Experimental and Constitutive Model Study on Dynamic Mechanical Behavior of H96 Brass Alloy

Ping Zhou, Xiangyan Luo and Baojun Liu
Aviation Maintenance NCO Academy, Air Force Engineering University, Xinyang 464000, China
Email: zhouping79@outlook.com

Abstract. To study the mechanical response of H96 brass, the quasi-static and dynamic compression experiments were performed by the universal-testing machine and the split Hopkinson pressure bar system. The selected temperature range was 293 K ~ 873 K, the selected strain-rate range was 0.001 /s ~ 6000 /s and the strains were up to 0.6. It was shown that, this alloy has remarkable strain hardening character, and this alloy is sensitive to strain-rate and temperature. In addition, the Dynamic Strain Aging phenomenon of this alloy occurs under the condition of 473 K and 0.001 /s. According to the testing results and the thermal-activation dislocation mechanism, a plastic flow constitutive model was brought forth. This constitutive model can predict and describe the plastic flow behavior of H96 brass alloy in a wide range of temperature and strain rate.

Keywords. H96 brass alloy, temperature, strain rate, mechanical behaviour, constitutive model.

1. Introduction
The application of brass alloys is very extensive in many industrial sectors for good mechanic and casting properties. It is known that, most of the previous studies were focused on static domain, such as continuous extrusion [1-2], thermal deformation [3-4], forming process [5-6], resilience [7-8] and so on. Therefore, it is of great theoretical and practical value to explore the dynamic mechanical responses of the brass alloys. To investigate the dynamic mechanical behavior of H96 brass, the universal-testing machine and the separated Hopkinson pressure bar system (SHPB) with high temperature synchronous assembly system were used for the compression experiments with different temperatures (293 K, 373 K, 473 K, 673 K, 873 K) and different strain rates (0.001 /s, 0.1 /s, 3000 /s, 6000 /s). The temperature sensitivity and strain-rate sensitivity of plastic flow behaviour were analyzed. A physically-based constitutive model was brought forth. This constitutive model can be used to describe the mechanical behavior of H96 brass alloy over a wide range of temperature and strain-rate. These results from this work can provide reference for research of such materials.

2. Experimental Procedures

2.1. Material and Samples
The investigated material in this work was selected to be industrial H96 brass alloy (single-phase brass, simple Cu-Zn Alloy). Under room temperature, the microstructure of this alloy is FCC crystallographic structure. The composition of the H96 brass alloy (in wt pct) is: 95.0~97.0 Cu, 0.10 Fe, 0.03 Pb, 0.5 Ni, 2.37~4.37 Zn. The samples of H96 brass alloy used in quasi-static and dynamic experiments were cylindrical samples and the dimensions were approximately Φ5 mm × 4 mm. Aim at getting the good
parallelism and perpendicularity, waterproof abrasive papers with small granularity (800#, 1500# and 3000#) were used to polish the two end faces of all static and dynamic compression samples.

2.2. Compression Experiments
The static compression experiments (0.001 /s and 0.1 /s) were carried out by CRIMS DNS100 universal-testing machine. The selected temperatures in the quasi-static compression experiments were 293 K, 373 K, 473 K, 673 K and 873 K, respectively. Two heat-resisting ceramics bars were used to load the samples and molybdenum disulphide, having good lubricating property, was used as a good solid lubricant. The deformation of all static compression samples was measured by the linear variable differential transducer, which was installed over the CRIMS DNS100 universal-testing machine.

The dynamic compression tests (3000 /s and 6000 /s) were performed by an enhanced split Hopkinson pressure bar system (SHPB) [9]. The selected temperatures for the dynamic compression experiments were also 293 K, 373 K, 473 K, 673 K and 873 K, respectively. This enhanced SHPB can preheat one specimen within the furnace, while the incident bar and the transmission bar are placed outside the high-temperature zone. Then the incident bar and the transmission bar are automatically brought into contact with the sample, just before the stress wave arrives at the end of the incident bar. The needed high temperatures in the dynamic compression experiments were produced through the radiant-heating furnace.

3. Results and Discussion
Figure 1 show the measured flow stress-strain curves, which were tested under 293 K ~ 873 K and 0.001 /s ~ 6000 /s. It was shown that the flow stress increases rapidly with the increasing strain, especially at relatively low temperatures. The measured mechanical behavior exhibits significant strain hardening effect. The H96 brass alloy has an FCC crystallographic structure. The plastic flow behavior of the materials with FCC structure appears by the slip of edge dislocations. Meanwhile, the start-up of plastic flow of the materials with FCC structure is easier than the materials with BCC structure, whose plastic flow appears by slip of screw dislocation. Thus, there’s obvious strain hardening effect for the H96 brass alloy, but the strain hardening effect will lower at the increasing temperatures.

Figure 2 and 3 show the flow stress at different temperatures and different strain rates. It can be seen from figures 2 and 3 that the plastic flow stress increases rapidly with the increasing temperatures and strain rates, and the plastic flow stress increases obviously with the increasing strain rates when the true strain is 0.2. Such observation indicates a significant strain-rate sensitivity of this alloy. Aim at further investigating the strain-rate sensitivity of this alloy, the plastic flow stress as a function of strain rate with the temperature of 873 K and the strain of 0.05 is plotted in Figure 3. Obviously, the stress increases rapidly with the strain rates and there is an approximately linear relationship between them. Such observation suggests the viscous drag effect of H96 brass alloy. This effect is caused by the mobile dislocation, which is pulled by phonons and electrons [10, 11].

Figure 4 show the flow stress with respect to temperatures under static compression. It can be seen that the flow stress decreases with the increasing temperatures, especially under the low strain rates. Such observation indicates a significant temperature sensitivity of this alloy. The stress decreases more slowly under the condition of 0.001 /s, 473 K and 0.1 /s, 673 K. This phenomenon occurs due to the Dynamic Strain Aging (DSA) effect. The Dynamic Strain Aging effect is hardening effect that appears in metals or alloys [12].

4. Constitutive Model
For the purpose of describing the strain-stress relationship of H96 brass alloy under a wide range of temperatures and strain rates, a constitutive model including physical conception was brought forth. This constitutive model was built according to the dislocation kinematics and the dislocation kinetics, and there are some parameters to describe physical characters of material in this model. According to the concept of dislocation kinetics of metal and alloy, the flow stress (τ) can be divided into two terms:
the thermal term $\tau^*(\varepsilon, \dot{\varepsilon}, T)$ and the athermal term $\tau^a(\varepsilon)$. So, the flow stress can be expressed as an addition of these two terms:

$$\tau = \tau^a(\varepsilon) + \tau^*(\varepsilon, \dot{\varepsilon}, T)$$  \hspace{1cm} (1)

The athermal term $\tau^a(\varepsilon)$ relies on elastic stress, impurity, etc., and not the temperature or the strain-rate. The athermal stress always equals to specific stress value at a certain high temperature. The flow stress decreases to one very small value when the temperature exceeds the specific value. According to the phenomenological theory and the exponential relation between the flow stress and the strain, then the athermal stress term $\tau^a(\varepsilon)$ can be defined by equation (2).

![Figure 1](image1.png)

**Figure 1.** Flow stress-strain curves under different strain rates and different temperatures.

![Figure 2](image2.png)

**Figure 2.** Flow stress at different temperatures.

![Figure 3](image3.png)

**Figure 3.** Flow stress at different strain rates.
\[ \tau^* \approx a_0 + a_1 \varepsilon^{n_1} + \ldots \]  \hspace{1cm} (2)

in which \( a_0, a_1, \ldots \) and \( n_1, \ldots \) are material constants that can be fitted with the experimental result.

The athermal stress term \( \tau'(\varepsilon, \dot{\varepsilon}, T) \) denotes the resistance force for the dislocations getting over short-distance obstructions. This stress can be expressed as a function of strain-rate, temperature and internal parameters that characterize metal’s or alloy’s microstructure. For the purpose of developing the expression among \( \tau' \) and, \( \gamma, \gamma , T \), assuming that \( \Delta G \) is the free activation energy that the dislocations need to get over, according to the dislocation kinematics and the dislocation kinetics, the expression is given [13]:

\[ \Delta G = G_0 \left[ 1 - \left( \frac{\tau^*}{\tau_c} \right)^p \right]^q \]  \hspace{1cm} (3)

where \( 0 < p \leq 1 \) and \( 0 < q \leq 1 \) define the resistance for dislocations getting over short-distance obstructions; \( \tau_c \) represents the critical stress under the condition of 0 K; \( G_0 \) denotes the free activation energy on which the dislocations depend to get over obstructions. With regard to the copper alloys, \( G_0 = 2eV/atom \). Then the mathematic expression about the strain-rate \( \dot{\varepsilon} \) and the free activation energy \( \Delta G \) can be written in the form of Orawan expression:

\[ \dot{\varepsilon} = \dot{\varepsilon}_0 \exp \left( -\frac{\Delta G}{kT} \right) \]  \hspace{1cm} (4)

in which \( \dot{\varepsilon}_0 \) is the reference strain rate, \( k \) represents the Boltzmann constant and equals \( 1.38 \times 10^{-23} J/K \).

Using expressions (3) and (4), the following expression can be developed:

\[ \tau^* = \tau_c \left[ 1 - \left( \frac{kT}{G} \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{1/q} \right]^{1/p} \]  \hspace{1cm} (5)

Based on the effect of dislocations’ accumulation on plastic flow stress, the following expression was brought forth [14]:

\[ \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} = \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} + \ln f(\varepsilon, T) \]  \hspace{1cm} (6)

where \( \ln f(\varepsilon, T) = 1 + a'_0 \left[ 1 - \left( \varepsilon \varepsilon_m \right)^2 \right]^{1/2} \) defines the effect of dislocation density on stress. Due to the corresponding relationship between the dislocation density and the strain, the strain can be used to represent the dislocation density. \( a'_0 \) relies upon the crystallographic structure and \( T_m \) is the melting temperature of H96 brass alloy.

Combining these above expressions, a physically-based constitutive model can be expressed as:

\[
\begin{align*}
\tau^* &= \tau_c \left[ 1 - \left( \frac{kT}{G} \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} + \ln f(\varepsilon, T) \right)^{1/q} \right]^{1/p} \cdot f(\varepsilon, T) + a_1 \varepsilon^{n_1} \\
f(\varepsilon, T) &= 1 + a'_0 \left[ 1 - \left( \frac{T}{T_m} \right)^2 \right]^{1/2} \frac{1}{\varepsilon_m}
\end{align*}
\]  \hspace{1cm} (7)
Substituting the compression experimental result data and the known physical constants of this material into equation (7), the unknown parameters for H96 brass alloy can be fitted (as shown in table 1).

Table 1. Parameter values for H96 brass alloy.

| $\bar{\epsilon}$ (MPa) | $k/\Gamma_0$ | $\gamma_0$ (s) | $a_0$ | $a_1$ | $m$ | $n$ | $p$ | $q$ | $T_m$ (K) |
|------------------------|-------------|----------------|--------|--------|-----|-----|-----|-----|----------|
| 39                     | 3.3×10^{-3} | 1.0×10^{10}   | 15     | 100    | 2   | 0.2 | 0.5 | 1   | 1356     |

5. Conclusions
According to the compression experimental result, the dislocation kinematics and kinetics, and taking into account the effect of viscous drag, a physically-based strain-stress constitutive model for H96 brass alloy is brought forth. Compared with other constitutive models, this constitutive model can describe the mechanical behavior over a wide range of temperatures and strain rates.

References
[1] Jiang H 2010 Study on numerical simulation and deforming microstructure of H65 brass during continuous extrusion Dalian: Dalian Jiaotong University
[2] Sui X, Song B, LI Bing, Yun X and Gao F 2009 Characteristic of microstructure and properties evolution of H65 brass alloy during continuous extrusion process The Chinese Journal of Nonferrous Metals 19 (6) 1049-1054
[3] Wang Y, Gong B and Li B 2008 Flow stress of H65 brass alloy during hot compression deformation Journal of Plasticity Engineering 15 (6) 113-117
[4] Zhang H, Zhang H, Peng D and Lin Q 2003 Rheologic stress of C194 copper alloy under hot compression deformation Natural Science Journal of Xiangtan University 25 (3) 82-86
[5] Ni H 2005 Research on Microforming of H62 Brass by Upsetting Nanjing: Nanjing University of Aeronautics and Astronautics pp 5-6
[6] Li P, Zhao B and Xue K 2015 Mechanical properties of copper alloy during micro-plastic forming and its constitutive model Chines Journal of Solid Mechanics 36 (5) 401-409
[7] Liu Y, Ren J, Zhu Y and Yang H 2012 Stress-strain analysis of bending and springback for thin-wall rectangular tube of H96 brass Froging & Stamping Technology 37 (1) 146-148
[8] Zhu Y, Liu Y and Yang H 2012 Sensitivity of springback and section deformation to process parameters in rotary draw bending of thin-walled rectangular H96 brass tube Trans. Nonferrous Met. Soc. China 22 2233-2240
[9] Guo W 2006 The split Hopkinson pressure bar technique of high temperatures and its application Journal of Experimental Mechanics 21 (4) 447-453
[10] Zerilli F J and Armstrong R W 1992 The effect of dislocation drag on the stress - strain behavior of FCC metals Acta Metal lurgicaet Materialia 40 (8) 1803-1808
[11] Nemat-Nasser S, Guo W G and Kihl D P 2001 Thermo mechanical response of AL-6XN stainless steel over a wide range of strain rates and temperatures Journal of Mechanical Physics Solid 49 1832-1846
[12] Qian K, Li X, Xiao L, Chen W, Zhang H and Peng K 2001 Dynamic strain aging phenomenon in metals and alloys Journal of Fuzhou University (Natural Science) 29 (6) 8-23
[13] Kocks U F, Argon A S and Ashby M F 1975 Thermodynamics and kinetics of slip: Progress in materials science New York: Pergamon Press pp 1-271
[14] Nemat-Nasser S and Li Y L 1998 Flow stress of FCC polycrystals with application to OFHC Cu Acta Materialia 46 565-577