Effect of iron powder content on microstructure and mechanical properties of Al₂O₃p/high manganese steel composites prepared by casting infiltration

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Abstract

Al₂O₃p/high-manganese steel-matrix composites were successfully fabricated by gravity casting infiltration, with iron powder added in the preforms to adjust the Al₂O₃p fraction. The effects of the iron powder content (38, 48, and 55 wt%) on the microstructures and mechanical properties of the composites were investigated. With the increase in the iron powder content in the preform, the Al₂O₃p fraction decreased (57–38 vol%), while the hardness and compressive strength of the composite gradually increased. The highest compressive strength was 1000.3 MPa (55-wt% iron powder). The highest work hardening rate (55-wt% iron powder) well reflected the synergistic effect between the matrix and reinforcement to prevent dislocation movement. The water glass binder formed thick interface layers between Al₂O₃p and matrix, which transformed the Al₂O₃/metal interface bonding from mechanical bonding to metallurgical bonding. A too thick interface layer deteriorated the mechanical properties of the composites.

1. Introduction

Wear-resistant parts applied in mining, cement, metallurgy, and electric power industries, such as hammer heads, lining plates, grinding balls, grinding rollers, and grinding discs, are strongly worn off and quickly fail by various materials such as sands, ores, soils, and grinding bodies [1–4]. Traditional metallic wear-resistant materials, such as austenitic high-manganese steel [5], cannot easily simultaneously meet the requirements of high hardness and high toughness. Based on the high strength and toughness of metal materials, ceramic-particle-reinforced metal-matrix composites (MMCs) include high-hardness ceramic particles into the metal materials and exhibit a synergistic coupling effect between the matrix and ceramic particles through interface control to simultaneously meet the requirements of high hardness and high toughness and improve the performances of traditional metal wear-resistant materials. Therefore, MMCs become a new generation of wear-resistant materials with high wear performances [6–10].

In recent years, extensive studies have been carried out on the fabrication and wear resistances of Al₂O₃ particle (Al₂O₃p)-reinforced steel-matrix composites (Al₂O₃p/steel), owing to the high hardness, wear resistance, and low cost of Al₂O₃p and high adaptability to large-scale industrial applications. However, the wettability between Al₂O₃ and molten iron is very low, which hinders the fabrication of Al₂O₃p/steel composites by liquid-phase fabrication technologies such as casting infiltration [11] and leads to poor mechanical properties and wear resistances of the composites due to the poor bonding of the Al₂O₃p/steel interface [12]. To overcome the low wettability, Wang et al [13] plated Ni on the surface of alumina particles and fabricated Al₂O₃p/heat-resistant steel-matrix composites by a negative-pressure infiltration technology. Lu et al [3, 14]
fabricated Al2O3p/40Cr steel-matrix composites by squeeze casting infiltration. Tian et al [15] prepared coarse-grained (1–3 mm) Al2O3p/high-manganese steel-matrix composites by lost foam casting. The above studies overcame the preparation problems of Al2O3p/matrix composites through particle coating, external force, and coarse Al2O3p particles, and thus have limitations in terms of cost and application. Gravity casting infiltration is a promising method to prepare composite materials. Compared to squeeze casting and vacuum casting, the preparation cost is lower, the process is simpler, and it is easier to prepare large-scale and complex composites.

Jiang et al [16] fabricated a honeycomb ZTAp/high-chromium cast iron composite and ZTAp/high-manganese steel composite by gravity casting infiltration combined with powder activation, in which a microscale reactive powder was wrapped around Al2O3p particles in preforms, which reacted with the iron melt and promoted its infiltration into the preforms during casting. ZTAp were coarse particles with sizes of 1–3 mm, which are conducive to the infiltration as well as the honeycomb structure of the ceramic preforms. Jiang et al prepared 1–3 mm coarse-ZTAp reinforced high-chromium cast iron honeycomb composites by gravity casting infiltration. Zhou et al [17] prepared a 150–180 μm fine-particle-reinforced high-manganese steel honeycomb composite by gravity casting infiltration. Thus, there are few reports on the fabrication of fine Al2O3p-reinforced steel-matrix composites by gravity casting infiltration and mechanical properties of Al2O3p/matrix composites.

In this study, fine microscale Al2O3ps (average size: 150 μm) uniformly reinforced high-manganese steel-matrix composites were prepared by a powder-activated gravity casting infiltration technology. An iron powder was added into the preforms to adjust the volume fraction of Al2O3p in the composites. The effects of the iron powder content on the microstructures and mechanical properties of the composites were studied, particularly the structure of the Al2O3p/steel interface.

2. Experimental procedures

2.1. Raw materials

Abrasive-grade Al2O3ps (Al2O3 ≥ 95.0 wt%, Fe2O3 ≤ 0.2 wt%, SiO2 ≤ 1.2 wt%, TiO2 ≤ 3.0 wt%, and magnetic materials ≤ 0.03 wt%), with an average size of 150 μm, were applied as a reinfocer, while ZGMn13 (1.1 wt% C, 13.1 wt% Mn, 0.8 wt% Si, 0.7 wt% Cr, S ≤ 0.05 wt%, P ≤ 0.1 wt%) was used as a matrix material. The applied iron powder (Fe ≥ 98 wt%, C ≤ 0.01 wt%, P and S ≤ 0.03 wt%) had a size of 50 μm. Figure 1 shows the morphologies of Al2O3p and iron powder.

2.2. Fabrication of composites

Al2O3p and iron powder with mass ratios of 10:6, 10:9, and 10:12 (contents of iron powder of 38%, 48%, and 55%, respectively) were mixed in a ball mill tank at a speed of 40 r min⁻¹ for 2 h. A sodium silicate binder (3 mass%, modulus: 3.0) was added to the mixture and fully stirred. The mixture was filled into a mould and heated to 200 °C in a muffle furnace for 2 h to obtain the Al2O3p preforms.

A high-manganese steel was melted with a medium-frequency induction furnace. The preforms were fixed in the cavity of a sand box. Finally, gravity casting was carried out at 1600 ± 10 °C. Al2O3p/40Cr steel-matrix composites were obtained after the steel melt solidified.

A LJWJ2515H4S water jet cutter was used to cut the composites from the casting ingots, and then machined to compressive test specimens with sizes of 10 mm × 10 mm × 20 mm and metallicographic samples with sizes of 10 mm × 10 mm × 10 mm. The composites, whose preforms had iron powder contents of 38%, 48%, and 55%, are denoted as S1, S2, and S3, respectively. High-manganese steel samples were also cut from the composite casting ingots without ceramic preforms, denoted as S0. The hardness of the materials were measured with an HR-150 Rockwell hardness tester. The microstructure of the materials was observed by a Leica EZ4D optical metallographic microscope and S-3400N scanning electron microscope. The composition was analysed by a Bruker energy spectrometer. The volume fraction of Al2O3p in the composite was calculated by the Image-Pro Plus software. The compressive properties of the materials was measured with an SHT4305 mechanical testing machine.

3. Results and discussion

3.1. Optical micrographs

Figure 2 shows optical micrographs of the Al2O3p/40Cr steel composites and matrix material. Figures 2(a)–(c) show the composites S1, S2, and S3, respectively. They show grey reaction interface layers between the matrix and Al2O3p. Some interface layers are too thick and connect the adjacent Al2O3ps. From the sample in figure 2(a) to that in figure 2(c), the Al2O3p fraction in the matrix gradually decreases as well as the interface layer. Figures 2(d) and (e) show the as-cast microstructure of the matrix alloy S0, composed of matrix grains and coarse network of carbides distributed at grain boundaries. Figure 2(f) shows the composite S2
Figure 1. Morphologies of the raw materials: (a) Al$_2$O$_3$ particles and (b) iron powder.

Figure 2. Optical micrographs of the composites and matrix: (a) S1, (b) S2, (c) S3, (d) S0 at a low magnification, (e) S0 at a high magnification, and (f) S2 at a high magnification.
microstructure at a high magnification, in which Al₂O₃p well contacts the matrix, without obvious cracks, casting defects, porosities, and shrinkage cavities. The matrix around Al₂O₃p is a grey pearlite and white ferrite. These pearlite and ferrite phases could have emerged from the addition of iron powder in the preforms. The dilution of the infiltrated high-manganese steel melt by the iron powder in the preforms during casting reduces the carbon and manganese contents so that the composite cannot achieve a single-phase austenite microstructure, but only forms the pearlite and ferrite structure [18]. Through a calculation with the Image-Pro Plus software, the volume fractions of Al₂O₃p (including the interface layer) in figures 2(a)–(c) are determined to be 57%, 48%, and 38%, respectively. Figure 3 shows the effect of the mass ratio of the iron powder in the preforms on the volume fraction of Al₂O₃p in the composites. A lower iron powder content led to a higher Al₂O₃p fraction in the composite; i.e., the addition of iron powder adjusted the volume fraction of Al₂O₃p in the composites.

3.2. Phases in the composites
Figure 4 shows the phase analysis results of S2, which are typical for all composites besides the difference in the addition amount of iron powder. In addition to ferrite and Al₂O₃, there is FeAl₂O₄ or MnAl₂O₄ in the

![Figure 3. Relationship between the amount of iron powder in the preform and volume fraction of Al₂O₃p in the composites.](image)

![Figure 4. X-ray diffraction (XRD) analysis results of S2.](image)
It is not possible to determine which phase is present, because FeAl₂O₄ and MnAl₂O₄ have almost the same diffraction peaks. This requires further characterisation.

### 3.3. Interface analyses of the composites

In this study, a thick reaction interface layer is formed around Al₂O₃ₚ, which has a significant impact on the bonding of Al₂O₃ and steel matrix. Therefore, it is necessary to thoroughly study the interface layer and its combination with Al₂O₃ₚ and steel.

Figure 5 shows the results of energy-dispersive spectroscopy (EDS) scanning of the interface of S₃. Figure 5(a) shows that the black particles are Al₂O₃ₚ, the white part is the matrix, and the grey part is the interface layer. The interface layer is mainly composed of amorphous substances[19], such as Na₂SiO₃, transformed from the water glass binder, so that it cannot be detected by the XRD pattern in figure 4.

Figures 5(b)–(f) show that the concentrations of Si, Mn, O, and Al elements in the interface layer are high. Na, Si, and part of O should originate from the sodium silicate binder, Al and part of O from Al₂O₃ₚ, and Mn from the high-manganese steel matrix. The high concentrations of Mn and Al atoms in the interface layer indicate that Mn diffuses from the steel liquid to the interface layer during pouring and that Al in Al₂O₃ₚ diffuses from Al₂O₃ₚ to the interface layer. In other words, when the high-manganese steel liquid was infiltrated into the Al₂O₃ preform, reactions occurred between the steel liquid and binder as well as between Al₂O₃ₚ and binder, so that large numbers of Mn atoms from the liquid steel and Al atoms in Al₂O₃ migrated to the amorphous interface layer.

Further, the element composition variations between the interface layer, Al₂O₃ₚ, and steel matrix are thoroughly analysed through EDS line scanning, as shown in figure 6. The composition of the interface layer (area (1) + (2)) is mainly Si, Mn, O, and Al, which is consistent with that in figure 5. The comparison of the contents of Fe and Mn in the interface layer shows that the generated phase in figure 4 is MnAl₂O₄, rather than FeAl₂O₄, because the Fe content is considerably lower than the Mn content.

Two diffusion regions are formed between the interface layer and steel matrix and interface layer and Al₂O₃ₚ. Area (2) is the main region of the interface layer, in which the contents of Si, Mn, O, and Al remain stable. Area (1) is the diffusion region between the interface layer and steel matrix, with a thickness of approximately 2 μm. In area (1), the content of Fe increases largely from the low content in the interface layer to the high content in the steel, while the content of Si decreases largely from the high content in the interface layer to the low content in the steel. The contents of Mn, O, and Al change simultaneously with that of Si. This reflects the gradual diffusion of elements between the interface layer and steel matrix. Notably, the source of Mn element is the high—manganese steel matrix. As a result of its diffusion, the content of Mn element in the interface layer is twice that
This further shows that Mn reacts with the binder to form MnAl2O4 in the interface layer, so that its Mn content is higher than the solid solution value in the steel, as Mn is a strongly oxidising element [20].

Area (3) is the diffusion region between Al2O3 and interface layer, with a thickness of 4 μm, where the Si content decreases largely from the high content of the interface layer to the low content of Al2O3 (almost 0). The diffusion ability of Mn is so high that it continues to diffuse into Al2O3 across the interface layer. In the combined area (3), the total depth of Mn element diffusing into Al2O3 is approximately 12 μm, considerably larger than the diffusion depth (4 μm) of Si in Al2O3, which also demonstrates that Mn has a high ability to react with Al2O3.

There is a diffusion zone between the interface layer and steel matrix and between the interface layer and Al2O3, which indicates a reactive interface between the interface layer and steel matrix.

### 3.4. Mechanical properties of the composites

#### 3.4.1. Hardness

Table 1 shows the mechanical properties of the tested materials. The hardness of the high-manganese steel is 43.7 HRC as the as-cast structure contains a large amount of carbides (figure 2(e)). With the increase in the iron powder content in the preform, the hardness of the composites gradually increases from 41.1 to 50.1 HRC. (1) With the increase in the iron powder content, the fraction of Al2O3p in the composites decreases from 57 to 38 vol%, while the hardness unexpectedly increases. (2) In addition, unexpectedly, the hardness of the composite containing 57-vol% Al2O3 is 2.63 HRC lower than that of the matrix steel. According to the mixing law of composites [21], the hardness of the composite should increase with the volume fraction of hard reinforcements and be higher than those of the matrix alloys. Therefore, the results of this experiment are not consistent with the theoretical prediction.

#### 3.4.2. Compressive properties

Figure 7 shows the stress–strain curves of the Al2O3p/high-manganese steel composites and matrix steel under a unidirectional compression. Figure 7 and table 1 show that, with the increase in the iron powder content in the preform, the compressive strength of the composite increases. This trend is the same as that of the hardness. In addition, compared to the matrix steel, the strengths and compressive strains of the composites are considerably lower, while the elastic moduli of the composites are considerably higher according to the slopes of the curves of
the composites. Considering the considerable increases in the hardness and moduli of the composites compared to the matrix, the composites could be used to improve the wear resistance of the high-manganese steel under a low impact energy.

The compressive strength of the Al₂O₃p/high-manganese steel composite with 55-wt% iron powder is 1000.3 MPa, higher than 918.86 MPa for the reported honeycomb ZTAp/high-manganese steel-matrix composite (80–100-mesh ZTAp, porosity of 74.8% in the preform) [22]. The honeycomb composite is an architecture composite, and thus should have a higher strength than those of ceramic-particle uniformly distributed composites. Therefore, the composites prepared in this study have excellent strengths.

Figure 8 shows the work hardening rate ($\dot{\theta}$) and effective flow stress ($\sigma - \sigma_y$) curve. The work hardening rate characterises the change rate of the flow stress with the strain ($\dot{\theta} = d\sigma/d\varepsilon$). The effective flow stress ($\sigma - \sigma_y$) is the effective stress for plastic deformation, i.e., the stress obtained after subtracting the yield stress from the total stress [23]. Figure 8(a) shows that it well reflects the work hardening ability of the high-manganese steel. Because of the high dislocation density in the austenitic high-manganese steel during deformation, a large number of dislocations form a high-density dislocation region, which hinders the dislocation movement, produces a strengthening effect, and results in work hardening of the high-manganese steel [24]. Figure 8(b) shows that the Al₂O₃p/high-manganese steel composite has a high work hardening ability as that of the high-manganese steel matrix. The highest work hardening rate and largest effective flow stress are obtained for the composite with the 55-wt% iron powder. The parabolic curve of the Al₂O₃p/high-manganese steel composite with the 55-wt% iron powder with two peaks and valleys can better reflect the synergistic action between the reinforcement and matrix to prevent dislocation movement [25]. These types of matrix and reinforcement have a good synergistic effect on the ability to block dislocations, which results in the best compressive properties. According to the analysis in figure 3, the composite with the smallest interface layer has the best work hardening rate. Thus, a thinner interface layer yields a better comprehensive performance. We believe that the thickness of the interface layer will be one of the crucial factors of composites of interest in material research in the future.

3.4.3. Compression fracture morphologies of the composites

Figure 9 shows the fracture morphologies of S1 and S3 under the same magnification. As shown in figures 9(a) and (b), the fracture surface of S1 is mainly composed of the interface layer and Al₂O₃, with a low amount of steel, which shows that the fracture occurs preferentially in the interface layers. There are two parallel cracks extending in the thick interface layer. The longer crack passes through Al₂O₃p and Al₂O₃p/steel interface, which indicates cracking at the Al₂O₃p/steel interface. A few small dimples are observed on the metal fracture surface, which indicates a ductile failure of the matrix. A cascade fracture is observed in one Al₂O₃p, which indicates a cleavage fracture [26]. These characteristics show that the fractures of the composites are mixed; brittle fracture is the main mode. Figures 9(c) and (d) show that the characteristics of the fracture morphology of S3 are similar to those of S1.
Figure 8. Work hardening rate ($\dot{\theta}$) and effective flow stress ($\sigma - \sigma_y$) curve: (a) high-manganese steel and (b) Al$_2$O$_3$/high-manganese steel composite.

Figure 9. BSE and SE images of the fracture morphologies of (a), (b) S1 and (c), (d) S3, respectively.
3.4.4. Effect of the composite microstructure on the mechanical behaviour

The above mechanical property analyses show that, with the increase in the iron powder content in the preform, the fraction of $\text{Al}_2\text{O}_3$ in the composite decreases, while the hardness and compressive strength of the composite increase. The hardness of the composite with a high $\text{Al}_2\text{O}_3$ volume fraction (57 vol%) (38 wt% iron powder) is lower than that of the matrix. These results are contrary to the prediction by the composite mixing law.

According to the analyses of the microstructures and fracture surfaces, the contradiction between the experimental results and mixing law is attributed to the thick interface layers. The interface layers consist of a silicate amorphous material, $\text{MnAl}_2\text{O}_4$, and other fine crystal phases. The amorphous phases are hard and brittle. They have two effects on the composites. The first is to transform the $\text{Al}_2\text{O}_3$/metal interface bonding (figure 6), which has a favourable influence on the mechanical properties of the composites. Second, the too thick interface layer is conducive to crack initiation and propagation (figure 8), which results in a serious deterioration of the mechanical properties of the composites. This occurs because of the existence and cracking effect of the thick interface layer in the composite, and thus the strengthening effect of $\text{Al}_2\text{O}_3p$ on the composite cannot be fully manifested. The increase in the iron powder content in the preform is conducive to a uniform dispersion of the binder in the preform and melting, floating, and removal of water glass during the subsequent infiltration to reduce the thickness of the amorphous interface layer and improve the mechanical properties of the composite. Therefore, it is important to reduce the thickness of the interface layer in future studies.

4. Conclusions

(1) $\text{Al}_2\text{O}_3p$/high-manganese steel composites were successfully fabricated by gravity casting infiltration, with water glass as an adhesive and iron powder as an adjusting agent for the $\text{Al}_2\text{O}_3p$ fraction.

(2) With the increase in the iron powder content in the preform from 33 to 55 wt%, the $\text{Al}_2\text{O}_3p$ fraction decreased from 57 to 38 vol%, while the hardness and compressive strength of the composite gradually increased. When the content of iron powder was 55 wt% and the $\text{Al}_2\text{O}_3p$ fraction was 38 vol%, the compressive strength of the $\text{Al}_2\text{O}_3p$/high-manganese steel composite reached 1000.3 MPa and the work hardening rate ($\theta$) and effective flow stress ($\sigma - \sigma_y$) curve could better reflect the synergistic action between the reinforcement and matrix to prevent dislocation movement.

(3) The water glass binder formed thick interface layers between $\text{Al}_2\text{O}_3p$ and steel in the composites, which mainly consisted of amorphous materials and $\text{MnAl}_2\text{O}_4$ crystal phase. The interface layer formed diffusion regions with the matrix and $\text{Al}_2\text{O}_3p$, and thus changed the $\text{Al}_2\text{O}_3$/metal interface bonding from mechanical bonding to metallurgical bonding.

(4) The cracks in the $\text{Al}_2\text{O}_3p$/high-manganese steel matrix composites mainly occurred in the amorphous interface layer. A too thick interface layer deteriorated the mechanical properties of the composites.

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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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References

[1] He H, Jiang Y H, Ru J and Hua Y X 2021 Compression performance and abrasive wear resistance of CuNi-modified zirconium oxide-toughened alumina particles-reinforced iron matrix composites phys Status Solidi A 219 2100625
[2] Qiu B, Xing S, Dong Q and Liu H 2020 Comparison of properties and impact abrasive wear performance of ZrO2-AL2O3/Fe composite prepared by pressure casting and infiltration casting process Tribol. Int. 142 105979
[3] Ma W, Lu D H, Tang L, Gong W H and Yan Q H 2021 Effect of matrix hardness on the impact abrasive wear performance of ZTAp/steel architecture composite Mater. Res. Express 8 026507

[4] Li C, Li Y, Shi J, Li B, Li Y, Gao Y, Zhao S, Goei R, Yoong and Tok A I 2022 Enhancing interfacial bonding of oxide ceramic particles/high manganese steel-based composites by NiCr alloy coating Materials Today Communications 31 103257

[5] An H and Rui Z 2018 Research on the hardening mechanism of high manganese steel in plastic deformation and the modifying property of it Modern Manuf. Eng

[6] Rohatgi P K, Ray S and Liu Y 1992 Tribological properties of metal matrix-graphite particle composites Int. Mater. Rev. 37 129–52

[7] Wang Y Q, Afzar A M, Jiang J H, Han K S and Song J J 2010 Room temperature dry and lubricant wear behaviors of Al2O3/SiCp/Al hybrid metal matrix composites Wear 268 863–70

[8] Zhang Z, F, Zhang L, C and Mai Y, W 1995 Wear of ceramic particle-reinforced metal-matrix composites J. Mater. Sci. 30 2687–91

[9] He L and Hassani M 2020 A review of the mechanical and tribological behavior of cold spray metal matrix composites J. Therm. Spray Technol. 29 1563–608

[10] Alizadeh A, Khayami A, Karamouz M and Hajizamani M 2022 Mechanical properties and wear behavior of Al5083 matrix composites reinforced with high amounts of SiC particles fabricated by combined stir casting and squeeze casting; A comparative study Ceram. Int. 48 179–89

[11] Jian C, Gu M and Pan F 2001 A model of work of adhesion for reactive metal/ceramic systems Metallurgical and Materials Transactions A 32 2033–8

[12] Li C, Li Y, Shi J, Li B, Goei R, Yoong and Tok A I 2022 The effect of multi-arc ion plating NiCr coating on interface characterization of ZrO2–Al2O3 ceramics reinforced iron-based composites Vacuum 196 110758

[13] Bao C, Xing J, Gao Y and Wang E 2003 Wear resistant of Al2O3/heat-resistant steel at high temperature Key Eng. Mater. 280–283 1119–22

[14] Lu D H, Li H Z and Ren B 2018 Effect of Si content on impact-abrasive wear resistance of Al2O3p/steel composites prepared by squeeze casting J. Iron. Steel Res. Int. 25 984–94

[15] Tian S X, Tu X H, Yang H and Li W 2017 Research the wear resistance of high manganese steel composite material reinforced with Al2O3/Ceramic Foundry 66 476–80

[16] Zhou M J, Sui Y D and Jiang Y H 2020 Growth behavior of aluminum borate whiskers on zirconia toughened alumina (ZTA) particle surface Ceram. Int. 46 8839–8847

[17] Zhou M J, Wang N, Sui Y D and Jiang Y H 2021 Effect of honeycomb wall thickness on strength of ZTAp/high-manganese steel structural Composites Foundry 70 74–8

[18] He J A and Wang Y W 2001 Material wear and wear resistant materials (ShenYang: Northeast University Press)

[19] Sui Y, Zhou M and Jiang Y 2018 Characterization of interfacial layer of ZTA ceramic particles reinforced iron matrix composites J. Alloys Compd. 741 1169–74

[20] Homma R, Kadoi K and Inoue H 2021 Effects of Ti and Al on the formation of intragranular ferrites in the ultra-low-oxygen Si-Mn weld metals of low-carbon steel Materials Today Communications 29 102963

[21] Kim H S 2000 On the rule of mixtures for the hardness of particle reinforced composites Materials Science & Engineering A 289 30–5

[22] Wang N 2018 Effect of space configuration size on properties of ZTAp/high manganese steel matrix composites (Kunming: Kunming University of Science and Technology)

[23] Ghosh A, Roy A, Ghosh, Ghosh A and Ghosh M 2021 Influence of temperature on microstructure, crystallographic texture and mechanical properties of EN AW 6061 alloy during plane strain compression Materials Today Communications 26 101808

[24] Chen H, Zhao D, Wang Q L, Qiang Y H and Q J 2017 Effects of impact energy on the wear resistance and work hardening mechanism of medium manganese austenitic steel Friction 5 447–54

[25] Zeng H B, Sui Y D, Niu G, He H, Jiang Y H and Zhou M J 2021 Effect of alloy powder on the properties of ZTA particles reinforced high chromium cast iron composites Mater. Res. Express 8 036509

[26] Hull D 1999 Fractography: observing, measuring, and interpreting fracture surface topography (Cambridge: Cambridge University Press)