Materials Research Express

PAPER

Mechanical properties and constitutive model of Sn-58Bi alloy

Kebin Zhang1, Wenbin Li1,2, Ping Song1, Changfang Zhao1 and Kewen Zhang3
1 School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, People’s Republic of China
2 Research Institute of Chemical Defense, Beijing 102205, People’s Republic of China
3 China Jikan Research Institute of Engineering Investigations and Design Co., LTD, Xi’an 710043, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: kb2018@njust.edu.cn, lackychang@njust.edu.cn, sp2016@njust.edu.cn, zhangkw93@qq.com and lwb2000cn@njust.edu.cn

Keywords: Sn-58Bi alloy, Johnson–Cook, SHPB, constitutive model

Abstract
Sn-58Bi alloy is a strain-rate-sensitive material. To study the mechanical properties of Sn-58Bi alloy, an MTS universal testing machine and split-Hopkinson pressure bar were used to conduct quasi-static and dynamic testing on Sn-58Bi alloy, obtaining the stress–strain curve of Sn-58Bi alloy at the strain rate of 0.001–6316 s−1. By comparing the tensile and compressive stress–strain curves of Sn-58Bi alloy under quasi-static conditions, it is found that Sn-58Bi alloy is brittle, with its tensile yield strength lower than its compressive yield strength. By comparing the compressive stress–strain curves of Sn-58Bi alloy at different strain rates, it is found that the yield strength of Sn-58Bi alloy increases with increasing strain rate, and a strain-hardening phenomenon is manifested at high strain rate. By revising the Johnson–Cook constitutive model, the constitutive model of Sn-58Bi alloy at different strain rates was established, with the calculated results of the model in good agreement with the experimental results.

1. Introduction
Sn-Bi alloy is widely used in the field of electronic packaging because of its low process temperature, high reliability and good compatibility with specific matrix. In the welding packaging of electronic devices, low process temperature can reduce the risk of thermal shock caused by thermal expansion mismatch between different materials of electronic devices [1]. Sn-Bi alloy, especially Sn-58Bi alloy with eutectic composition, is an ideal material for low temperature welding [2].

Because of the excellent properties of Sn-58Bi alloy, Sn-58Bi alloy is often used in the packaging of projectile electronic guidance components in the field of weapon manufacturing. In the process of projectile launching, the strain rate of the projectile parts reaches 103 s−1 [3]. Therefore, to study the reliability of Sn-58Bi alloy packaging for projectile electronic guidance components, it is very necessary to study the dynamic mechanical properties of Sn-58Bi alloy.

Researchers have studied the modifications and mechanical properties of Sn-Bi alloys to improve the mechanical properties of Sn-Bi alloys and meet the different requirements for Sn-Bi alloys in different industries. McCormack et al [4] found that adding small amounts of Ag to the Sn-Bi eutectic could refine the microstructure, significantly improving the tensile ductility of Sn-Bi alloy. El-Daly et al [5] studied the impact of Bi content on the microstructure and thermal and mechanical properties of eutectic Sn-Zn alloy. The results showed that the addition of Bi reduced the melting point and heat of fusion of Sn-9Zn solder alloy. As the Bi content increased, the tensile strength of the Sn-Zn alloy gradually increased. Hu et al [6, 7] studied the effect of stirring time on the solidified microstructure and mechanical properties of a semi-solid slurry of Sn-Bi alloy using mechanical stirring, and showed that the non-dendritic structure of Sn-Bi alloy could be obtained by the semi-solidification process, which significantly improved the elongation of Sn-Bi alloy. Peng et al [8] investigated the impact of multi-walled carbon nanotubes (MWCNTs) on the mechanical strength and ductility of Sn-58Bi alloy, revealing that Sn-58Bi-0.03CNTs (mass fraction, %) had better bending strength, tensile strength, and elongation than other composite materials with different CNT contents. Gao et al [9] studied the
influence of La2O3 content on the microstructure and mechanical properties of Sn-58Bi alloy and found that the addition of La2O3 inhibited the segregation of Bi-rich phases and reduced the brittleness of the solder alloy. The hardness of the solder alloy increased with the increasing amount of La2O3 added. Dan et al [10] investigated the influence of Bi content on the microstructure and mechanical properties of Sn-Bi alloys, and revealed that the hardness of Sn-xBi alloy first increased and then decreased with increasing Bi content. The hardness reached the maximum at a Bi content of 7.25 wt.%. Among Sn-14.5Bi, Sn-29Bi, and Sn-58Bi alloys, Sn-14.5Bi had the highest bending fracture energy, whereas Sn-29Bi had the lowest. Yamauchi et al [11] found, by conducting quasi-static testing, that the elongation of Sn-Bi alloy increased with increasing temperature and decreased with increasing strain rate. Xu et al [12] studied the mechanical deformation mechanism of eutectic Sn-Bi alloy through the combination of tensile test, in situ observation and nano-indentation. The results showed that the deformability of eutectic Sn-Bi alloy decreases at high strain rate, and the deformation mechanism changes from phase boundary correlation mechanism to dislocation slip mechanism. Yang et al [13] introduced the changes of wettability, melting properties, electromigration, mechanical properties, microstructure, intermetallic compound reaction and creep behavior of Sn-Bi alloy after adding Al, Cu, Zn, Ga, Ag, In, Sb and other elements, which provided a reference for the study of Sn-Bi-based alloy. Xu et al [2] studied the tensile mechanical properties of Sn-58Bi/Cu solder joints by uniaxial micro-force testing system. The results revealed that the fracture behavior of Sn-58Bi/Cu solder joints is ductile fracture at low strain rate (5 × 10⁻⁴ ~ 1 × 10⁻³ s⁻¹) and brittle fracture at high strain rate (2 × 10⁻³ ~ 1 × 10⁻² s⁻¹). Wentlent et al [14] used a joint stage micromechanical tester to carry out ball shear tests on SAC-SnBi samples in reflux and aging state under a series of strain rates. The results found that SAC-SnBi samples show obvious brittle failure at higher strain rates.

However, the aforementioned research has been primarily aimed at the quasi-static (1 × 10⁻⁴ ~ 1 × 10⁻¹ s⁻¹) mechanical properties and the modifications of microstructure properties of Sn-Bi alloy. There have been few studies on static to dynamic mechanical properties and constitutive model of Sn-58Bi alloy. To study static and dynamic mechanical properties of Sn-58Bi alloy, a universal testing machine (MTS Systems, Inc., Eden Prairie, MN, USA) and split-Hopkinson Pressure bar (SHPB) were used to compare the tensile and compressive mechanical properties of Sn-58Bi alloy under quasi-static conditions. The deformation behaviour of Sn-58Bi alloy at strain rates ranging from 0.001 to 6316 s⁻¹ was also investigated. In this paper, the constitutive model of Sn-58Bi alloy at 0.001–6316 s⁻¹ was obtained by improving the Johnson–Cook (JC) model [15], the results of which were in good agreement with experimental results. Through the experimental study on the mechanical properties of Sn-58Bi alloy, it can provide data and theoretical support for the influence mechanism of Sn-58Bi alloy on the packaging reliability when it is used as the packaging material of projectile electronic guidance components, and also provide reference for the related research on the mechanical properties of Sn-58Bi alloy.

2. Experimental procedures

2.1. Materials and sample preparation

The material studied in this paper is a commercially produced Sn-58Bi alloy that is widely used in the electronic packaging industry. Sn-58Bi alloy was prepared by high-temperature melting and mixing. Sn ingot (42 wt.%) and Bi ingot (58 wt.%) were sealed in a quartz tube that was heated to 500 °C and maintained at that temperature in a vacuum furnace. The melted solder alloy was then cooled to 400 °C and cast at room temperature to obtain Sn-58Bi alloy.

The quasi-static tensile, quasi-static compression, and dynamic compression specimens of Sn-58Bi alloy were obtained by lathe turning. The specific dimensions of the specimens are shown in figure 1. The dynamic compression specimen is designed as a cylinder with a diameter D = 6 mm and a height H = 3 mm. The aspect ratio H/D = 0.5 can well reduce the influence of the inertia and friction effects of the end surface of the dynamic compression specimen [16]. The prepared specimens were stored at room temperature for 48 h to eliminate the residual stress of processing before testing [17].

2.2. Quasi-static testing

To compare the tensile and compressive mechanical properties of Sn-58Bi alloy, quasi-static mechanical experiments on Sn-58Bi alloy were carried out on the MTS testing machine. The quasi-static compression tests were performed at constant compression rates of 1.2, 12, and 120 mm min⁻¹, and quasi-static tensile tests were performed at constant tensile rates of 2.16, 21.6, and 216 mm min⁻¹. The strain rate of specimen deformation was calculated according to the formula \( \dot{\varepsilon} = \frac{v}{L} \). Where \( \dot{\varepsilon} \) is the displacement rate of the indenter and \( L \) is the initial gauge length of the specimen.
When processing the test data, the true stress and strain of the specimen were calculated according to the load data recorded by the sensor and the displacement data of the indenter, and the true stress-strain curve was drawn. Each test was repeated three times and averaged.

2.3. Dynamic testing

The SHPB apparatus (see figure 2 for a schematic) was used to test the dynamic compressive mechanical properties of Sn-58Bi alloy.

The bars in the experiments were all made of 18Ni steel with the elastic modulus of the bar material $E_0 = 210$ GPa and the density $\rho = 8.4 \text{ g cm}^{-3}$. The diameter $d$ of the striker, incident, and transmitted bars was 14.5 mm, and their lengths were 400, 1500, and 1500 mm, respectively. According to the strain signals $\varepsilon_i(t)$ and $\varepsilon_t(t)$ obtained by the strain gauges on the incident and transmitted bars, the engineering stress $\sigma_E$, the engineering strain $\varepsilon_E$, and the nominal strain rate $\dot{\varepsilon}$ of the material during the deformation process were calculated as follows:

\[
\dot{\varepsilon} = -\frac{2C_0}{L_s} \varepsilon_i(t),
\]

\[
\varepsilon_E = \int_0^t \dot{\varepsilon} dt,
\]

\[
\sigma_E = \frac{A_0E_0}{A_S} \varepsilon_t(t),
\]

where $A_s$ and $L_s$ are the initial cross-sectional area and length of the specimen, respectively, and $C_0$, $A_0$, and $E_0$ are the elastic wave velocity, cross-sectional area, and elastic modulus of the bar, respectively. The obtained engineering stress and strain were transformed into true stress $\sigma_T$ and true strain $\varepsilon_T$. The test at the same strain rate was repeated for 3 times, and the average value was taken to ensure the accuracy of the experimental data.
3. Results and discussion

3.1. Quasi-static experiments

The purpose of quasi-static testing is to compare the tensile and compressive mechanical properties of Sn-58Bi alloy. As shown in figures 3 and 4, the true stress–strain curves of Sn-58Bi alloy at strain rates of 0.001, 0.01, and
0.1 s\(^{-1}\) at room temperature were obtained by processing the data from the quasi-static tensile and compression testing. Table 1 summarizes the mechanical properties obtained in testing.

According to figures 3 and 4, Sn-58Bi alloy has no evident yield limit. In this paper, the stress value of 0.2\% residual deformation was considered its yield limit [18]. Both compression and tensile yield stresses of Sn-58Bi alloy show a strain-rate effect. As the strain rate increases, the yield stress of the material increases while the elastic modulus of the alloy exhibits no strain-rate effect.

By comparing the tensile and compressive mechanical properties of the alloy in table 1, it can be seen that the tensile yield stress of Sn-58Bi alloy is lower than that of compression at the same strain rate. This illustrates that the content of Bi in Sn-58Bi alloy is high, which shows a certain degree of brittleness [9]. Numerically, the compressive yield stress of Sn-58Bi alloy is 1.38, 1.22, 1.21 times of the tensile yield stress at strain rates 0.001 s\(^{-1}\), 0.01 s\(^{-1}\) and 0.1 s\(^{-1}\), respectively. The tensile property of Sn-58Bi alloy is poor, which is mainly due to the micro-crack under very small load in the tensile process. Once the crack is formed in the tensile process, it will propagate rapidly and cause the sample to crack immediately. When the alloy is under pressure, even if there are cracks, it will not propagate to crack immediately, so the tensile yield stress of Sn-58Bi alloy is lower than the compressive yield stress.

From table 1, it can also be seen that as the strain rate increases, the tensile strength of the alloy increases, the elongation decreases, and the brittleness increases. It was also found that Sn-58Bi was eventually compressed into a pie shape without being crushed during quasi-static compression testing at the strain-rate range of 0.001–0.1 s\(^{-1}\).

### 3.2. Dynamic experiments

It was found in the aforementioned investigation that the elastic modulus of Sn-58Bi alloy has neither a strain-rate effect nor yield limit. When a material is subjected to dynamic compression testing by the SHPB, it is difficult to achieve a constant strain rate in the elastic stage of the material. The strain rate is continuously in the rising stage, causing errors in the measured elastic modulus [19]. Therefore, per provisions of the ASTM E21-2009 standard, the true stress corresponding to the 0.2\% residual deformation of the specimen was taken as the yield strength of the material, and the data before the yield point were deleted so that the compressive true stress–true strain curve at a strain rate of 0.001–6316 s\(^{-1}\) was converted into an equivalent stress–equivalent plastic strain curve [20], as shown in figure 5.

From figure 5, it is revealed that, at high strain rates (2499–6316 s\(^{-1}\)), Sn-58Bi alloy exhibits a strain-hardening effect, and the equivalent stress increases with increasing equivalent plastic strain. This strain-hardening phenomenon is not evident under quasi-static conditions. At high strain rates, there is also a strain-rate effect in Sn-58Bi alloy, the yield stress of which increases with increasing strain rate. It was also observed in the experiments that the Sn-58Bi alloy specimens were all crushed after SHPB testing, indicating greater brittleness of the material at high strain rates.

### 3.3. Constitutive model

In 1983, Johnson and Cook proposed a constitutive equation (the JC constitutive model) suitable for describing the stress–strain relationship of materials at high temperatures and strain rates [15]. The model considers the strain-hardening, strain-rate, and temperature effects on equivalent stress. The model uses three mutually independent items to represent the relationships between strain, strain rate, and temperature and equivalent stress. The effects of the three relationships are coupled by multiplying them, as shown in the form

\[
\sigma = (A + B\dot{\varepsilon}_p^n)(1 + C \ln \dot{\varepsilon}^*)\left(1 - T^m\right)
\]

where \(\sigma\) is the initial yield stress at the reference strain rate and temperature, \(A\) and \(B\) and \(n\) the material strain-hardening coefficient and hardening exponent, respectively, \(\dot{\varepsilon}_p\) the plastic strain, and \(C\) the material strain-rate-strengthening parameter. \(\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0\) is a dimensionless ratio of the strain rate to the reference strain rate, where

\[
\dot{\varepsilon}_0 = \frac{\sigma_0}{E}
\]

Table 1. Quasi-static mechanical properties of Sn-58Bi alloy.

| Strain rate (s\(^{-1}\)) | Elastic modulus (GPa) | Yield stress \(\sigma_{0.2}\) (MPa) | Tensile strength (MPa) | Elongation |
|--------------------------|----------------------|----------------------------------|-----------------------|-----------|
| Tensile                   |                      |                                  |                       |           |
| 0.001                    | 7.87 ± 0.54          | 44.79 ± 0.62                     | 60.22 ± 0.74          | 119.70%   |
| 0.01                     | 7.50 ± 0.37          | 56.77 ± 0.41                     | 73.62 ± 0.57          | 116.54%   |
| 0.1                      | 7.92 ± 0.41          | 58.65 ± 0.25                     | 75.04 ± 0.36          | 104.90%   |
| Compression              |                      |                                  |                       |           |
| 0.001                    | 14.55 ± 0.88         | 61.96 ± 0.43                     |                       |           |
| 0.01                     | 14.79 ± 0.74         | 69.18 ± 0.50                     |                       |           |
| 0.1                      | 14.46 ± 0.29         | 71.25 ± 0.35                     |                       |           |

It was found in the aforementioned investigation that the elastic modulus of Sn-58Bi alloy has neither a strain-rate effect nor yield limit. When a material is subjected to dynamic compression testing by the SHPB, it is difficult to achieve a constant strain rate in the elastic stage of the material. The strain rate is continuously in the rising stage, causing errors in the measured elastic modulus [19]. Therefore, per provisions of the ASTM E21-2009 standard, the true stress corresponding to the 0.2\% residual deformation of the specimen was taken as the yield strength of the material, and the data before the yield point were deleted so that the compressive true stress–true strain curve at a strain rate of 0.001–6316 s\(^{-1}\) was converted into an equivalent stress–equivalent plastic strain curve [20], as shown in figure 5.

From figure 5, it is revealed that, at high strain rates (2499–6316 s\(^{-1}\)), Sn-58Bi alloy exhibits a strain-hardening effect, and the equivalent stress increases with increasing equivalent plastic strain. This strain-hardening phenomenon is not evident under quasi-static conditions. At high strain rates, there is also a strain-rate effect in Sn-58Bi alloy, the yield stress of which increases with increasing strain rate. It was also observed in the experiments that the Sn-58Bi alloy specimens were all crushed after SHPB testing, indicating greater brittleness of the material at high strain rates.

### 3.3. Constitutive model

In 1983, Johnson and Cook proposed a constitutive equation (the JC constitutive model) suitable for describing the stress–strain relationship of materials at high temperatures and strain rates [15]. The model considers the strain-hardening, strain-rate, and temperature effects on equivalent stress. The model uses three mutually independent items to represent the relationships between strain, strain rate, and temperature and equivalent stress. The effects of the three relationships are coupled by multiplying them, as shown in the form

\[
\sigma = (A + B\dot{\varepsilon}_p^n)(1 + C \ln \dot{\varepsilon}^*)\left(1 - T^m\right)
\]

where \(A\) is the initial yield stress at the reference strain rate and temperature, \(B\) and \(n\) the material strain-hardening coefficient and hardening exponent, respectively, \(\dot{\varepsilon}_p\) the plastic strain, and \(C\) the material strain-rate-strengthening parameter. \(\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0\) is a dimensionless ratio of the strain rate to the reference strain rate, where
is the reference strain rate. $T^* = (T - T_r) / (T_m - T_r)$ is the homologous temperature, $T_r$ the reference temperature, $T_m$ the melting temperature, and $m$ the thermal softening parameter.

From the above research, it can be concluded that Sn-58Bi alloy has strain-strengthening and strain-rate-strengthening effects. Therefore, the JC constitutive model was used in the present work to fit the stress–strain curve of the material. In this study, the influence of the ambient temperature was not considered, so the temperature function $(1 - T^*)^m$ was set to 1.

### 3.3.1. Yield stress

When the yield stress of Sn-58Bi alloy at different strain rates is predicted using the JC constitutive model at the reference strain rate $\dot{\varepsilon}_0$ of $0.001 \text{ s}^{-1}$, the plastic strain $\varepsilon_p = 0$ in equation (4), which is transformed into

$$\sigma_{0.2} = A (1 + C \ln \dot{\varepsilon}^*).$$  \hspace{1cm} (5)

Equation (5) is used to fit the yield stress of Sn-58Bi alloy at different strain rates (as figure 6). Figure 6 shows that the logarithm of yield stress and strain rate of Sn-58Bi alloy is obviously nonlinear in the strain rate range $(0.001 \sim 6316 \text{ s}^{-1})$, while equation (5) describes the yield strength $\sigma_{0.2}$ and $\ln \dot{\varepsilon}$ as a linear relationship, which leads to the deviation between the predicted results of the equation and the experimental values.

Compared with the linear simplified form of JC constitutive model (equation (5)), Huh and Kang [21] proposed a one-variable quadratic strain-rate function (equation (6)) based on the simplified linear form of the...
By using equation (6) to fit the experimental data (figure 7), it can be seen that the strain-rate-related function proposed by Huh and Kang has a better correlation with the experimental data. The R square of the fitting result of equation (6) is greater than that of equation (5).

\[
\sigma_{0.2} = A(1 + C_1 \ln \dot{\varepsilon}^* + C_2 \ln \dot{\varepsilon}^{*2}).
\]

Although the fitting results of equation (6) have better correlation with the experimental data than equation (5). However, there is still a certain deviation between the results of the dynamic test (2499 ~ 6316 s\(^{-1}\)) in figure 7 and the predicted results. To more accurately predict the nonlinear relationship between the yield stress and strain rate of Sn-58Bi alloy, the Eyring theory \[22\] was used in this paper, and a constitutive model was proposed as shown in the following equation:

\[
\sigma_{0.2} = A + D \sinh^{-1}(\dot{\varepsilon}/\dot{\varepsilon}_0)E,
\]

where \(A\) is the initial yield stress at the reference strain rate and temperature, and \(D\) and \(E\) the experimentally determined material constants.

Figure 8 shows the results obtained by fitting equation (7). Comparing figure 7 with figure 8, it can be found that the R square of the fitting result of equation (7) is larger than that of equation (6), and the dynamic test results are closer to the predicted results. This shows that equation (7) is more suitable to describe the relationship between yield stress and strain rate of Sn-58Bi alloy, especially in the stage of high strain rate.

3.3.2. Plastic stage
From the above analyses, it is found that the strain-hardening behaviour of Sn-58Bi alloy under dynamic conditions is different from that under quasi-static conditions. Therefore, separate investigations on the quasi-static and dynamic strain-hardening behaviours of the material were carried out in the present work. The reference strain rate was 0.001 s\(^{-1}\) for quasi-static conditions and 2499 s\(^{-1}\) for dynamic conditions. When the strain rate is the reference strain rate, \((1 + C \ln \dot{\varepsilon}^*) = 1\), equation (4) can be simplified as

\[
\sigma = A + B\dot{\varepsilon}_p^n.
\]

Figure 9 shows the fitting results obtained by equation (8).

3.3.3. Constitutive equations and parameters
Based on the above analyses, the constitutive equations of the compressive mechanical properties of Sn-58Bi alloy at different strain rates are summarized as follows:

\[
\sigma = \begin{cases} 
E_0, & \sigma < \sigma_{0.2} \\
A + D \sinh^{-1}(\dot{\varepsilon}/\dot{\varepsilon}_0)E, & \sigma = \sigma_{0.2}; \\
\sigma_{0.2} + B\dot{\varepsilon}_p^n, & \sigma > \sigma_{0.2}
\end{cases}
\]

where \(E_0\) is the elastic modulus of the material, \(A\) the initial yield stress at the reference strain rate, \(D\) and \(E\) the experimentally determined material constants, \(B\) and \(n\) the material strain hardening coefficient and hardening.
Figure 8. Relation curve between yield stress and strain rate (equation (7)).

Figure 9. Theoretical and experimental equivalent stress–equivalent plastic strain curves of Sn-58Bi alloy.
exponent, respectively, and \( \varepsilon_p \) the plastic strain. The constitutive parameters obtained by experimental fitting are summarized in Table 2.

### 3.3.4. Verification

The equivalent stress–equivalent plastic strain curve of Sn-58Bi alloy at different strain rates is predicted by equation (9) and the parameters in Table 2. It can be seen from Figure 10 that when the plastic strain \( \varepsilon_p < 0.06 \), the predicted results of the model are in good agreement with the experimental results. When the plastic strain \( \varepsilon_p > 0.06 \), there is a deviation of more than 6% between the test results and the predicted results of the strain rate \( 4643 \sim 6316 \text{ s}^{-1} \). This is due to the fact that when the strain rate continues to increase above \( 4643 \text{ s}^{-1} \), the specimen will deform in a very short time and release more heat at the same time, resulting in a rapid increase in the deformation temperature of the material, and the thermal effect leads to the softening of the material and the decrease of stress. The Sn-58Bi alloy studied in this paper is a brittle material, and the strain range of the constitutive model is \( 0 \sim 0.14 \). The stage of material softening caused by adiabatic temperature rise is small, so the effect of adiabatic temperature rise is ignored in this paper.

### 4. Conclusions

In this paper, an MTS universal testing machine and SHPB testing apparatus were used to conduct mechanical tests on Sn-58Bi alloy, obtaining the stress–strain curves of the material at different strain rates. Based on the stress–strain curve of Sn-58Bi alloy, its mechanical properties were analysed and the constitutive model of the material established. The following conclusions were drawn.

At the same strain rate in the quasi-static experiments, the compressive yield stress of Sn-58Bi alloy is higher than the tensile yield stress. As the strain rate increases, the elongation of Sn-58Bi alloy decreases with more prominent brittleness.

There is a strain-rate effect in Sn-58Bi alloy in which the yield stress of the material increases with increasing strain rate. The compressive yield stress at different strain rates has a nonlinear relationship with the logarithm of the strain rate, which can be better described by the Eyring theory than by the JC constitutive model. The strain-hardening behaviour of Sn-58Bi alloy under dynamic conditions is more prominent than that under quasi-static conditions.

---

**Figure 10.** Sn-58Bi alloy equivalent stress–equivalent plastic strain curves at different strain rates.

**Table 2.** Constitutive equation parameters.

|        | \( E_0 \) (GPa) | \( A \) (MPa) | \( D \) (MPa) | \( E \) | \( B \) (MPa) | \( n \) |
|--------|-----------------|---------------|--------------|------|-------------|------|
| 0.001–0.1 s\(^{-1}\) | 14.6 | 61.96 | 3.86E-6 | 0.16 | 24.71 | 0.38 |
| 2499–6316 s\(^{-1}\) | 425.93 | 0.81 |

---

Mater. Res. Express 9 (2022) 016505 K Zhang et al
conditions. A revised constitutive model of Sn–58Bi alloy at different strain rates was established based on the JC constitutive model. The calculated results of the model are in good agreement with experimental results.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Kebin Zhang https://orcid.org/0000-0002-5722-3147

References

[1] Schetty R and Ronal S 1998 Pb-free external lead finishes for electronic components Tin-bismuth and tin-silver. V Ient/Imc Symposium IEEE
[2] Hu X, Xiao Y, Li Y, Qiang H, Yi L and Min Z 2014 Effect of strain rate on interfacial fracture behaviors of Sn–58Bi/Cu solder joints J. Mater. Sci. 25 57–64
[3] Li M 2017 Study on transient characteristics of initial motion of projectile in bore Nanjing University of Science and Technology
[4] McCormack M, Chen HS, Kammlott GW and Jin S 1997 Significantly improved mechanical properties of Bi–Sn solder alloys by Ag-doping J. Electron. Mater. 26 854–8
[5] El-Daly A A, Swilem Y, Makled M H, El-Shaarawy M G and Abdrahboh A M 2009 Thermal and mechanical properties of Sn–Zn–Bi lead-free solder alloys Journal of Alloys & Compounds 484 134–42
[6] Hu Y J, Zhong B Q, Li F, Cheng X L, Xiao X T, Li Y, He J N, He Y C, Zheng C C and Zheng Y C 2011 Microstructure and mechanical properties of semi-solid Sn–58Bi alloy Key Eng. Mater. 480–481 687–90
[7] Li F, Hu Y J, Cheng X L and Xiao X T 2010 Microstructure and mechanical properties of Sn–Bi alloy treated in the semi-solid state by mechanical stirring process Advanced Materials Research 150–151 4
[8] Peng H E, Xiao-Chun L, Lin T S, Hai-Xin L I, Jing A N, Xin M A, Feng J C, Yan Z, Qi L I and Qian Y Y 2012 Improvement of mechanical properties of Sn–58Bi alloy with multi-walled carbon nanotubes Transactions of Nonferrous Metals Society of China 22 692–6
[9] Gao L, Wang J, Lin T, Peng H and Lu F 2014 Improvement of microstructure and mechanical properties of Sn–58Bi alloy with La2O3 Int. Conf. on Electronic Packaging Technology
[10] Dan Y, Du C, Wu M and Lai Z 2015 Microstructure and mechanical properties of Sn–x Bi solder alloy J. Mater. Sci., Mater. Electron. 26 3629–37
[11] Yamauchi A, Ida K, Fukuda M and Yamaguchi T 2018 Tensile properties of Sn–Bi lead-free solder alloys Solid State Phenomena 273 72–6
[12] Xu C, Jian Z, Feng X and Yao Y 2016 Mechanical deformation behavior and mechanism of Sn–58Bi solder alloys under different temperatures and strain rates Materials Science & Engineering A 662 251–7
[13] Yang F, Zhang L, Liu Z, Zhong S J, Ma J and Bao L 2016 Properties and microstructures of Sn–Bi–X lead-free solder alloys Advances in Materials Science and Engineering 2016, (2016-12-29) 2016 1–15
[14] Wentlent L A, Wilcox J and Ding X 2019 Strain rate sensitivity of mixed SAC-SnBi solder joints Int. Symp. on Microelectronics 2019, 000480–7
[15] Johnson G R 1983 A constitutive model and data for materials subjected to large strains, high strain rates, and high temperatures Proc. 7th Inf. Sympo. Ballistics 21, 541–7
[16] Yang Z 1985 Optimum size of specimens in dynamic mechanical properties test of transversely isotropic materials Explosion and Impact 5 2
[17] Wang H D, Zhu L N and Xing Z G 2002 A tension split Hopkinson bar for investigating the dynamic behavior of sheet metals Exp. Mech. 42 8–12
[18] Richeton J, Ahsi S, Vecchio K S, Jiang F and Adharapurapu R R 2006 Influence of temperature and strain rate on the mechanical behavior of three amorphous polymers: characterization and modeling of the compressive yield stress International Journal of Solids & Structures 43 2318–35