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Research on dynamic mechanical behavior and damage evolution mechanism of Cu/WCp laminated composites

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Abstract
In this paper, the effect of WCp particle content (3 and 15 vol.%) and laminate orientation on the mechanical behavior of laminated Cu/WCp/15p and Cu/WCp/3p composites under dynamic impact was investigated using the split Hopkinson pressure bar (SHPB) test. Subsequently, the microdamage evolution mechanism of the composites was observed by scanning electron microscopy (SEM) and optical microscopy. The results demonstrated that Cu/WCp composites are strain-rate-sensitive, and a significant reinforcing effect of WCp particle content on composite properties was observed. Furthermore, the gradient direction revealed a remarkable effect on the dynamic compressive behavior of functionally gradient materials (FGMs). Microscopic analysis revealed that, under the same strain rate, there were no apparent damage characteristics in Cu/WCp/3p, while obvious shear cracks appeared in Cu/WCp/15p. SEM analysis revealed that, in FGM, when the laminate orientation was parallel to the stress wave propagation direction, cracks initiated from one side of Cu/WCp/15p, and then grew through the interface to the other side. A relatively large sliding dislocation was observed at the interlayer interface, and the crack arrested at the Cu/WCp/3p layer. However, although the cracks in FGM also initiated from the side of Cu/WCp/15p, they did not cross the interface, but caused a direct split in the interlayer interface, when the laminate orientation was perpendicular to the stress wave propagation direction.

1. Introduction

Functionally graded materials (FGMs), are a relatively new class of materials, which have been widely used in diversified fields, such as aerospace industry, nuclear energy, wear-resistant coating, biomedical equipment, nanotechnology, geological structures, and high-temperature structures [1, 2]. FGMs comprise two or more types of single material, which can be obtained through spatially consecutive changes according to specific rules [3]. FGMs can be classified into continuous gradient materials and laminated gradient materials [4–7]. Functionally graded metal matrix composites (FGMMCs) are one of the developmental directions of laminated gradient materials, due to their relatively simple preparation process [1, 8, 9]. As an important part of FGMMCs, the interlayer interface plays an important role in their mechanical properties [5], and has therefore attracted the attention of a large number of researchers.

Doan et al [10] investigated the dynamic crack propagation in a functionally graded glass-filled epoxy under hybrid phase field simulation, and the results confirmed a significant effect of elastic gradients on the final crack paths. Uzun et al [11] investigated the fatigue crack growth behavior in Al2124/SiC/10p FGMs, and found that FGMs exhibited good fatigue crack propagation resistance compared to traditional homogeneous composites. Xu et al [8] studied the fatigue crack growth behavior of SiC particulates reinforced Al matrix graded composite, revealing that the crack growth rate decreased due to deflection and bifurcation at the interface. The relationship

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between microstructure and mechanical properties of Al2024/SiC functionally graded composites, prepared by powder metallurgy, was investigated by Erdemir et al[1]. Their results suggested that the increase in microhardness and intermetallic formation play a major role in improving the mechanical properties of the composites. In addition, Milan et al[12] found that the effect of interlayer interface and elastic mismatch on the crack growth rate of bimaterials should not be neglected.

With the extensive application of FGMs in industrial production, as well as the increasing complexity of the working environment, components manufactured by FGMs are inevitably affected by the high-speed impact load during service. On the one hand, the mechanical properties of materials under high strain rate are quite different from those under quasi-static state. On the other hand, there are differences in the elastic modulus and thermal expansion coefficient between the two sides of the interface, due to changes in composition. This has indicated that the continuous and complex interaction between compression waves and sparse waves at the interface is involved in the propagation of stress waves in laminated gradient materials [13]. Consequently, the study of the mechanical behavior of FGMs under impact load has also attracted the attention of scholars.

Kidane et al[14] studied the quasi-static and dynamic fracture initiation toughness of Ti/TiB layered functionally graded materials under thermo-mechanical loading using split Hopkinson pressure bar (SHPB) test. The results demonstrated that the fracture toughness of the materials was quite sensitive to temperature and the fracture initiation toughness, which is associated with the strain rate, increased with increasing temperature. Fracture initiation toughness under dynamic loading is higher than that under quasi-static loading. In addition, a systematic comparison of the dynamic compression mechanical properties between homogeneous and graded epoxy/glass particulate composites was performed by Seaglar et al[15]. In a study concerning the design and impact resistant analysis of functionally graded Al2O3–ZrO2 ceramic composites conducted by Huang et al[16], it was concluded that the FGM structure can prevent delamination and increment the abrasive effect of each ceramic layer on the projectile, improving the impact resistance, and suggested that a mixture of high-hardness and high-toughness ceramics could be used in future FGM design and manufacturing. Aydin et al[17] investigated the damage of Al/SiC gradient composites under ballistic impact load. In that study, three gradient structures with different through-thickness direction were designed, including FGMs with metal component enrichment, linear change of two components, and ceramic component enrichment. According to the results, the FGMs with linear composition exhibited the best ballistic performance.

Although some researchers have tried to investigate the dynamic impact behavior of FGMs, their studies have mainly focused on the dynamic fracture properties. The literature on the effect of microstructure on dynamic mechanical properties and impact damage evolution is not systematic enough, which has currently led to insufficient understanding of the dynamic impact on FGMs. FGMMCs are composed of different volume fraction particle reinforced metal matrix composites (MMCs) by gradient stacking and sintering according to the design, since the dynamic impact mechanical properties of MMCs have been well investigated and applied in engineering components [18–22]. Thus, it is feasible to compare the dynamic impact mechanical behavior of FGMMCs to homogeneous MMCs.

Moreover, the presence of interlayer interfaces and the anisotropic material properties of FGMs, affect the macroscopic mechanical properties, and the damage modes may be more complex under high strain-rate load. A study has suggested that the overall gradient and local variations in step interfaces affect the failure behavior in layered graded composites [5]. However, to the best of our knowledge, the effect of the material property mismatch and tungsten carbide particle (WCp) content on the microstructure and impact mechanical properties of Cu/WCp FGMs has not been yet investigated. Reliable material performance parameters provide guarantee for their use in engineering applications, while they offer reference and guidance for material processing design. Therefore, the research on the dynamic mechanical properties of gradient laminated MMCs has certain engineering application value and scientific research significance.

In this study, the effect of particle content on the dynamic compression behavior of Cu/WCp composites prepared through powder metallurgy was investigated using SHPB test. Then, the Johnson–Cook (JC) constitutive model was employed to fit the experimental data, and a dynamic compression constitutive equation for Cu/WCp composites was established. In addition, the dynamic mechanical behavior of laminated materials with two gradient directions was studied. Furthermore, the effect of microstructure and interface structure on the dynamic impact deformation and damage mechanism of FGMs was analyzed.

2. Materials and methods

2.1. Materials and specimens

The raw material used in this study was dendritic copper powder and irregular WCp. The mean WCp particle size was 6 μm. The Cu/WCp composites with 3 and 15 vol.% WCp content and the Cu/WCp/3p-Cu/WCp/15p laminated composite were prepared by powder metallurgy hot pressing sintering. In brief, the fabrication
processes were as follows: (1) powder mixing with a planetary ball mill; (2) pre-forming of the uniformly mixed composite powder in a graphite mold; (3) sintering of the pre-formed mixed powder at 950 °C. For the detailed manufacturing process, please refer to [23].

The bulk materials were processed into cylindrical specimens with dimensions $\varphi \times L = 6 \text{ mm} \times 6 \text{ mm}$ by wire-electrode cutting (figure 1). For ease of description, the sample with an interface vertical to the load was named FGM1, and the sample with an interface and parallel to the load was named FGM2. Samples were tested until stress wave data repeated for 3 times under each strain rate loading case to ensure the results reliable. During dynamic compression tests, the strain rates of specimens were controlled by velocity of strike bar.

2.2. Experimental principle and process
2.2.1. SHPB test system
A schematic of the SHPB device used in this paper for the dynamic compression experiments is illustrated in figure 2. As it can be seen, the SHPB device comprised a bullet, an incident bar, a transmission bar, an absorption instrument, a data acquisition module, and a processing module. The test specimen was located between the incident bar and the transmission bar. The material of the bullet, incident bar, and transmission bar was steel, with a diameter $\varphi = 15 \text{ mm}$ and length $L = 1200 \text{ mm}$. During the experiment, the bullet accelerates by air pressure and impacts the incident bar. The stress wave propagates along the axial direction of the bar and passes through the specimen.
through multiple reflections at both ends of the sample. The incident, reflected, and transmitted waves are collected by a strain gauge attached on the bar.

2.2.2. Experimental Principle

The SHPB test principle of dynamic properties is based on the theory of one-dimensional stress wave propagation, where two assumptions should be satisfied; the one-dimensional stress wave assumption and the stress uniformity assumption [24, 25]. The one-dimensional stress wave assumption assumes that any cross-section of the Hopkinson bar and specimen is always maintained plane when the stress wave propagates, ensuring its propagation in both structures preserves an one-dimensional unidirectional stress state. The stress uniformity assumption assumes that the stress wave in the Hopkinson bar is an one-dimensional linear elastic wave. According to this, the stress \( \sigma \), strain \( \varepsilon \) and strain rate \( \dot{\varepsilon} \) can be derived from the incident \( \varepsilon_I \) (t), reflected \( \varepsilon_R \) (t) and transmitted strain \( \varepsilon_T \) (t) pulse waves (figure 3).

In the derivation process, the expressions of stress, strain, and strain rate can be obtained according to the material homogeneity assumption:

\[
\sigma = \frac{A_H E_H}{A_S} \varepsilon_T
\]

\[
\varepsilon = -\frac{2c}{L} \int_0^1 \varepsilon_R dt
\]

\[
\dot{\varepsilon} = -\frac{2c}{L} \varepsilon_R
\]

where \( \sigma \) is the yield stress; \( \varepsilon_T \) is the amplitude of the transmitted strain wave; \( \varepsilon \) is the strain; \( \varepsilon_R \) is the amplitude of the reflected strain wave; \( \dot{\varepsilon} \) is the strain rate; \( c = \sqrt{E_H / \rho} \) is the one-dimensional elastic wave velocity of the rod; \( \rho \) is the density of the rod; \( A_H \) and \( E_H \) are the cross-sectional area and elastic modulus of the rod, respectively; and \( A_S \) and \( E_S \) are the initial cross-sectional area and initial length of the specimen, respectively. Equations (1)–(3) represent the engineering stress, engineering strain, and engineering strain rate. The nominal stress and strain need to be converted into true stress and strain, since, in this test, the actual compressive strain is large. The specific conversion equations [26] are as follows:

\[
\sigma_T = \sigma_{En}(1 + \varepsilon_{En})
\]

\[
\varepsilon_T = \ln (1 + \varepsilon_{En})
\]

\[
\dot{\varepsilon}_T = \dot{\varepsilon}_{En} / (1 + \varepsilon_{En})
\]

Here, the ‘\( T \)’ subscript represents the real physical quantity, the ‘\( En \)’ subscript represents the engineering physical quantity, and the strain rate is the average strain rate in the compression process.

2.2.3. Experimental procedure

Dynamic compression tests on composite Cu/WCp and laminates Cu/WCp/15p-Cu/WCp/3p were performed at room temperature using the SHPB system. The stress-strain curves of the homogeneous composite and the laminated composites (FGM1 and FGM2) were contrastively analyzed at the same strain rate.
level. Based on the JC constitutive model and proper modification, the dynamic impact constitutive equation of the composite was obtained by fitting the stress-strain curve of the homogeneous composite. In order to analyze the relationship between microstructure and macro-mechanical properties, as well as the dynamic impact damage evolution mechanism, after the dynamic compression test, microstructural analysis of the post-impact specimens (Cu/WCp composites and Cu/WCp/15p-Cu/WCp/3p laminated composites) was performed using a Zeiss optical microscope and scanning electron microscopy (SEM).

3. Results and discussion

3.1. Dynamic impact behavior of Cu/WCp composites

3.1.1. Stress strain curves

Figure 4 exhibits the true stress-strain curves of the Cu/WCp/3p and Cu/WCp/15p composites under various strain rates. It can be observed that the flow stress of Cu/WCp composites increased with increasing strain rate, indicating that the Cu/WCp composite is a strain-rate-sensitive material.

In addition, when the strain was low, the flow stress of the two composites was boosted with the increase of plastic strain at all strain rates, indicating that the Cu/WCp composite had an apparent work hardening effect. However, as the plastic strain increased, the work hardening effect gradually decreased. It was observed that the work hardening effect of the Cu/WCp/3p composite lasted as long as the strain value was in the range of 0–0.45. When the plastic strain was higher than 0.45, the flow stress decreased with increasing strain. This was mainly due to the adiabatic status of the dynamic compression process, the softening effect of the material became dominant with the increasing temperature, and shear band damage occurred at local areas. In the Cu/WCp/15 composites, the work hardening effect was mainly concentrated in the range of 0–0.37, while the temperature softening effect dominated when the strain exceeded 0.37.

The strain hardening effect can be quantitatively analyzed by the strain hardening index, formula (7).

\[
\eta = \frac{d(\ln(\sigma_f))}{d(\ln(e_{f}))}
\]  

(7)

Figure 5 is the strain hardening index curves of different composites. It can be seen that the strain hardening index of composite Cu/WCp/3p is significantly higher than that of composite Cu/WCp/15p.

It suggested that there was a negative correlation in the particle content and the strain hardening effect. Similar conclusions have been obtained by researchers. Tan et al [27] reported that the strain hardening effect of the SiCp/2024Al composite was weaker than that of the 2024Al matrix. Zhu et al [28] found that different from the strain hardening phenomenon of 2024Al, the SiCp/204Al composite exhibits a strain softening phenomenon. The reason may be that the larger the particle content, the higher the temperature rise during impact process, the more significant the strain softening effects. It can be concluded that the dynamic compression of the Cu/WCp composite at high strain rate is a mutual competition process involving strain rate strengthening, work hardening, and high temperature softening. At the same time, the flow stress improves by the first two factors, and deteriorates by the last factor.
The influence of particle content on the stress-strain curve can be seen in figure 4. It can be observed that the flow stress and the elastic modulus of the composites increased with the increasing WCp particle content under all strain rate levels. The flow stress under specific strain and the ultimate stress of composites was listed in Table 1. $\sigma_{0.1}$ and $\sigma_{0.3}$ represent the corresponding flow stress when the strain is 0.1 and 0.3, respectively, and ultimate stress $\sigma_{\text{max}}$ represents the maximum value of flow stress. As shown in Table 1, it can be found that the influence of particle content on the flow stress of composites is more significant. The flow stress of the Cu/WCp/15p composite was about 60 MPa higher than that of the Cu/WCp/3p composite under different strain rate levels (2670 s$^{-1}$–2657 s$^{-1}$, 2100 s$^{-1}$–2147 s$^{-1}$), and the ultimate stress under strain rate 3086 s$^{-1}$ of Cu/WCp/15p composite is 341.22 MPa, higher than that of the Cu/WCp/3p composite under strain rate 3139 s$^{-1}$, 61.67 MPa.

Combining figure 5 with Table 1, it can be concluded that the flow stress of the composites increases with the increasing WCp particle content. The strengthening mechanism of the particles has been reported previously, Behm's research [29] demonstrated that the strengthening mechanism of Orowan and the dislocation packing due to the difference in the thermal expansion coefficient were the particle strengthening mechanisms of the dynamic mechanical properties of the composites.
3.1.3. Microstructure analysis

After dynamic impact, a lot of macro-shear cracks were observed around the Cu/WCp/15p composite when the strain rate was 3086 s\(^{-1}\); however, there were no cracks or macro-damage features around the Cu/WCp/3p composite specimens when the strain rate was 3139 s\(^{-1}\). The damage characteristics of the specimens were analyzed using a Zeiss optical microscope, in order to better understand the deformation and damage mechanisms. The micro-analysis results on the peripheral areas of the Cu/WCp/15p and Cu/WCp/3p specimens are illustrated in figure 6. In figures 6(a) and (c), it was demonstrated that there was no shear band or crack on the surface and inside the Cu/WCp/3p composite under a strain rate of 3139 s\(^{-1}\). However, as shown in figures 6(b) and (d), when the strain rate was 3086 s\(^{-1}\), shear cracks appeared in the Cu/WCp/15p composite, as well as a number of particles inside the shear cracks.

This phenomenon can be explained by the temperature increase in the test piece during the dynamic impact process. Due to the short duration of the SHPB dynamic impact process, a large amount of heat accumulated in the specimen sharply, causing a rapid increase in temperature. This led to softening or even melting of the Cu matrix, which resulted in a drop in flow stress. The average temperature rise \(\Delta T\) inside the specimen during adiabatic compression can be calculated by the following equation:

\[
\Delta T = \frac{\eta}{\rho C} \int_{0}^{\varepsilon} \sigma d\varepsilon
\] (8)

where \(\rho\) represents the density, \(C\) the specific heat capacity, \(\eta\) the energy conversion coefficient equal to 0.9, and \(\sigma\) and \(\varepsilon\) the stress and strain of the composites, respectively. According to the compound rule of materials, the \(\rho C\) of a composite with particle content \(V\) can be calculated by the following equation:

\[
\rho C = V \rho_{WC} C_{WC} + (1 - V) \rho_{Cu} C_{Cu}
\] (9)

Therefore, the average temperature rise of the Cu/WCp/15p and Cu/WCp/3p composites with specific strain rate of 3086 s\(^{-1}\) and 3139 s\(^{-1}\) can be calculated according to table 2 and figure 7, and was found to be 147 °C and 123 °C, respectively. This indicated that, in the impact process, there was a higher temperature increase and more serious damage in the composites with increasing particle content.

3.1.4. Constitutive relation fitting and modification

At present, there is a variety of available mature models for fitting the dynamic compression behavior of materials based on experimental data, such as the JC model, KHL model, PB model, and NNL model\[31\]; however, there are differences and diverse fitting outcomes for the material and scope of each model. In the

![Figure 7. Plastic work of composites (Since the research object of the micro morphology was the specimen after dynamic, the temperature rise occurs during the entire impact process. Therefore, the full stress-strain curve was used to calculate the plastic work).](image)
study of Xu [31], the constitutive model of pure copper was fitted under different strain rates and the fitting effect on given models was compared. It was concluded that different models should be selected according to the specific details of the constitutive behavior in order to obtain more accurate fitting results in engineering applications.

In this paper, the obtained stress-strain curves has three characteristics. Firstly, the flow stress increased due to work hardening; secondly, the flow stress decreased due to the temperature softening effect; thirdly, the flow stress increased with increasing strain rate. Therefore, the JC constitutive model could be used to fit the dynamic impact compression behavior of the composites, since it couples the work hardening, strain rate, and temperature softening effects of metal materials.

In general, the JC constitutive model [32] can be expressed as:

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

where \( \varepsilon \) represents the equivalent plastic strain; \( \dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_b \) is the dimensionless strain rate for \( \dot{\varepsilon}_b = 1 \text{ s}^{-1} \); \( T^m = (T - T_r)/(T_m - T_r) \), where \( T \) is the absolute temperature, \( T_r \) is the reference temperature and is equal to 93 K, and \( T_m \) is the melting temperature of the material; and \( A, B, n, C, \) and \( m \) are material constants. The flow stress is expressed as the product of work hardening, strain rate, and temperature effects. The variable separation method was employed to determine the relevant unknown parameters since the three terms in the model were not coupled.

The specific fitting process of \( A, B, n, \) and \( C \) has been shown in [33–35]. According to [36], the strain rate sensitivity coefficient \( C \) is a function of \( \dot{\varepsilon} \), i.e., \( C = f(\dot{\varepsilon}) \). In addition, Yu et al [33] found that \( C \) is not a constant, but a variable constant changing with temperature and strain rate, i.e., \( C = f(\dot{\varepsilon}, T) \). The high-temperature experimental data of the composites were not measured in this study, due to a limitation in the experimental conditions. Consequently, the temperature softening coefficient \( m \) could not be obtained directly. Therefore, in this research, \( C \) was considered to be related only to strain rate, i.e., \( C = f(\dot{\varepsilon}) \).
According to the parameters determined in the first two steps and the preliminary fitted experimental data based on $A$, $B$, $n$, and $C = f(\dot{\varepsilon})$ (figure 8), it was observed that the fitting consequence was in accord with the experimental results at the first stage, while the coincidence worsened with increasing plastic strain. Therefore, the softening effect of temperature rise on material properties was significant. Combining the stress-strain curve and equation (9) [31], it was found that the plastic strain increased with increasing plastic work, resulting in higher temperature rise. Therefore, the softening effect of temperature had a positive correlation with strain.

This study proposed the replacement of the temperature softening effect $T_1m^{*}$ (figure 8) with $\varepsilon_1m^*$ in order to modify the preliminary fitting results. Thus, the coefficient $m$ can be determined by fine-tuning in combination with the actual test results. The modified fitting equations of the Cu/WCp/15p and Cu/WCp/3p composites are expressed as follows:

$$\sigma_{3p} = (44 + 85.6e^{0.59})(1 + (0.0524 \ln \dot{\varepsilon} - 0.1323) \ln \dot{\varepsilon}^*) (1 - \varepsilon)^{0.25}$$

$$\sigma_{5p} = (50 + 94e^{0.55})(1 + (0.0509 \ln \dot{\varepsilon} - 0.0501) \ln \dot{\varepsilon}^*) (1 - \varepsilon)^{0.38}$$

As a consequence, the modified JC model was again used to fit the experimental data of the composites (figure 9). In order to evaluate the fitting effect of JC model before and after modification, the Pearson’s correlation coefficient and R$^2$ of the fitting results were compared in table 3. The Pearson’s correlation coefficient and R$^2$ of the modified model has been significantly improved. It can be concluded that the fitting results after modification were basically consistent with the experimental data, which indicated an effective fitting outcome.

### 3.2. Dynamic impact behavior of gradient materials

#### 3.2.1. Effect of gradient direction on stress-strain curve

Although SHPB experiments of composite structures do not strictly satisfy the one-dimensional stress uniformity assumption, Tasdemirci et al [37] believed that the mechanical properties of composite structures can be reflected by the stress-strain curve. Therefore, the dynamic stress-strain behavior of gradient MMCs with interlayer interfaces is explored in this paper.

Figure 10 shows the dynamic compression true stress-strain curve of gradient composites under different high strain rates. In addition, the ultimate stress at different strain rates was put into the stress-strain curve diagram. It can be observed in figure 10(a) that the flow stress improved when the strain rate increased from 1208 s$^{-1}$ to 3280 s$^{-1}$, indicating that the FGM1 was sensitive to strain rate. Meanwhile, the flow stress boosted...
with increasing plastic strain, reaching its maximum value when the strain reached about 0.45. The ultimate stress increased as the strain rate increased, from 275.43 MPa at strain rate 1208 s\(^{-1}\) to 302.82 MPa at strain rate 3280 s\(^{-1}\). This indicated that the flow stress of FGM1 contributed from the strain hardening and strain rate effects. As it can be seen in figure 10(b), the flow stress of FGM2 mainly contributed from the strain hardening effect. The flow stress increased with increasing plastic strain, and it reached its a maximum value when the
strain was about 0.4. The flow stress increased when the strain rate increased from 1150 s\(^{-1}\) to 2040 s\(^{-1}\), the ultimate stress increased from 283.32 MPa to 295.75 MPa, however, when the strain rate reach to 2730 s\(^{-1}\) or 3124 s\(^{-1}\), the stress–strain curve almost coincided with that under 2040 s\(^{-1}\), and the ultimate stress were 290.95 MPa and 290.98 MPa respectively, indicating that the flow stress of FGM2 was not sensitive to strain rate.

The comparison results of the stress–strain curves of FGM1 and FGM2 at the highest strain rate level (3280 s\(^{-1}\) and 3124 s\(^{-1}\), respectively) and the lowest strain rate level (1208 s\(^{-1}\) and 1150 s\(^{-1}\), respectively) are shown in figure 11. It was found that the flow stress of FGM2 was higher than that of FGM1 when the level of strain rate was the lowest. However, this was reversed when the strain rates were high (3280 s\(^{-1}\) and 3124 s\(^{-1}\)). This suggested that FGM2 had better impact resistance at low strain rates, while FGM1 had better impact resistance at higher strain rates.

The flow stress of a functionally graded material under indicated plastic strain is presented in figure 12. According to figure 12(a), the flow stress of FGM1 was affected by the interaction between the strain hardening and strain rate effects, with the first being dominant. In addition, a higher strain rate appeared with higher flow stress. However, the flow stress of FGM2 was affected by the strain hardening effect, but the flow stress increased first and then decreased with increasing strain rate.

3.2.2. Comparison between FGM and composites stress-strain curves

Figure 13 shows the comparison between the stress-strain curves of laminated FGMs and homogeneous Cu/WC\(_p\) composites at high strain rates. It can be observed that the Cu/WC\(_p\)/15p composite had the highest flow stress and stiffness, followed by FGM, and the Cu/WC\(_p\)/3p composite had the lowest, at both strain rate levels.

According to the mechanical mixing ratio of composite materials [13]:

\[
\sigma_Y = \sigma_{Yp} V_p + \sigma_{Y3p} V_{3p}
\]  (13)

where \(\sigma_Y\) is the flow stress and \(V\) is the volume proportion of the homogeneous layer composites. In this research, \(V = 0.5\), meaning that the flow stress of the laminated material was about the average of the two homogeneous composites. It was found that the stress–strain curves at the strain rate range of 2028 s\(^{-1}\)–2147 s\(^{-1}\) basically conformed to the compound law; however, the flow stress of FGM2 was lower at high strain rates (3086 s\(^{-1}\)–3280 s\(^{-1}\)).

(a) strain rate level 2028 s\(^{-1}\)–2147 s\(^{-1}\); (b) strain rate level 3086 s\(^{-1}\)–3280 s\(^{-1}\).

3.2.3. Effect of gradient direction on macro-deformation

Figure 14 exhibits the macro-deformation morphology of the laminated material after high-speed impact. The results indicated that the height of the specimen was getting smaller with increasing strain rate, leading to more severe plastic deformation. In figure 14(a), it was found that the FGM1 interface was located at the middle of the entire height of the specimen; the upper part was Cu/WC\(_p\)/15p and the lower part was Cu/WC\(_p\)/3p. In the laminated materials, although the axial stress of the upper and lower layers was consistent, the lateral deformation was not symmetrical. In other words, the lateral deformation of the upper part was smaller than that of the lower part, while the two deformations were coordinated with each other due to displacement continuity at the interface.

In addition, some shear cracks appeared in the 45\(^\circ\) direction around the surface of the specimens under a strain rate of 3280 s\(^{-1}\), with the shear cracks above the interface being more serious. In figure 14(a), it was observed that the macro-shear crack at the Cu/WC\(_p\)/15p composites initiated above the interface, and then the cracks propagated through the interface to the Cu/WC\(_p\)/3p layer.
In Figure 14(b), it was presented that the interface was located in the radial direction of the entire specimen. The deformation of the specimen increased with increasing strain rate, and the indirect tensile stress at the interface was also increased. When the strain rate reached 2730 s\(^{-1}\), cracks appeared at the interface, which grew from the outermost periphery of the cylindrical specimen to its center. The interfacial cracking was mainly attributed to the summation of the indirect tensile stress developed by impact compression and to that the residual stress existing at the interface exceeded the bonding strength of the interface. In addition, the 45° shear cracks were distributed on one side of the Cu/WCp/15p composite. The same phenomenon was observed when the strain rate was 3124 s\(^{-1}\), and the only difference was that the interface crack had a larger opening displacement and larger shear crack density and scale.

In summary, there was the more severe damage in the gradient materials with higher strain rate. In FGM1, the main damage characteristic was 45° shear cracks initiated above the interface at the Cu/WCp/15p composite layer, which then propagated through the interface to the Cu/WCp/3p layer. In FGM2, the main damage characteristic was interface cracking accompanied with shear cracking at the Cu/WCp/15p composite layer. Therefore, the interlayer interface plays a significant role in the dynamic impact behavior of laminated composites.

### 3.2.4. Effect of gradient direction on micro-damage evolution

From the above analysis on the macro-deformation characteristics, it was found that obvious macro-cracks appeared on the periphery of the specimen when the strain rates were 3124 s\(^{-1}\) and 3280 s\(^{-1}\). Therefore, micro-analysis was mainly focused on the areas where macro-cracks occurred. Micro-analytical samples with an area with apparent macro-damage features were cut by wire cutting, and then were progressively sanded and polished with sandpaper. Surfaces that were difficult to polish due to the small size of the impact specimen, were coated with phenolic resin. The micro-damage characteristics were analyzed by SEM.

Figure 15 shows the laminated material microstructure after dynamic impact loading observed by SEM, and details are presented in figures 15(c) and (d). In figure 15(c), it was found that a large displacement, approximately 100 µm, emerged on the FGM1 interface under shear force. Moreover, a complete shear crack initiated from the Cu/WCp/15p layer, grew through the interface to the Cu/WCp/3p layer, and arrested in the Cu/WCp/3p layer. Subsequently, a ductile hole appeared in the shear crack path. When the crack tip interacted with the WCp particle, the crack propagated around the particle along the interface along a 45° direction (figure 15(e)).
Figure 15(d) revealed that a micro-damage characteristic of FGM2 was some vertical cracks (voids) initiated at the interface area, which were mainly concentrated in the same area where the particles were concentrated. The initiation of the vertical cracks was mainly caused by the melting of the matrix due to the high temperature of the particle enrichment; more details can be observed in figure 15(f). In addition, in figure 15(b), a 45° macro-shear crack appeared on the right side of the interface crack. According to the microstructure analysis of the shear crack region, the matrix copper was white with traces of plastic flow, and cracks and particle debonding appeared, indicating that the damage of FGM2 was mainly concentrated in the Cu/WCp/15p layer.

According to the analysis results of the micro-damage characteristics, a large amount of heat was generated inside the material at the moment of dynamic impact compression, which caused the generation of adiabatic shear bands, appearance of holes, and formation of shear cracks. In FGM1, the main damage feature was that the cracks initiated in the Cu/WCp/15p layer and then grew through the interface, and arrested at the Cu/WCp/3p layer. A relatively large displacement occurred on the interface under the action of shear stress. In addition, the shear crack propagated around the particle, which led to particle interface debonding when a shear crack interacted with a particle. The damage of FGM2 under dynamic impact was mainly concentrated in the Cu/WCp/15p layer. The particle-enriched region near the Cu/WCp/15p interface between the interlayers was the area where the interface crack initiated and propagated. In addition, several adiabatic shear bands resulted in the appearance of final shear cracks. Overall, it can be concluded that, at the same high strain rates, FGM2 was more severely damaged, while Cu/WCp/3p in FGM1 absorbed part of the plastic deformation as a buffer. This is the reason why the flow stress of FGM1 was higher than that of FGM2 under the same high strain rate levels.

4. Conclusions

In this study, the dynamic impact mechanical behaviors of Cu/WCp composites and their laminated materials were investigated using the split Hopkinson dynamic compression loading device. First, the effect of particle content (3 and 15 vol.%) on the mechanical properties of Cu/WCp composites under dynamic compression was analyzed, and then the dynamic impact deformation and micro-damage characteristics of composites with different particle content were investigated. In addition, the effect of gradient direction on the dynamic impact behavior of laminated materials was studied.

1. Cu/WCp composites are strain-rate-sensitive materials. The flow stress of the composites increased with increasing WCp particle content. The dynamic damage characteristics of Cu/WCp composites were also sensitive to changes in particle content. A large number of shear cracks appeared around the periphery of the Cu/WCp/15p composite specimen when the strain rate was 3086 s⁻¹, but there were no cracks or macro-microscopic damage features on the Cu/WCp/3p composite specimen when the strain rate was 3139 s⁻¹.

2. The gradient direction had a significant effect on the mechanical behavior of FGMs under dynamic compression. The flow stress of FGM1 increased gradually with increasing strain rate and strain, with work hardening being the dominant mechanism. However, the flow stress of FGM2 increased when the strain rate increased from 1150 s⁻¹ to 2040 s⁻¹. The stress-strain curves basically coincided with 2040 s⁻¹ at 2730 s⁻¹ and 3124 s⁻¹, which indicated that, above 2040 s⁻¹, the flow stress of FGM2 was not sensitive to strain rate.

3. According to the comparison of the FGM and PMMCS stress-strain curves, the optimal strength was exhibited by Cu/WC/15p, but it was prone to penetrating crack generation, which resulted in brittle structural instability. Even though the ductility of Cu/WC/3p was the best, its strength was the lowest. Compared to FGM1, FGM2 could exert its strength advantage when the strain rate was lower than 2040 s⁻¹, but when the strain rate was more than 2040 s⁻¹, it was also prone to brittle failure. FGM1 exhibited better strength and ductility characteristics, which exerted its comprehensive performance in the dynamic compression process.

In conclusion, the mechanical properties of particle-reinforced composites and gradient materials have their own advantages and disadvantages based on their design and performance anisotropy. Therefore, it is necessary to understand their basic properties before optimizing the material structure, in order to maximize the advantages of these new materials in engineering applications.
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Data availability statement

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

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