A modified Johnson-Cook model for dynamic behavior of spray-deposition 17 vol.% SiCp/7055Al composites at high strain rates

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Abstract
In this study, the dynamic impact tests of spray-deposited 17 vol% SiCp/7055Al composites at various strain rates were performed with a Split Hopkinson Pressure Bar (SHPB). In these tests, the strain rate was 392 s\(^{-1}\)–2002 s\(^{-1}\), and the temperature was 293 K–623 K. Subsequently, the Johnson–Cook (JC) model was used to describe the flow behaviors under high speed impact deformation, and its effectiveness was assessed. Results show that the stress values predicted by the JC model could be inconsistent with the experimental ones. A modified JC constitutive model of 17 vol% SiCp/7055Al composites was developed by modifying the strain rate hardening term and considering coupling effects of strain, temperature and strain rate. According to the comparison between the experimental data and the results assessed with the modified JC model, the proposed model could assess the stress–strain values more accurately, especially in the beginning of plastic deformation. This indicates that the composites exert the joint effects of strain rate hardening and temperature softening during high-speed impact deformation.

1. Introduction

SiCp/Al composites have been extensively applied in the automobile, aerospace, defense industries and other industries for their prominent properties in both physical and mechanical performance (e.g., light-weight, high wear resistance, high stiffness, excellent strength, good thermal stability and low price) [1–7]. Among considerable additive manufacturing technologies, spray-deposition is considered an advanced production technology for forming fine structure and fabricating high density metallic components [1, 8–10].

In recent decades, domestic and foreign scholars have fabricated SiCp/Al composites based on spray-deposition and conduct relevant research [11–13]. However, existing researches mainly focus on mechanical properties, the interface effects on the mechanical properties and static deformation characteristics [14, 15]. As a matter of fact, composite components are likely to experience dynamic impact loading in several applications, it is generally known that all materials exhibit different deformation characteristics under static and dynamic loading conditions [1, 5]. Studying flow behaviors of SiCp/Al composites at high strain rates is critical to explain the dynamic characteristics of the material in their application [16]. However, the dynamic impact test can obtain the performance parameters and dynamic flow characteristics of the spray-deposition SiCp/Al composites at high strain rates.

Under the varied loading, flow behaviors of the materials were affected by the strain, strain rate as well as temperature. On the whole, the flow behaviors of materials during hot deformation are complex, whereas the constitutive relationship can describe the stress–strain relationship of materials in a mathematical model [16–18]. The applicable constitutive model should be capable of expressing the dynamic characteristics of the materials under various loading conditions, which is a prerequisite for accurate numerical analysis of material deformation including finite element simulation [17]. Constitutive equations of materials have been primarily
split into two categories [19]: Physically-based constitutive models and phenomenological constitutive models. As compared with physics-based models, however, phenomenological constitutive models involve fewer material constants and require limited experimental data; they are always prioritized by the users to assess the stress-strain values of materials. Besides, the phenomenological constitutive models have been successfully adopted to describe the sophisticated flow behaviors of materials under larger loading forming conditions [20, 21].

The Johnson–Cook (JC) constitutive model has been extensively employed in phenomenological constitutive models for its simple form and simplified calculation [21–23]. The JC model initially proposed by Johnson and Cook in 1983, has been adopted for large deformation, high strain rates and high temperature of metals [23–25]. The JC model considering strain rate hardening, strain hardening and thermal effect; it can describe the flow behaviors of various materials under specific loading conditions. It is noteworthy that the JC model has been extensively used in impact dynamics research [26]. The original JC model only gives the expression of yield stress, and the material constants are easy to acquire from experimental. However, it is found that the original JC model has some deviations in the prediction of deformation behavior. To enhance the accuracy of the JC model, the model also has been widely modified in available literature. Among these proposed modified JC models, strain, strain hardening and temperature softening terms in the modified models have been applied most frequently. These researches primarily established JC models of alloys and partial composites. At present, the spray-deposition processed SiCp/Al composites have been rarely reported, let alone constructing the JC constitutive equation of spray-deposition SiCp/7055Al composites. Thus far, whether the existing related constitutive model is applicable to the SiCp/7055Al composites remains unclear.

In the present work, dynamic uniaxial compression tests were performed on the spray-deposited 17 vol% SiCp/7055Al composites, the stress-strain data were obtained with a Split Hopkinson Pressure Bar (SHPB); besides, their effects on the flow behaviors were discussed. The JC model and the modified JC model constitutive equation of SiCp/7055Al composites were constructed to describe the dynamic behavior. The deformation behaviors of SiCp/7055Al composites under various strain rates at different temperatures were discussed. As revealed from the results, the predicted values of the original JC equation are greatly different from the experimental values, and the proposed modified JC equation is capable of precisely assessing the composites deformation behaviors.

### 2. Experimental procedures

#### 2.1. Experimental material

In the present study, the commercial 7055 aluminum alloy was used. 7055 aluminum alloy have been widely used in aerospace, transportation and other fields because of its excellent mechanical properties, its chemical composition is given in table 1. SiC particles with the size of 15–20 μm acted as the reinforcement. The SiCp/7055Al composites were fabricated by spray-deposition. Before spray-deposition, to reduce the agglomeration of SiC particles, the SiC particles were heated for 10 h at 523 k to remove crystalline water and adsorbents. The spray-deposition process parameters included: Atomization temperature at 1023–1123 K; Nebulizer pressure under 0.6–0.8 MPa; The diameter of sedimentary disk as 530 mm; Matrix rotation speed at 150–250 r min⁻¹; Powder-feeding pressure under 0.1–0.2 MPa. The volume fraction of added alpha-SiC particles was 17%, and the density of the composite was 92.3%. The size of the deposited cylindrical sample is 160 × 320 mm.

#### 2.2. Experience of dynamic tests

The cylindrical impact sample size is 10 mm in diameter and 6 mm in height. The cylindrical bar specimens processed from the original spray-deposition 17 vol% SiCp/7055Al composites with EDM PW2UP wire cutter. And all the test specimens were processed to develop the coincident axis along the radial direction to ensure consistency. SHPB was adopted to perform the dynamic compressive tests, and the incident, reflected and transmitted waves were transmitted to the data processing system by using the strain gauge on the incident bar and the transmission bar. The strain gauge resistance of SHPB’s data acquisition system is 120 Ω. To minimize the impact of shock waves on the results of the experiment, a small amount of vaseline was applied on both ends of the sample and 2 mm long rubber was applied on the other end of the incident bar. In accordance with the one-dimensional stress wave theory, the strain rate (ε), strain (ε) and stress (σ) of the tested material can be

| element | content | balance |
|---------|---------|---------|
| Al      | 2.0–2.6 | Bal.    |
| Cu      | 1.8–2.3 |         |
| Mg      | 7.6–8.4 |         |
| Zn      | <0.1    |         |
| Si      | <0.15   |         |
| Fe      | <0.04   |         |
| Cr      | <0.06   |         |
| Ti      | <0.05   |         |
| Mn      | 0.08–0.25 |       |
| Zr      |         |         |

Table 1. The chemical composition of Al7055 (wt%).
expressed as follows [23]:

$$\sigma(t) = \frac{A}{2A_0} E (\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)) \quad (1)$$

$$\varepsilon(t) = \frac{C}{I_0} \int_0^t (\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)) dt \quad (2)$$

$$\dot{\varepsilon}(t) = \frac{C}{I_0} (\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)) \quad (3)$$

Where C and E are the elastic wave velocity and the Young’s modulus in the bars, respectively. $\varepsilon_i(t)$, $\varepsilon_r(t)$ and $\varepsilon_t(t)$ are the incident wave amplitude, the reflected wave amplitude and the transmitted wave amplitude, respectively; $l_0$ is the initial length of the specimen; $A$, $A_0$ are the bar cross-sectional area and the specimen cross-sectional area.

The dynamic test stress-strain curves can be obtained by eliminating the time term. The specimens were subjected to high-speed impact tests on SPHB at the strain rate ranging from 392 s$^{-1}$ to 2002 s$^{-1}$, as well as at the temperatures of 293 K, 523 K, 573 K and 623 K, respectively.

3. Results and discussion

3.1. Microstructure and phase structure

The SEM micrograph, element mapping and XRD pattern of 17 vol% SiCp/7055Al composites were obtained, as shown in figure 1. Figures 1(a) and (b) suggest that the SiC particles were uniformly distributed, however, there are agglomeration around the grain boundaries, and the matrix materials presentation micro-cracks and porosity defects. It can be observed that there are clubbed and flocculent white precipitate phases in the matrix as show in figures 1(a) and (b). Figure 1(c) gives the EDS element mapping confirms that the main elements of the precipitates were aluminium and copper, and maybe also contain zinc. Existing studies revealed that the precipitates of 7055 alloys mainly includes MgZn$_2$ and Al$_3$Cu [1], however, the XRD pattern (figure 1(d))
indicates that the precipitate of the materials phase is Al$_2$Cu. In the meantime, some weak peaks of magnesium compounds (such as Al$_2$CuMg and MgZn$_2$) were also found in the XRD pattern, but these could not be completely determined to be Al$_2$CuMg and MgZn$_2$. This may be due to the low content of Mg compounds precipitates in the spray-deposition composites as shown in figures 1(c) and 1(d).

3.2. Flow behavior
The strain rate ($\dot{\varepsilon}$), strain ($\varepsilon$) and stress ($\sigma$) data of the high-speed impact experiments can be obtained by using the one-dimensional stress wave theory. The calculation formulas are (1), (2) and (3), as shown in section 2.2. The true stress-true strain curves that were obtained through SPHB tests are illustrated in figure 2. It can be seen from figure 2 that the stress values increased rapidly at the initial stage, and then with the increase of the strain, the flow stress gradually varied to the steady-state flow stage. The values of flow stress increase with the strain rates show the material has a positive strain rate sensitivity at varied temperatures. In the initial stages of dynamic deformation, strain hardening and strain rate hardening have an effect on the flow behaviors of 17 vol% SiCp / 7055Al composites. The true strain of the material are obviously improved under high strain rates, the higher the strain rate is, the larger the true strain. However, the true strain values are very low when the strain rate is around 400 s$^{-1}$, and there are no obvious plastic deformation stage. This was primarily because the amount of deformation was small, and the heat accumulation of the materials was not adequate to achieve the significant increase in the dislocation motion.

3.3. Johnson-Cook model
The current JC model, considered the strain, strain rate and temperature effects on the plastic deformation mechanism of the metals. For its simple form and ease of use, the variables used have been already available in most calculation programs, and the model has been widely used in general the high-speed impact dynamics studies. The JC model is expressed as follow [25]:

$$
\sigma = (A + B|\dot{\varepsilon}|^n)(1 + C \ln \dot{\varepsilon}) (1 - T^m)
$$

where $\sigma$ is the flow stress, $A$, $B$, $n$, $C$ and $m$ are material constants, $A$ is quasi-static yield stress (MPa) at reference temperature and reference strain rate, $B$ is strain hardening parameter (MPa), $n$ is strain hardening exponent, $C$ represents the coefficient of strain rate hardening; $m$ is thermal softening exponent. $\dot{\varepsilon}_p$ is equivalent plastic strain,
and $\dot{e}^{*}$ is dimensionless equivalent plastic strain rate, which is expressed as $\dot{e}^{*} = \dot{e}/\dot{e}_0$. $T^*$ is homologous temperature as expressed by equation (5).

$$T^* = \frac{T - T_r}{T_m - T_r}$$  \hspace{1cm} (5)

Where, $T$ is deformation temperature, $T_m$ is melting temperature of the composites at normal conditions and $T_r$ is the reference temperature. $T_r$ can be room temperature, the lowest temperature of interest or the lowest temperature of the experiment, and $T^*_m$ cannot be negative.

In the present experiment, the reference temperature is $T_r = 293$ K and the reference strain rate is $\dot{e}_0 = 0.001$ s$^{-1}$ to evaluate the material constants of the JC model. The elastic modulus and yield stress ($A$) can be obtained by quasi-static test, as shown in figure 3. It is found that the SiCp/7055Al composites have no obvious yield point, therefore, $\sigma_{0.2}$ was taken as the yield point, and the yield stress of the material is 242.29 MPa. The melting point of SiCp/7055Al composite is $T_m = 900$ K, the DSC curve as shown in figure 4.

3.3.1. Determination of constant B and n
When the reference temperature is $T = T_r = 293$ K, and the reference strain rate is $\dot{e} = \dot{e}_0 = 0.001$ s$^{-1}$, ignored the effects of strain rate strengthening and thermal softening the equation (4) will reduce to as follow:

$$\sigma = A + B\dot{e}^{n_p}$$  \hspace{1cm} (6)
Then equation (6) can be denoted as:

\[ \ln (\sigma - A) = n \ln \varepsilon_p + \ln B \]  

(7)

The parameters B and n could be obtained from the straight line fitted to the plastic deformation (after the yield point) of the quasi-static experimental data. The \(\ln(\sigma-A) - \ln \varepsilon\) is plotted, and subsequently a linear fitting was performed, as shown in figure 5(a). The values of B and n could be calculated from the intercept and the slope of the fitting line, \(B = 5383 \text{ MPa}\) and \(n = 1.33\), respectively.

3.3.2. Determination of constant C

In equation (4), the second bracket on the right side of the equal sign indicates the strain rate enhancement effect, and the parameter \(C\) is the material strain rate sensitivity coefficient. At the test temperature of \(T = T_r = 293 \text{ K}\), the relationship between the dynamic yield stress and the strain rate at normal temperature can be obtained as:

\[ \sigma = (A + B\varepsilon_p^m)(1 + C \ln \dot{\varepsilon}^*) \]  

(8)

Equation (8) can be transformed into:

\[ \frac{\sigma}{A + B\varepsilon_p^m} - 1 = C \ln \dot{\varepsilon}^* \]  

(9)

Then, the high speed impact flow stress data at room temperature were used for calculation, corresponding the strain rates of \(423 \text{ s}^{-1}, 916 \text{ s}^{-1}, 1298 \text{ s}^{-1}\) and the strains of \(0.05, 0.075, 0.1\) and \(0.125\), respectively. \(\frac{\sigma}{A + B\varepsilon_p^m}\) and \(\ln \dot{\varepsilon}^*\) curves are fitted using linear regression fitting, as shown in figure 5(b), which the mean average slopes of the regression lines is the value of \(C = 0.16\).

3.3.3. Determination of constant m

As mentioned above, at the reference strain rate \(\dot{\varepsilon} = \dot{\varepsilon}_0 = 0.001 \text{ s}^{-1}\), the flow stress would be independent of thermal softening term, the JC constitutive equation is simplified to:

\[ \sigma = (A + B\varepsilon_p^m)(1 - T^m) \]  

(10)

Rearrange and take natural logarithms on both sides of equation (10), then equation (10) can be transformed to equation (11):

\[ \ln \left(1 - \frac{\sigma}{A + B\varepsilon_p^m}\right) = m \ln T^* \]  

(11)

The stress values corresponding to the specified strains at different deformation temperatures were obtained, similar to the method for calculating the value of C. Then, the linear fitting of \(\ln \left(1 - \frac{\sigma}{A + B\varepsilon_p^m}\right) - \ln T^*\) was performed, which is presented in figure 6. The slope of the linear fit gives the exponent \(m = 0.49\). Therefore, all the material constants of the JC model for SiCp/7055Al composites have been calculated, as gave in table 2.

Lastly, the JC model of SiCp/7055Al composites is expressed as:

\[ \sigma = (242.29 + 5383\varepsilon_p^{1.35})(1 + 0.16 \ln \dot{\varepsilon}^*)(1 - T^{0.49}) \]  

(12)

As shown in figure 7, the comparisons between the experiment and predicted values. It is suggested that the predicted values of JC model differs significantly from the experimental values. Even in the initial stages of plastic
deformation, the JC model cannot accurately predict and loses its application value. It is therefore revealed that the original JC model cannot well describe the flow behaviors of the composite in the range of high strain rates, temperatures and strains. As a result, the JC model cannot comprehensively reflect the deformation mechanical properties at high-speed of the composites, to obtain a better prediction, the JC model needs to be modified.

### 3.4. Modified Johnson-Cook model

The JC model refers to a strain rate dependent constitutive model, considering strain, strain rate and temperature separately. These parameters can be determined by a few experiments. However, a considerable number of theories and experiments reported that shear modulus is a function of pressure and temperature [16, 26–28]. Thus, if the model is not modified, it cannot appropriately describe the stress-strain relationship of spray-deposition SiCp/7055Al composites at high-speed impact, as shown in figure 7. In addition to the effects of strain, strain rate, and temperature on the flow stress, the phase transition, dislocation density and material structure during deformation also have new effects on flow stress [16, 29–31]. To remedy the defects of the JC model, the coupling effects of the flow stress of these three factors were considered. Some modified JC models were proposed in the literature [22, 23, 32–34]. These modified JC models can well describe the stress-strain

![Figure 6. In $\ln \left(1 - \frac{\sigma}{A + B \cdot e^C \cdot T^m}\right) - \ln T^*$ relation curve.](image)

![Figure 7. Comparison of experimental values and predicted values by JC model under different deformation temperatures: (a) 523 K; (b) 573 K.](image)

| Table 2. Calculated parameters of the JC model for SiCp/7055Al composite. |
| --- | --- | --- | --- | --- | --- |
| Parameter | $A$ (MPa) | $B$ (MPa) | $T_m$ (K) | $n$ | $C$ | $m$ |
| Value | 242.29 | 5383 | 900 | 1.33 | 0.16 | 0.49 |
characteristics of their materials. The expression of the most widely used in these provided modified JC models is shown in equation (13). To determine whether this modified JC model is suitable for spray-deposition SiCp/7055Al composites, the equation (13) is verified.

\[
\sigma = (A_1 + B_1 \varepsilon + B_2 \varepsilon^2)(1 + C_1 \ln \dot{\varepsilon}^*) \exp [(\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*)(T - T_r)]
\]  

(13)

Where \(A_1, B_1, B_2, C_1, \lambda_1, \lambda_2\) are material constants, the meanings of other parameters are the same as those in equation (4).

3.4.1. Determination of constant \(A_1, B_1, B_2\)

At the reference temperature is \(T_r = 293\) K and reference strain rate is \(\dot{\varepsilon}_0 = 0.001\) s\(^{-1}\), equation (13) can be expressed as follow:

\[
\sigma = A_1 + B_1 \varepsilon + B_2 \varepsilon^2
\]  

(14)

Draw the stress-strain curve under the reference condition, and fit it with 2-order polynomial, as shown in figure 8. According to the coefficient of the fitted 2-order polynomial, the values of \(A_1, B_1, B_2\) are determined to be 155 MPa, 5306 MPa, \(-39769\) MPa, respectively.

3.4.2. Determination of constant \(C_1, \lambda_1, \lambda_2\)

In equation (13), at the test temperature of \(T = T_r = 293\) K, equation (13) can be expressed as follow:

\[
\sigma = (A_1 + B_1 \varepsilon + B_2 \varepsilon^2)(1 + C_1 \ln \dot{\varepsilon}^*)
\]  

(15)

The equation (15) can be expressed as equation (16).

\[
\frac{\sigma}{A_1 + B_1 \varepsilon + B_2 \varepsilon^2} - 1 = C_1 \ln \dot{\varepsilon}^*
\]  

(16)

Then, the method of obtaining \(C_1\) is the same as the method of obtaining the \(C\) value, refer to the section 3.3.2. Using linear regression fitting the \(\frac{\sigma}{A_1 + B_1 \varepsilon + B_2 \varepsilon^2}\) and \(\ln \dot{\varepsilon}^*\) plots as shown in figure 9, in which the mean average slopes of the regression lines is the value of \(C_1 = 0.23\).

Rearrange equation (13) and take natural logarithm on both sides, could be obtained equation (17), expressed as follow:

\[
\ln \left[ \frac{\sigma}{(A_1 + B_1 \varepsilon + B_2 \varepsilon^2)(1 + C_1 \ln \dot{\varepsilon}^*)} \right] = (\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*)(T - T_r)
\]  

(17)

Using the flow stress data for 0.001 s\(^{-1}\), 0.01 s\(^{-1}\) and 0.1 s\(^{-1}\), strain rates at deformation temperatures of 523 K, 573 K, 623 K, the graphs of \(\ln \left[ \frac{\sigma}{(A_1 + B_1 \varepsilon + B_2 \varepsilon^2)(1 + C_1 \ln \dot{\varepsilon}^*)} \right] - T - T_r\) were plotted. The values of \(\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*\) obtained from the slopes of those graph. As shown in figure 10, when the strain rates are 0.001 s\(^{-1}\), 0.01 s\(^{-1}\), and 0.1 s\(^{-1}\), the values of \(\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*\) are obtained as \(-0.0084\), \(-0.0067\), \(-0.0056\), respectively. Linearly fit the \(\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^* - \ln \dot{\varepsilon}^*\) plot, as shown in figure 11, and then get the values of \(\lambda_1\) and \(\lambda_2\), \(\lambda_1 = -0.0083, \lambda_2 = 0.0061\).

Thus, the modified JC constitutive equation can be express as follow:

\[
\sigma = (155 + 5306\varepsilon - 39769\varepsilon^2)(1 + 0.23 \ln \dot{\varepsilon}^*) \exp [(-0.0083 + 0.00061 \ln \dot{\varepsilon}^*)(T - T_r)]
\]  

(18)

Figure 8. The \(\sigma - \varepsilon\) curve and the two-order polynomial fitting curve.
However, the comparison with the experimental values reveals that the predicted results of equation (18) of the modified JC constitutive significantly differed from the experimental results. The prediction error values of this modified JC model are shown in table 3. The reason for the excessive errors is that the SiCp/7055Al composites not only has the strain rate hardening effect but also the softening effect, which is not taken into account in equation (18) [16, 23, 35–37]. For some materials, the combined effect of thermal softening and strain hardening on the flow stress should be considered during dynamic deformation [22, 23, 38]. In view of the influence of thermal softening effect, it is reasonable to retain the thermal softening exponent in the temperature softening item. Considering the interaction influences of the factors on the flow stress, a modified JC model was proposed, as shown in equation (19).

\[
\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_1 \ln \varepsilon^*)(1 - T^{\alpha m_1})
\]  

(19)
Rearranging equation (19) one obtains:

\[
\ln \left[ 1 - \frac{\sigma}{(A_1 + B_1 \varepsilon + B_2 \varepsilon^2)(1 + C_{\varepsilon} \ln \dot{\varepsilon}^*)} \right] = m_1 \ln T^*
\]

The material constant \(m_1\) is obtained from the slopes of the graphs \(\ln \left[ 1 - \frac{\sigma}{(A_1 + B_1 \varepsilon + B_2 \varepsilon^2)(1 + C_{\varepsilon} \ln \dot{\varepsilon}^*)} \right]\) versus \(\ln T^*\), as shown in figure 12. Can get \(m_1 = 0.4\).

Thus, the modified JC model can be expressed as:

\[
\sigma = (155 + 5306\varepsilon - 39769\varepsilon^2)(1 + 0.23 \ln \dot{\varepsilon}^*)(1 - T^{-0.4})
\]

### 3.5. Analysis of constitutive equation accuracy

To verify the reliability and practicability of modified Johnson-Cook model for the spray-deposition SiCp/7055Al composites at high strain rates, the experimental stress-strain values are compared with the stress-strain values predicted by the modified JC model, as given in figure 13. It can be found by comparing figures 7 and 13 that the proposed modified JC model exhibited accurate predictions with experimental results at different strain rates and varying temperatures. Since the modified JC model takes into account the coupling effects of temperatures, strain rate and strain rate softening effects on flow stress the accuracy of the proposed modified JC model are significantly improved. Note that in the initial deformation stage, the predicted values and the experimental values almost coincide at most conditions. However, when the strain is larger than 0.06, the predicted values gradually deviates from the experimental values, except at 523 k/971 s\(^{-1}\). This is primarily due to the limited elongation of the material under the reference conditions. Thus, the prediction results are inaccurate once the impact deformation exceeds the material elongation. For the temperature at 523 K and the strain rate of 971 s\(^{-1}\), the predicted values are more accurate when the strain is larger than 0.06, which may be due to experimental errors or changes in the microstructure of the material under this condition. Given this, the appropriate strain of the modified JC model should not exceed 10%. In fact, the addition of SiC particles greatly reduces the plasticity of the composites and improves the strength, so it is sufficient to predict the values of stress-strain in the initial stages of plastic deformation.

To compare the prediction accuracy of the JC model and the modified JC model, an error analysis was performed, as shown in table 3. The error between the predicted values and the experimental values was calculated by equation (22). Table 3, clearly shows that the commonly used modified JC model (equation (13)) and the original JC model errors were noticeably larger than those of the proposed modified JC model in this paper. The standard deviations of the JC model were 10.97% and 9.06% at 523 k and 573 k, while the standard deviations of the proposed modified JC model were 4.68% and 2.23% at 523 k and 573 k. However, the standard deviations of the modified JC-1 model at 523 K and 573 K are 15.75% and 34.43%, respectively. The modified JC-1 is not suitable for spray-deposition SiCp/7055Al composites at all. The proposed model can make accurate predictions the flow stress of the composites.

\[
\text{error} = \frac{\sigma_P - \sigma_E}{\sigma_E} \times 100\%
\]
The proposed modified JC model was built, and its effectiveness was verified based on the experimental data of spray-deposition 17 vol% SiCp/7055Al composites at high-speed impact temperatures range of 293 K–623 K and in strain rates range of 392 s\(^{-1}\)–2002 s\(^{-1}\). The proposed modified JC model models can effectively assess the stress of the composite in the mentioned ranges.

![Figure 12](image_url). Relationship between \(\ln \left(1 - \frac{\sigma}{(A + B \varepsilon + A \varepsilon^2 + C \ln \varepsilon)}\right)\) and \(\ln T\) (a) 0.001 s\(^{-1}\); (b) 0.01 s\(^{-1}\); (c) 0.1 s\(^{-1}\).

### Table 3. Calculated values of Error and Standard deviation for the JC model and MJC model.a

| Temperature (K) | Strain rate (s\(^{-1}\)) | Strain | JC  | Standard deviation, % | MJC-1 (equation (13)) | Standard deviation, % | MJC-2 (equation (19)) | Standard deviation, % |
|----------------|--------------------------|--------|-----|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 523            | 0.025                    | 392    | 5.43| 10.97                 | 201.28                | 15.75                 | 4.63                  | 4.68                  |
|                | 971                      | −12.93 |                 | 175.56                | 231.92                |                       | 4.28                  |
|                | 1750                     | −7.01  |                 | 201.35                | 209.05                |                       | 2.16                  |
| 0.05           | 971                      | −21.00 |                 | 213.92                | 209.05                |                       | 2.41                  |
|                | 1750                     | −12.95 |                 | 205.56                | 209.05                |                       | 2.67                  |
| 0.075          | 971                      | 13.63  |                 | 205.56                | 192.92                |                       | 3.32                  |
|                | 1750                     | −3.68  |                 | 212.68                | 192.92                |                       | 3.32                  |
| 573            | 0.025                    | 473    | −5.61| 9.06                  | 222.11                | 34.43                 | 2.96                  | 2.23                  |
|                | 1248                     | −3.95  |                 | 287.91                | 296.68                |                       | 1.54                  |
|                | 2002                     | −3.65  |                 | 287.91                | 296.68                |                       | 2.28                  |
| 0.05           | 1248                     | −1.21  |                 | 303.34                | 303.34                |                       | 0.62                  |
|                | 2002                     | 1.48   |                 | 334.32                | 303.34                |                       | 2.67                  |
| 0.075          | 1248                     | 18.62  |                 | 309.06                | 329.09                |                       | 2.97                  |
|                | 2002                     | 15.01  |                 | 329.09                | 329.09                |                       | 2.87                  |

a The JC model is the original JC model; the MJC-1 model is the modified JC model that is widely used in published literature; MJC-2 is the modified JC model used in this article.
4. Conclusions

In this study, the 17 vol% SiCp/7055Al composites were fabricated by spray-deposition, the SiC particles were uniformly distributed, and minor cracks and porosity defects were displayed. The SHPB was used for the dynamic compression tests at the strain rates of $392 \text{s}^{-1}$–$2002 \text{s}^{-1}$ and the temperatures of 293 K–623 K were conducted. The main conclusions are drawn as follows.

1. The spray-deposition 17 vol% SiCp/7055Al composites exhibit a positive strain rate sensitivity at varying temperatures. The original JC model cannot adequately describe the temperature, strain, and strain rate flow behaviors in the tests range since the JC model cannot consider the coupling effects of strain, strain rates and temperature.

2. When the modified JC model considers the strain rate hardening effect, instead of the softening effect, the modified JC model will not apply to the composites. It is therefore revealed that the composites have the joint effect of temperature softening and strain rate hardening during high-speed impact deformation.

3. Using the proposed modified JC model that considers the coupling effects of strain rate, deformation temperature and strain rate softening effects on flow stress, the true stress-strain values can be accurately assessed, especially in the initial stages of plastic deformation. However, when the strain exceeds the elongation of the composites, the prediction results of the modified JC model will gradually deviate from the experimental results.

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