$ as a Function of $\ln(Z)$](image)

Figure 20 illustrates the level to which the flow stress data matches the Zener-
Hollomon model developed for UNS C12200 copper. A coefficient of determination,
$R^2=0.997$, was determined for the Zener-Hollomon model.
Figure 20: Plot Comparing Data from the Compression Tests to the Zener-Hollomon Model
CHAPTER 7

7.0 Extrusion Trials Results

Figure 21 shows data from a constant velocity (0.152 mm/s) extrusion trial with UNS C12200 copper for the 11 channel design. The friction factor was determined from Equation 7 and indicated in Figure 21. The slope of Figure 21 is equal to $m \sigma p_c / \sqrt{3} A_c$

where $\sigma$ is equal to 4110 psi (28.2 MPa), $p_c$ is 1.959 inches (49.76 mm), and $A_c$ is 0.2685 in$^2$ (173.2 mm$^2$). The friction factor was determined to be 0.7. The experimental uncertainty in the friction factor is ±.038. Analysis of other data from Kochis [11] indicate that the friction factor does show some variability and can vary to as low as 0.6. This may explain some of the discrepancies between the extrusion model (Equations 10 and 12) and the experiential data. The effect of variability is addressed in the subsequent chapter.

The deformation efficiency was subsequently determined from constant force extrusion trials. The efficiency value was that which provided the best fit of Equation 12 to the data. Analysis of the data to determine the efficiency parameter is unique and expedient since it is evaluated over a range of ram speeds or strain rates.
Extrusion trials 1 through 4 were completed, in that order, according to the test plan. The results of these extrusion trials are presented in Figures 22-25. Superimposed onto each plot is either Equation 10 or 12 for the prediction of ram force or speed, respectively.
Figure 22: Extrusion Trial #1: 11 Channel Die Profile, 0.152 mm/s Ram Velocity, 76.2 mm Billet Length

Figure 23: Extrusion Trial #2: 2 Channel Die Profile, 0.152 mm/s Ram Velocity, 76.2 mm Billet Length
Figure 24: Extrusion Trial #3: 11 Channel Die Profile, 200 kN Constant Force, 95.25 mm Billet Length

Figure 25: Extrusion Trial #4: 2 Channel Die Profile, 200 kN Constant Force, 95.25 mm Billet Length
Figures 26 – 29 show the temperature data for trials #1 – 4 respectively. Thermocouples were inserted into special grooves of the heaters located in the container and in the die holder. These thermocouples were used to provide the feedback to the two temperature controllers, and hence the temperatures at these locations were essentially constant. Additional thermocouples were located at the entrance of the die and at the center of the container, between two heaters. The data indicate a temperature gradient of about 25-45°C in the container (from a heater to a location between heaters). During extrusion, the container temperature decreased by as much as 20 °C, but this may be related to the evacuation of the billet from this region in the container. The temperature measurements at the entrance to the die remained essentially constant during extrusion, within about 10°C of variation. In addition, the die entrance temperature was generally within about 10°C of the container temperature. For the data of trials 1-3, the die holder thermocouple temperature was 70-80°C higher than the die entrance temperature (in order to maintain the test temperatures). The temperature at the die entrance is the most representative temperature of the deforming billet (short of measuring the actual extrudate temperature). At slow extrusion speeds, much of the deformation/friction heat is expected to dissipate, thereby promoting near isothermal extrusion.
Figure 26: Temperature Data for Extrusion Trial #1: 1 Channel Die Profile, 0.152 mm/s Ram Velocity, 76.2 mm Billet Length

Figure 27: Temperature Data for Extrusion Trial #2: 2 Channel Die Profile, 0.152 mm/s Ram Velocity, 76.2 mm Billet Length
Figure 28: Temperature Data for Extrusion Trial #3: 11 Channel Die Profile, 200 kN Constant Force, 95.25 mm Billet Length

Figure 29: Temperature Data for Extrusion Trial #4: 2 Channel die Profile, 200 kN Constant Force, 95.25 mm Billet Length
7.1 Extrusion Trial Analysis

The data for extrusion trial #1 presented in Figure 22 did not follow the expected trend of decreasing force with ram position (and decreasing billet length). The temperature data shows a near isothermal process with die temperature averaging around 741°C ± 1°C. The likely cause of the trial not following the expected trend is the likelihood that the ram stems came into contact with the side of the container. This event caused increased friction and produced the process seen in Figure 22. Extrusion trial #1 was the only extrusion trial in which the “horse shoe” ram guide was not utilized.

To support the applicability and versatility of the extrusion model, previous extrusion test data by Kochis were considered [11]. This prior test was performed, under similar conditions as extrusion trial #1 albeit with a different extrusion die design for the 11-channel profile. The die design used in Kochis’ extrusion trials had a deformation efficiency of about 0.21, per analysis with the extrusion model. This extrusion trial data is shown in Figure 30. The temperature data correlating to this extrusion trial is presented in Figure 31.
Figure 30: Extrusion Data for UNS C12200 using a Different 11-Channel Extrusion Die Design, 0.152 mm/s Ram Velocity, 76.2 mm Billet Length. Data from Kochis [11]

Figure 31: Temperature Data for UNS C12200 using a Different 11-Channel Extrusion Die Design, 0.152 mm/s Ram Velocity, 76.2 mm Billet Length. Data from Kochis [11]
The extrusion trial data shown in Figure 23 and Figure 30 demonstrate the degree to which the parameters for UNS C12200 copper can predict the ram force. Of particular importance for extrusion modeling is the ability to estimate the maximum force at the beginning of extrusion. For the constant force extrusion trials, disregarding extrusion trial #1, the maximum discrepancy between the ram force data and Equation 10 is 7%. This maximum occurred at the maximum extrusion force in Figure 30. This discrepancy could be largely due to the die efficiency used in the calculation of ram pressure. The approximate 0.21 die efficiency used in Figure 30 was determined by Kochis [11] for a different die and copper. Figure 31 shows the temperature variation for data presented in Figure 30. Container temperature decreased from 754°C to 744°C. The die temperature remains essentially constant at 745°C ± 2°C.

For the data presented in Figure 23, the maximum force is predicted with the model (Equation 10) to within 1.6%. Through the entire course of extrusion, Equation 10 predicts the force within 5.6%. The dip seen in extrusion force, in Figure 23, can be attributed to variation in extrusion temperature. Figure 27 shows that there was indeed a variation in temperature seen by the thermocouples located in the container and at the top of the die. As container temperature decreases below 750°C, die temperature increases from 745°C at 120 seconds to 754°C at approximately 240 seconds. As die temperature increases it is expected that extrusion pressure will decrease by approximately 3.2% to temperature change alone. As temperature increases friction is also expected to decrease and lower extrusion pressure by up to 5.8%. The timing of this temperature change correlates with the drop in extrusion pressure seen in Figure 23. The change in container
temperature is less significant for extrusion trial #2 due to the fact that the shorter billets used in the trial spend less time in the container and therefore are less affected by variation in container temperature.

In the constant force extrusion trial #3 with the 11 channel die, the model for ram speed is within 10% of the experimental data above 0.0023 in/s (0.058 mm/s) ram speed. This is graphically shown in Figure 24. Below this speed the model over-predicts ram speed by about 20%. This discrepancy can be attributed to the drop in container temperature seen in Figure 28. The container temperature drops from 756°C to 749°C in the first 240 seconds of extrusion. As the temperature decreases in the container, the friction between the billet and container walls increases, thus reducing ram speed. Die temperature remains relatively constant for extrusion trial #3 and this explains why the model more accurately predicts ram speed above 400 seconds. Above 400 seconds the majority of the extruding billets are in close proximity to the thermocouple located at the die entrance. During this time very little variation in temperature is seen (753°C ± 1°C) and the model reasonably predicts ram speed.

For the constant force extrusion trial #4 presented in Figure 25, the predicted ram speed (with Equation 12) is within 24% of the experimental data. This discrepancy was maximum above a ram speed of 0.0024 in/s (0.061 mm/s). This could be attributed to the variation in container and die temperature over the duration of the process. The container temperature drops from 744°C to 734°C, over the entire extrusion trial. This drop in temperature is most significant, and can explain why the model over predicts ram speed below 900 seconds. Similar to extrusion trial #3 as the temperature decreases the friction
between the billets and container increase, thus reducing ram speed. However, unlike extrusion trial #3 the die temperature increases significantly after 1000 seconds. The die temperature increases from 725°C to 731°C. This explains why Equation 12 under predicts ram speed after 1000 seconds. As temperature increases in the die, friction between the billet and die decreases, thus increasing ram speed and efficiency.

The effects of temperature and friction variability were evaluated in light of the discrepancies between the extrusion model and experimental data. Temperature and friction factor were varied and compared to the ram speed data for extrusion trials #3 and #4. The temperature was varied by approximately ±1% (±10°C) from that of the average temperature value (753°C) for extrusion trial #3 and (727°C) for extrusion trial #4. The friction factor was also varied by ±5%, for both extrusion trials, due to its significance relevant to extrusion temperature. Small variations of both parameters were chosen to show the sensitivity of the extrusion model. Table 8 and 9 give the variations in temperature and friction factor as different case numbers for the respective extrusion trial. Figures 32 and 33 shows the difference in predicted ram speed based on the variation of temperature and friction factor for extrusion trials #3 and #4. Figures 32 and 33 illustrate the feasibility of temperature and friction factor as the cause of the discrepancy in Figures 24 and 25.

Table 8: Temperature and Friction Factor Variation for Extrusion Trial #3

<table>
<thead>
<tr>
<th>Case #</th>
<th>Friction Factor Value</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.735</td>
<td>743</td>
</tr>
<tr>
<td>2</td>
<td>0.665</td>
<td>763</td>
</tr>
</tbody>
</table>
Figure 32: Comparison of Temperature and Friction Factor Variation on the Prediction of Ram Speed for Extrusion Trial #3

Table 9: Temperature and Friction Factor Variation for Extrusion Trial #4

<table>
<thead>
<tr>
<th>Case #</th>
<th>Friction Factor Value</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.735</td>
<td>717</td>
</tr>
<tr>
<td>2</td>
<td>0.665</td>
<td>737</td>
</tr>
</tbody>
</table>

Figure 33: Comparison of Temperature and Friction Factor Variation on the Prediction of Ram Speed for Extrusion Trial #4
The variation in temperature and friction factor was also considered for the prediction of maximum ram pressure. It was determined from the model for extrusion trial #2 that varying the temperature and friction factor, by ±10°C and ±5% of the friction factor value, causes a 5.8% variation in the predicted maximum ram pressure. This calculated discrepancy value is above the maximum variation between the extrusion data and the model for extrusion trial #2. Similarly, the discrepancies in model prediction, for the data attained by Kochis in a constant speed extrusion trial, can be explained by the variation in temperature and friction factor.

Table 10 presents the die (deformation) efficiencies for the dies of both tube profiles extruded. Equation 12 was used to determine the die efficiencies for both the 2-channel and 11-channel dies.

<table>
<thead>
<tr>
<th>Die</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Channel</td>
<td>17%</td>
</tr>
<tr>
<td>11-Channel</td>
<td>15%</td>
</tr>
</tbody>
</table>

7.2 Discussion of Results

Data obtained during flow stress testing showed that the UNS C12200 copper tested had a lower flow stress than previous results for UNS C10100 copper (by about 4-8%). This was in the extrusion temperature range of 700-750°C and strain rates of 1.0, 0.1, 0.01 s⁻¹. The flow stress determined for UNS C12200 is not lower at a level of statistical significance. However, the data shows a strong trend in lower flow stress, for UNS C12200, for all temperatures and strain rates tested. The difference may be
attributed to metallurgical differences not evaluated. Metallurgical differences, other than alloy chemistry designation, were not investigated. The flow stress data indicate that the phosphorus content in UNS C12200 may not significantly increase the flow stress within the range of 700-750°C. The lower flow stress of UNS C12200 is consistent with a lower activation energy (176 kJ/mol) than that for UNS C10100 (234 kJ/mol). Extrusion data presented in Figures 23 and 26 are consistent with a lower flow stress because the maximum extrusion pressure is roughly 15% lower than similar extrusion trials using UNS C10100 copper performed by Kochis [11]. This discrepancy is not entirely attributed to only material variation. Extrusion dies used by Kochis were of a different design than those used in this work. The extrusion dies used in this work were 6 to 8% less efficient than those used by Kochis (for the 11-channel tube).

Ram force was predicted by the model to be within 7% of the maximum extrusion force. Ram speed was predicted by the model to be within 24% of experimental data. These discrepancies are largely due to variation in extrusion temperature and friction. By varying extrusion temperature by ±10°C of the average extrusion temperature and varying the friction factor by ±5% of its experimentally determined value, any discrepancies seen between the model and the extrusion data can be explained. These variations also show the sensitivity of the model to temperature and friction changes.

Four recommendations are made here for future work. First, UNS C12200 copper should be used for all future extrusion trials because of its believed lower flow stress and its wide use in industry for refrigeration applications. Second, extrusion dies of comparable design to those used by Kochis should be used in future extrusion trials.
because they have been found to have higher efficiencies. Third, any future compression testing on UNS C12200 should be performed within ±2°C of the desired temperature, and the ram speed should be recalculated for every .025 inches of compression. These test conditions would help reduce experimental uncertainty. Lastly, an appropriate temperature dwell time, at extrusion temperature but prior to extrusion, should be established for future extrusion trials. This dwell time should adequately allow for tooling and the extrudent material temperatures to reach equilibrium, therefore causing less variation in the temperature data. The purposed dwell time should be of a short enough period to minimize the effects of aging on the tooling materials.
CHAPTER 8

8.0 Summary/Conclusion

The development of a process to extrude thin-wall, multi-channel copper tube was advanced by 1) making apparatus improvements, 2) developing constitutive equation parameters from flow stress data for UNS C12200 copper, and 3) determining extrusion parameters (deformation efficiency and friction factor) from an array of extrusion trials. To achieve the objectives of this work an experimental apparatus, used in an MTS® 810 test machine, was modified/redesigned so that experimental work with UNS C12200 copper, for the determination of new extrusion process parameters, could be performed. Hot compression tests were performed on UNS C12200 copper compression specimens to determine flow stress at strain rates of 0.01 to 1.0 s\(^{-1}\) and at temperatures 700 and 750°C. Flow stress varied from 21 MPa (0.01 s\(^{-1}\) at 750 °C) to 51 MPa (1.0 s\(^{-1}\) at 700 °C). The experimental determination of these values allowed parameters for the Zener-Hollomon constitutive equation to be determined such that flow stress could be reasonably predicted within this range of temperature and strain rate. For these tests, the model predicted flow stress within 10%. These data were used in subsequent extrusion modeling and were capable of predicting extrusion conditions within a level of acceptable variability. Also, flow stress results for UNS C12200 copper were comparable to that of UNS C10100 copper, determined in previous work, with values generally about 5% lower. The lower flow stress of UNS C12200 is consistent with a lower activation energy (176 kJ/mol) than that of UNS C10100 (234 kJ/mol).
An array of extrusion trials were performed to determine the friction and efficiency parameters for a model that predicts the extrusion pressure required for a set of basic process parameters. Two different profiles (and hence, extrusion dies) were included in this testing. The methodology involved constant velocity extrusion trials to determine container friction factor, and constant force extrusion trials to determine deformation efficiencies in the extrusion dies. The friction factor was determined from the slope of the extrusion ram pressure – ram position data. These values ranged from 0.66 to 0.74. During the constant force tests, the ram velocity increased by approximately 5 times due to the reduction in container friction (from the shortening billet in the container). The efficiency value that provided the best fit of the model over this velocity range was taken as the overall deformation efficiency in the extrusion die. These efficiency values correlated well with constant velocity extrusion trials. The ram velocity model correlated reasonably well with the experimental data, generally within 20%, however it deviated by as much as 24% at the extreme velocities of the trials. Nevertheless, the efficiency and friction factor values resulted in ram pressure predictions within 7% of the experimental data, and maximum pressure predictions within 7%. The ability to predict extrusion pressure is important in the development of future work. The newly developed parameters, of this work, show the ability of the model to predict maximum extrusion force within an acceptable level of reason.

The discrepancies of the extrusion model from the extrusion data, for both speed and pressure was attributed to inherent uncertainties in temperature and variability in the friction condition. A temperature uncertainty of ±10°C and friction factor uncertainty of
±5% was shown to account for the discrepancies between the models and experimental data.
REFERENCES


