Effect of matrix hardness on the impact abrasive wear performance of ZTAp/steel architecture composite

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Abstract
The effect of the hardness of a steel matrix by heat treatment on the impact abrasive wear of ZTAp/40Cr steel architecture composites is investigated. Of these composites, the ZTA particles-reinforced 40Cr steel matrix composite and pure 40Cr steel formed a 3D network interpenetrating structure. The results show that the architecture composites with the martensite matrix demonstrate the best wear resistance, which is 32.76% higher than that with the troostite matrix and 163.60% higher than that with the pearlite matrix. Under the same quenching + 460 °C tempering conditions, the wear resistance of the architecture composites is 79.0% higher than that of the homogeneous composites. The wear mechanism analysis shows that the wear performance of composites depends on the interaction between the matrix and the reinforced particles. As the hardness of the composites increases, the reinforcement particles are more strongly supported by the matrix. Conversely, the matrix is preferentially worn, and the ZTA particles are shed due to the lack of protection. The main wear mechanisms include micro-cutting, plastic fatigue wear, and particle crushing and spalling.

Keywords: architecture composite, matrix hardness, impact abrasive wear, wear mechanism

1. Introduction
In the fields of mining, building materials, and electric power, material crushing is an important production process, in which the material produces serious abrasive wear on the wear-resistant material, resulting in the consumption of a large number of the wear-resistant part [1, 2]. Especially in the working environment of both strong impact and high hardness abrasives, such as crusher jaw plates, hammerheads, ball mill liners, grinding balls, etc. The impact abrasive wear on wear-resistant materials is more severe, resulting in lower service life [3–6]. Therefore, researching and developing new wear-resistant materials are of great significance in the industrial field [7].

Hardness is one of material properties which is mainly used to control wear behavior. In many cases, when the material hardness increases, the material wear resistance increases [8]. So far, various studies [8–10] investigate the effect of hardness on wear rate. Zhang Cheng et al [11] investigated the impact abrasive wear properties of 25Cr3Mo2NiWv steel after different tempering temperatures, the results show that the hardness of the steel at 550 °C tempering is higher than that at 680 °C tempering, thus exhibiting the lowest wear weight loss. Oskari Haiko et al [12] compared the impact abrasive wear performance of direct quenched steels with that of direct quenched and partitioned steels. The results show that the wear properties depend mainly on the initial surface hardness of the wear specimen. Directly hardened steels exhibit better wear resistance due to the higher surface hardness. There are also some related reports on metal matrix composites (MMCs) [13–16]. Subo Ren et al [15] investigated the wear properties of TiCp/Fe composites. The results show that after quenching and tempering, the matrix structure changes to bainite and martensite with high hardness, which improves the bonding between TiC and the matrix, thus reduces particle shedding during impact abrasive wear, thereby improves the wear resistance of the composites. Minglang Zhang et al [16] investigated the abrasive wear properties of TiC particle-reinforced H13 steel matrix composites. The results show that the hardness of the composites increases with the increase of the reinforcing particle content, which leads to a significant increase in wear resistance.
Meanwhile, in the last decade, space-structured MMCs have proven to have excellent wear resistance in the field of material crushing \cite{17}. For example, in recent years, MAGOTTEAUX (Belgium) and VEGA (India) have developed large grinding rolls made of honeycomb Al2O3 p/steel matrix composites, which have a life of more than three times that of high-chromium cast iron under impact abrasive wear conditions \cite{18}. The high manganese steel with cast carbide composite hammer head produced in China has been realized for industrial application, and its life under impact abrasive wear conditions is 30% to 100% higher than that of ordinary high manganese steel \cite{19}. Therefore, architecture MMCs are a new type of wear-resistant composite material with great potential for development.

However, because architecture MMCs are a new type of wear-resistant composites, systematic studies on the impact abrasive wear resistance and wear mechanism of space-structured MMCs are still rare. Based on the above analysis, a three-dimensional network interpenetrating structure of ZTA/40Cr architecture composites was prepared by our research group \cite{20}. Of these composites, the ZTA particles-reinforced 40Cr steel matrix composite and pure 40Cr steel formed a 3D network interpenetrating structure. In this paper, the effect of different steel matrix hardness on the impact abrasive wear performance of ZTAp/40Cr architecture composites after heat treatment was studied, our research is to establish the foundation for the development of highly wear-resistant architecture composites.

2. Materials and methods

2.1. Materials

ZTA (ZrO2-toughenedAl2O3) particles had a 99.75% purity, with an average-sized 80–100 mesh, and the micro-hardness is 1500–1700HV, produced by Saint-Gobain Ceramic Materials, the SEM micrograph of ZTA articles as shown in figure 1. 40Cr was chosen as the matrix of the composites, whose composition is shown in table 1.

| C     | Si     | Mn     | Cr   | P, S | Fe       |
|-------|--------|--------|------|------|----------|
| 0.39 ~ 0.41 | 0.30 ~ 0.34 | 0.65   | 1.0 ~ 1.2 | <0.035 | Bal      |

Figure 1. SEM morphology of ZTA particles.

Table 1. Composition of 40Cr steel.

2.2. Fabrication of the composites

2.2.1. Structure design of the composites

The architecture composites (A.C.) comprises a 3D network interpenetrating structure, as shown in figure 2. This composite consists of two networks: (a) the network of a pure matrix (figure 2(a)) and (b) the network of MMCs (figure 2(b)). The size of the composite’s sample is 15 × 15 × 30 mm. The diameter of the composite area is 4.3 mm, and the spacing between adjacent areas is 6.42 mm (figure 2(c)) \cite{21}.

2.2.2. Preparation of the composites

First, plastic patterns were printed by a 3D printer, according to the design shown in figure 2(a). Second, ZTA particles were mixed with sodium silicate and filled into the gaps in the plastic patterns. Third, the patterns were...
sintered in a furnace at 850 °C and held for 2 h to obtain ZTA preforms, whose shapes are shown in figure 2(b). Finally, the architecture composites (shown in figure 2(c)) were prepared by squeeze casting using ZTA preforms and 40Cr steel [22]. The detailed parameters of squeeze casting are shown in table 2.

For comparison, the ZTA particles uniformly reinforced 40Cr steel matrix composite (U.R.C.) was also prepared with the same method.

2.2.3. Heat treatment of the composites
To modify the matrix hardness of the composites, the samples were subjected to different heat treatments, such as 850 °C oil quenching, followed by 200 °C tempering (quenching + 200 °C tempering) and 850 °C oil quenching, followed by 460 °C tempering (quenching + 460 °C tempering) and 600 °C annealing. The flow chart for the heat treatments is shown in figure 3.

Table 2. Process parameters of composite extrusion casting.

| Mold preheating temperature °C⁻¹ | Melting temperature °C⁻¹ | Pressure MPa⁻¹ | Compressing speed mm⁻¹·s⁻¹ | Pressure holding time s⁻¹ |
|----------------------------------|--------------------------|----------------|--------------------------|--------------------------|
| 500                              | 1620                     | 50             | 5                        | 40                       |

Figure 2. Design diagram of A.C. (a) Matrix, (b) MMCs, and (c) Architecture composite.

Figure 3. Flow chart for the heat treatment process: (a) quenching + 200 °C tempering; (b) quenching + 460 °C tempering; (c) 600 °C annealing.

2.3. Microstructure and hardness
The metallographic samples were produced by a standard metallography method and etched using a 4% nitric acid solution. A Nikon ECLIPSE MA200 optical microscope and a ZEISS-EVO-18 scanning electron microscope (SEM) were used to observe the microstructure. The hardness was measured using an HBE-3000A electronic Brinell hardness tester, and the average of five measurements was calculated. The phases of the A.C. were also analyzed using X-ray diffraction (XRD; RIGAKUTTRIII-18KW, Japan).

2.4. Impact abrasive wear tests
All wear tests were conducted using an MLD-10 dynamic load wear tester, whose schematic diagram is shown in figure 4. The counterpart was quenched with 40Cr, the hardness was 55 HRC, and the rotation speed was 200 r min⁻¹. The impact load was 1.5 J and the impact frequency was 80 times min⁻¹. Quartz sand was used as
an abrasive with a mesh of 20 and a flow rate of 80 kg h$^{-1}$. The experimental time was 8 h, and the sample was weighed every 30 min. The experimental sample need to be pre-worn for 30 min before the experiment.

3. Results and Discussion

3.1. Microstructure

Figure 5 shows the microstructure of the architecture composite. Figure 5(a) confirms a perfect MMC interpenetrating structure in the architecture composite, as designed with the 3D model shown in figure 2(c). Figure 5(b) shows the macroscopic metallographic photograph of the composite area. The irregularly shaped ZTA particles are uniformly distributed in the 40Cr matrix, while the interface between the particles and the matrix is tightly bound. Image J software was used to calculate the area fraction occupied by ZTA ceramic particles as the volume fraction of ZTA in the composite area. The results showed a volume fraction of 50% in the MMC area.

The phases in A.C. are exhibited in figure 6. The phase contain α-Fe, Al$_2$O$_3$, ZrO$_2$ after quenching followed by tempering at 200 °C. The composites after quenching followed by 460 °C tempering and 600 °C annealing
contain the same phases, i.e., α-Fe, Al2O3, ZrO2, and Fe3C. The results indicate that different chemical reactions occurred in the composites during different heat treatments.

Figure 6. XRD analysis of A.C. after different heat treatments.

Figure 7. SEM Microstructure of the A.C. after different heat treatments: (a) quenching + 200 °C tempering; (b) quenching + 460 °C tempering; (c) 600 °C annealing.

Figure 7 shows the matrix microstructure of the A.C. after different heat treatments. After quenching and 200 °C tempering, the matrix consists of a small amount of lath-like and a large number of needle-like grains, as
shown in figure 7(a). After quenching and 640 °C tempering, the matrix contains the needle-like and lath-like morphology of the quenching and 200 °C tempering, while a large amount of white granular material is precipitated on the surface, as shown in figure 7(b). After annealing at 600 °C, the matrix of the A.C. consists of white lamellar and black lamellar, as shown in figure 7(c). To further analyze the matrix structure of the A.C., the chemical composition of the different phases was examined by EDS. According to EDS test results, points 1, 2, 3, and 5 are mainly composed of Fe, while points 4 and 6 are mainly composed of Fe and C and the atomic ratio is close to 3:1. Combined with the results of XRD analysis, it indicates that the structure of points 1, 2, 3, and 5 is ferrite, while the structure of points 4 and 6 is carbide (Fe₃C). The above analysis shows that the matrix structure after quenching + 200 °C tempering is typical martensite, and the matrix structure after quenching + 460 °C tempering is typical troostite. And the matrix structure after 600 °C annealing is pearlite composed of white lamellar carbide and black lamellar ferrite. Li et al [23, 24] also had the same results in their study.

### 3.2. Hardness

The impact abrasive wear resistance of the composite has a direct relationship with the hardness, the results of the hardness testing of the composites under different heat treatment states are shown in figure 8. The A.C. with a martensite matrix has the highest hardness (522.7 HBW), while that with a pearlite matrix has the lowest hardness (230.3 HBW). The changes in the hardness of the matrix conform to the general rules of hardness changes after the heat treatment of steel materials. Moreover, the variation of hardness of the composite areas in the A.C. is the same as the matrix areas. Due to the presence of the ZTA ceramic reinforced phase in the composite area, and the hardness of ZTA particles is much higher than that of 40Cr, the hardness of the composite area is higher than that of the matrix area under the same heat treatment conditions.

### 3.3. Wear resistance

Figure 9 shows the variation of the wear volume of different materials with time. It can be seen that the wear increases linearly with time. Under the same quenching + 460 °C tempering conditions, the wear resistance of the A.C. is 79.0% higher than that of homogeneous composites, indicating that space-structure design is an effective way to improve the wear performance of composites.

The wear rate shown in table 4 is obtained by linear fitting of figure 9. The table shows that the A.C. with a martensite matrix has the highest wear resistance, which is 32.76% higher than that with a troostite matrix and 163.60% higher than that with a pearlite matrix.

The relationship between the hardness and wear rate of the A.C shows in figure 10. The figure show that the hardness of the composites is directly proportional to the wear resistance. When the hardness increases, the composites exhibit more excellent wear resistance [25]. The results further show that increasing the hardness of the composite can effectively improve the wear resistance of the composites.
3.4. Wear surface observations

To obtain a better understanding of the wear mechanisms and study the influence of matrix hardness on the wear performance, the worn surfaces were observed. Figure 11 shows the wear topography of the A.C. with the matrix structure of pearlite. Figure 11(a) shows that the matrix area is higher than the composite area, while many cracks are produced in the transitional region. Figure 11(b) shows the wear topography of the composite matrix area. Because of the softer matrix after annealing and the harder ZTA particles being more abrasive than

![Graph showing wear rate variations over time.](image1)

**Figure 9.** Variations in the wear of different materials over time.

![Graph showing the relationship between hardness and wear rate.](image2)

**Figure 10.** Relationship between the hardness and wear rate.

| Different materials | Martensite Matrix (A.C.) | Troostite Matrix (A.C.) | Troostite Matrix (U.R.C) | Pearlite Matrix (A.C.) |
|--------------------|--------------------------|------------------------|-------------------------|-----------------------|
| Wear rate \((\text{cm}^3 \text{ min}^{-1})\) | \(4.7 \times 10^{-4}\) | \(6.2 \times 10^{-4}\) | \(1.3 \times 10^{-3}\) | \(1.2 \times 10^{-3}\) |

Table 4. Wear rates of the different materials.
the matrix, on the one hand, this causes a large amount of abrasive material to embed into the matrix; on the other hand, the abrasive material cuts the surface of the matrix, producing many fractured layers. The wear topography of the composite area of the composites is shown in figures 11(c) and (d), in which figure (c) and (d) show the BSE and SE morphology in the same area, it can be seen that the ZTA particles are lower than the matrix, and many fractured layers are also present on the surface of the composite area. The local stress of the material increased with the increase of the impact energy, leading to the appearance of the cracks and developing into the fatigue peeling (shown in figure 11(d)-A) [26]. Figure 8(e) shows an enlarged view of partial wear. Under longitudinal loading, the abrasive material acting on the surface of the ZTA particles leads to the breaking of the particles and the formation of a fractured layer of the ZTA particles [27]. At the same time, this effect causes many cracks and plastic deformation of the matrix around the ZTA particles.

Figure 12 shows the wear topography of the A.C. with the matrix structure of martensite. Figure 12(a) shows that the composite area is higher than the matrix area, with no cracks in the transition area. Figure 12(b) shows the wear topography of the composite matrix area, and only small amounts of particle embedding and microcutting are present [28]. The wear topography of the composite area of the composites is shown in figures 12(c), (d), in which figure (c) and (d) show the BSE and SE morphology in the same area. As the 40Cr matrix was a softer material compared to the SiO₂ abrasive. Therefore, the metal surrounding the particles was worn out first, and ZTA particles gradually protrude above the matrix (shown in figure 12(d)), reduce the contact area between the abrasive and the matrix. Thereby protect the matrix from further wear [2]. Figure 12(e) shows the topography of the abrasive plowing matrix. A large number of micro plow and deformation areas are formed next to the furrow. When subjected to subsequent abrasive action, the material accumulated on both sides of the furrow can

**Figure 11.** Wear morphology of the A.C. with pearlite matrix.
be re-flattened or subjected to another micro-cutting [28, 29]. The repeated plastic deformation makes the material partially insufficient to absorb load and flake off.

3.5. Subsurface morphology

The subsurface morphology of the A.C. is shown in figure 13. Figure 13(a) shows the subsurface wear morphology of the A.C. with the matrix structure of pearlite in the composite area. First, the interface between the matrix and ZTA particles in the mechanically bonded state generates many cracks under continuous impact. Under continuous impact, stress concentration occurs inside the brittle ceramic particles, and when the stress exceeds the strength limit, the particles are likely to break slightly, as shown in figure 13(a). The cracks within the ZTA particles and at the interface are subjected to sustained high-energy impacts and plastic shear, which gradually propagate until they cause particle spalling [30]. In contrast, the A.C. with martensite as the matrix has a high hardness and strong ability to carry impact loads, which leads to no significant particle breakage and spalling of the subsurface layer, as shown in figure 13(c).

Figures 13(b) and (d) show the wear subsurface topography of the matrix area of the A.C with pearlite and martensite matrix structure, respectively. Because of shear stresses during wear, plastic deformation in the direction of wear occurs on all wear subsurface. After erosion, the topography can be seen as clear rheological lines, and this area is referred to as the plastic rheological area [31]. Compared with the martensite structure, the pearlite structure is less hard and thus exhibits a deeper plastic rheology area. Under the action of impact loading, the local accumulation of plastic strain on the surface of the material causes cracks to form on the subsurface, and then the subsurface cracks gradually extend to the surface, finally causing the matrix to spall off.
and form wear fragments, as shown in figure 12(b), which belong to the spalling caused by high-stress surface plastic fatigue.

3.6. Wear mechanism analysis

In summary, under impact abrasive wear conditions, the material is subjected not only to tangential sliding wear of the abrasive but also to normal impact. The abrasive is pressed into the surface under a normal force and then cuts the material under a tangential force [26].

For the matrix area in the A.C., the quartz sands can severely cut 40Cr under applied loads due to their hard abrasive property compared to 40Cr steel. During the initial impact wear, the wear surface is subjected to tangential forces that produce many furrows and chisel marks. As the local stress in the material increases, abrasive grains embed into the wear surface under the action of the normal force, producing cracks. Further impact wear causes plastic fatigue spalling of the matrix. This result shows that the wear mechanism of the matrix area during the early wear process is mainly micro-cutting, and the wear mechanism in the late wear process is mainly plastic fatigue wear.

For the composite area in the A.C., the impact wear resistance of the composite depends on the synergistic effect of the metal matrix and reinforced particles. On the one hand, the ZTA particles are much harder than the quartz abrasives, so they can effectively resist the grinding action of the abrasives on the metal matrix and thus have a protective effect on the matrix. On the other hand, the good toughness of the metal matrix is supported by the ZTA particles. Therefore, the wear resistance of the composite area depends on whether the ZTA particles break or fall off during the impact wear process [26, 32]. As shown in figure 14, because the softer matrix is less supportive of the ZTA particles, the abrasive is more easily embedded while producing many cracks. During continuous impact wear, the particles more easily fall off, which results in severe wear in the composite area. When a hard matrix is in the composite area, the hard ZTA ceramic particles protrude from the matrix surface during wear, reducing the contact between the ZTA particles and the matrix. Only a small amount of cutting marks is left on the matrix surface, thus exhibiting excellent wear resistance. It is shown that the wear mechanism for the composite area with a soft matrix is mainly the shedding of ZTA particles, while the wear mechanism for the composite area with a hard matrix is mainly micro-cutting.
4. Conclusions

In this study, a three-dimensional network interpenetrating structure of ZTA/40Cr steel composites were successfully fabricated by combining 3D printing and squeeze casting, in which the three-dimensional spatial structure is kept intact, while the particles in the composite area are uniformly dispersed. And the effect of different steel matrix hardness on the impact abrasive wear performance of the composites after heat treatment was studied, our research is to establish the foundation for the development of highly wear-resistant architecture composites. The following conclusions were drawn:

(1) In the matrix area and composite area of the architecture composites, the composites with martensite structures have the highest hardness, while the pearlitic structure has the lowest hardness.

(2) Under the same quenching + 460 °C tempering conditions, the wear resistance of the architecture composites is 79.0% higher than that of homogeneous composites, indicating that space-structure design is an effective way to improve the wear performance of composites.

(3) Hardness directly affects the wear performance of composites. The architecture composites with the martensite matrix has the highest wear resistance, which is 32.76% higher than that with the troostite matrix and 163.60% higher than that with the pearlite matrix.

(4) For the matrix area of the architecture composites, the wear mechanism mainly consists of micro-cutting and plastic fatigue wear. For the composite area of the architecture composites, the impact wear resistance of the composite depends on the synergistic effect of the metal matrix and reinforced particles. When the hardness of the matrix is lower, the wear mechanism is mainly plastic fatigue and particle breakage and falls off. When the matrix hardness is higher, the wear mechanism is mainly micro-cutting.

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