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Preparation and Impact-abrasive Wear Behavior of NbC Reinforced iron Matrix Composites

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Abstract: Ceramic particle reinforced metal matrix composites (MMCS) have been recognized as a hot research hotspot as a local wear-resistant material for vital parts of mechanical equipment. Fe60 matrix and NbC particle (NbCp) reinforced Fe60 composites(NbCp/Fe60) were produced through vacuum sintering and tested on an MLD-10B Impact Wear Rig. As revealed by the results, NbCp played the role of fine grain strengthening. Under the mass fraction of 7% and at the sintering temperature of 1175°C, NbCp/Fe60 composite was found with uniform microstructure, superior hardness and relative density. The impact abrasive wear performance was higher than Fe60. NbCp/Fe60 composite with 7%NbC exhibited the optimal impact abrasive wear performance. Under the mass fraction of 8%, the composite begin to aggregate and the performance was significantly reduced. The impact abrasive wear mechanisms of NbCp/Fe60 composites primarily consisted of micro-cutting or micro-ploughing, impact plastic deformation and fatigue spalling.

Keywords: Composites material; NbC reinforced Fe60; Reinforcing particles; Impact abrasive wear

1. Introduction

Equipment in coal mining machinery, metallurgical industry and highway

transportation industry are subjected to impact abrasive wear, thus significantly shortening the service life of equipment and triggering economic losses of enterprises^[1-3]. Accordingly, it is of rising significance to design a reasonable process to prepare novel resistant impact abrasive wear composite materials, so as to produce vital parts of the equipment.

Ceramic particle reinforced metal matrix composites have been accepted and developed for their high hardness, strength, toughness and low density^[4]. Thus, it has become a research hotspot to investigate the preparation technology and properties exhibited by ceramic particle metal matrix composites. With the addition of ceramic particles, the microstructure of the steel matrix can be improved due to thermal stability dispersion, thus inhibiting the recrystallization and grain growth of austenite. When ceramic particles are evenly introduced into the steel matrix, local supercooling and large amount of crystallization will occur, and ceramic particles become the active center of crystallization, thus significantly affecting the mechanical properties of steel matrix composites^[5-11].

Niobium carbide (NbC) ceramic particles are characterized by high hardness, high melting point (nearly 3610°C) and chemical stability. NbC ceramic particles are capable of inhibiting the recrystallization of steel matrix, improving its strength, toughness and wear resistance of the matrix, as well as strengthening the matrix^[12-14]. Qin Zhigang prepared NbC particles reinforced 45CrMoV matrix composites using the powder metallurgy method. Compared with 45CrMoV, the wear resistance exhibited by the composites was significantly enhanced^[15]. Li Ziyang prepared WC/NbC particle

reinforced high chromium iron matrix composites on the basis of powder metallurgy and explored their properties. As revealed by the results, the tensile hardness and wear properties exhibited by the composites were significantly improved after the addition of WC and NbC^[16]. Wen Hao Kan et al. prepared the matrix composites of AISI304 stainless steel reinforced with NbC. As revealed by the results, NbC significantly reinforced the matrix and enhanced the hardness and wear resistance of the matrix^[17]. A series of NbC/FeCrNiCu high entropy alloy matrix composites (2.5, 5, 7.5 and 10 vol% of NbC) were prepared through vacuum induction melting. As revealed by the results, compared with the base alloy, the tensile yield strength, ultimate tensile strength and ductility of the new composite increased first and then decreased with the increase in the NbC content^[18]. Pang Yadan et al. tested the density and mechanical properties exhibited by TiC/NbC ceramic particles. As revealed by the results, the relative density of ceramic particles containing 16.67% TiC/NbC was the highest, and the Vickers hardness and bending strength were higher. TiC/NbC ceramic particles were uniformly dispersed in the iron matrix, and the interface between reinforcement and iron matrix was found to be excellent ^[19].V.L.Arantes et al. prepared Al₂O₃/NbC gradient composites by using technology. The material was found with higher density and better fracture toughness^[20]. High chromium cast iron and alloy steel are preferred as metal matrix composites. Fe60 and Fe45 are Fe-Cr-B-Si self-fluxing alloy powder, pertaining to high chromium cast iron alloy. It is a good choice to use them as wear-resistant materials since they are characterized by excellent wear resistance, impact and hardness. Thus, it is suitable for the repair

and pre protection of agricultural machinery, construction, mining, fan and other vulnerable parts.

In brief, numerous studies have been conducted on the preparation of composites with NbC as reinforcement phase, and some research results have been achieved. However, the preparation and wear behavior of NbCp reinforced Fe60 composites (NbCp/Fe60) have been rarely studied, thus hindering the development and prospect of NbCp/Fe60. NbCp/Fe60 was prepared through vacuum sintering, and the preparation process, strengthening mechanism, wear properties and wear mechanism were investigated. The above research results provide help for composite materials to solve the wear problems of related equipment components, (e.g., scraper conveyor plate).

2. Experimental materials and method

2.1. Powders and composite preparation

In this study, NbCp/Fe60 was prepared through vacuum sintering with NbC particle (NbCp) and Fe60 as the raw materials. Fig. 1, Table 1 and Table 2 present the the Electron microscopy (SEM) images and parameters of NbCp and Fe60. There have been rare studies on the preparation of NbCp/Fe60 through vacuum sintering, and the mass fraction of NbCp, sintering temperature and holding time significantly affect the properties exhibited by NbCp/Fe60. Accordingly, Exploratory experiments should be performed to prepare NbCp/Fe60 with excellent properties. Table 3 illustrates the preliminary experimental scheme designed in accordance with the actual situation.

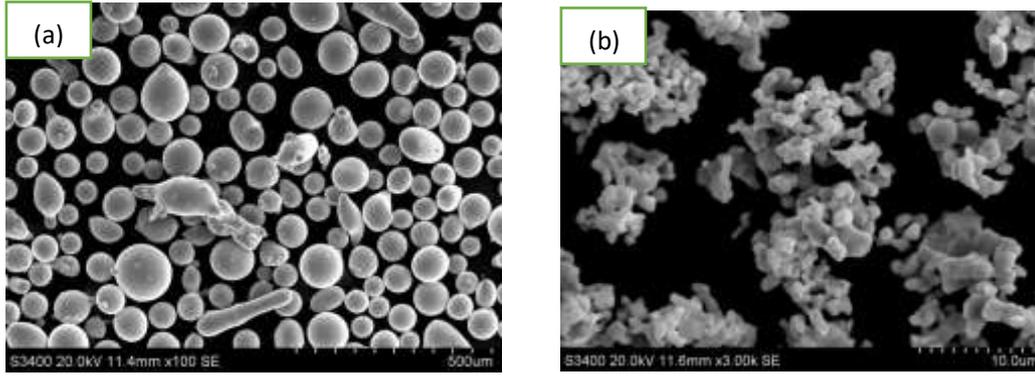


Fig. 1 (a) SEM pictures of Fe60, (b) SEM pictures of NbC_p

Table 1 Parameter information of raw material

Purity (%)	Particle size/(mesh)	Melting point/(°C)	Density/(g/cm ³)	Coefficient of thermal expansion/(10 ⁻⁶ K ⁻¹)	Hardness/(HV)	Modulus of elasticity/GPa
≥99.8	300	3500	7.79	6.65	2400	235

Table 2 Parameter information of raw material

Purity (%)	Particle size (mesh)	(wt%)						
		<i>C</i>	<i>Si</i>	<i>B</i>	<i>Ni</i>	<i>Cr</i>	<i>W</i>	<i>Fe</i>
100	300	4.0-4.5	2.0-3.0	1.5-2.5	4.0-6.0	24-30	2-3	Surplus

Table 3 Experimental scheme

NbC (wt. %)	Sintering temperature/(°C)	NbC particle size/(um)	Fe60 Particle size/(um)	Holding time/(h)
0~15	1165/1175/1185 /1195	5	48	1

NbC_p and Fe60 were mixed using the planetary ball mill. As revealed by several exploratory experiments and with the help of relevant researchers, when the loading volume accounted for 40% - 50% of the ball cylinder volume, it was considered the best. Thus, a ball material ratio of 2:1 and a milling time of 70 min were set; The mixture and binder polyvinyl alcohol (PVA) were poured into a beaker and then

stirred with a glass rod, and then pressed with a powder tablet press. To make the compacts more uniform, the segmented pressing was adopted. In accordance with the repeated tests and tests on site, the following steps were achieved. first, a 10t load was applied, and the pressure was held for 2 min. Subsequently, a load of 20 t was applied, and the pressure was held for 3 min, so the mixed material had enough time to flow and the density became uniform. Lastly, the pressure increased to 30t, and the pressure was held for 5 min, so the mixed material could flow and produce plastic deformation. The gap between particles was filled, and the compacts were densified. The pressed preformed samples were put into a vacuum sintering furnace for sintering. First, before the temperature increased to 200°C, the heating rate was 10 °C/min, and then the heat was preserved for 1 h because the volatilization temperature of PVAs was 200 °C^[21]. If the volatilization of PVAs was not sufficient without heat preservation, some gases would not be discharged from the compacts in time, thus resulting in gaps in the sintered samples and defects in the samples, and more significantly affecting the microstructure and properties exhibited by the sintered samples with mixed materials. It was heated to the set sintering temperature at the same heating rate and then the heat was preserved for 1 h. Holding could make the compact fully sintered. Lastly, it was cooled to ambient temperature with the furnace after sintering. Fig. 2. illustrates the preparation process of NbC_p/Fe60 composites.

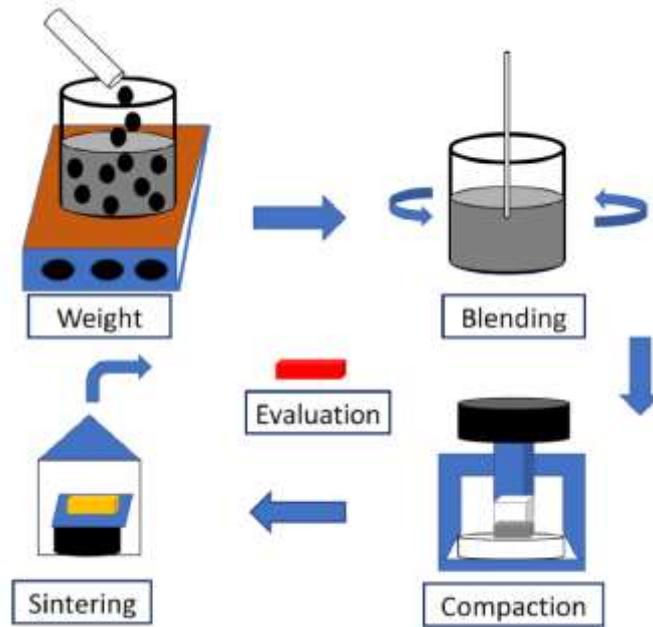


Fig. 2. The basic steps of preparing composite materials by powder metallurgy

2.2. Test method

2.2.1 Hardness

The hardness of the composite was tested using 450svd digital Vickers hardness tester. The load was 150kg and the loading time was 10s. Random 5 points were randomly tested on different parts of the respective sample. Subsequently, the average value was taken as the hardness result. The phase composition of the samples was analyzed using an Ultima IV XRD. The metallographic specimens (10 mm× 10mm × 8 mm) were prepared based on the standard mechanical polishing techniques and etched with 4% nitric acid ethanol solution. Hitachi S3400N and Gemini 300 scanning electron microscopes were employed to observe the microstructure and interface bonding of the composites. Furthermore, the energy spectrometer of SEM was adopted to study the composition of the composites.

2.2.2 Density reduction coefficient

The density of samples (ρ_1) was obtained using the Archimedes drainage method. To accurately indicate the densification degree of the sintered sample containing NbC, the density growth coefficient (σ) of NbC/Fe60 composites was obtained based on the density of Fe60. The σ can be calculated by:

$$\sigma = \left(1 - \frac{\rho_1}{\rho_2}\right) \times 100\%$$

Where ρ_2 denotes the density of sintered sample pure Fe60.

2.2.4 Impact abrasive wear tests

The dynamic load MLD-10B wear test machine was employed for the impact abrasive wear test (Fig. 3). The sample size was 30 mm×10 mm×10 mm, the abrasive material was quartz sand with 20~40 mesh, the flow rate reached 50 kg/h, the rubbing pair was Cr12MoV, the hardness was HRC57, and the outer radius of the grinding ring reached $R_w=25$ mm. The internal radius was $R_n=15$ mm, the rotation speed was 200 r/min, the impact energy was 2J, the impact frequency was 150 times/min, and the impact wear time reached 30 min. The sample was cleaned, air-dried and stabilized, and the quality of the standard sample was measured as the "original mass(W_1)". The experiment time of the respective group was 1 h. After the respective was performed experiment, the surface of the sample was immediately purified and cleaned with anhydrous ethanol. After the cleaning process, the moisture remaining on the sample surface was dried with a hair dryer, the quality of the standard sample(W_2) was weighed after the test with an electronic analysis balance, the wear amount was calculated, and the relative wear resistance (ε) of NbCp/Fe60 was obtained based on the wear loss of Fe60 matrix(W_0), which are written below:

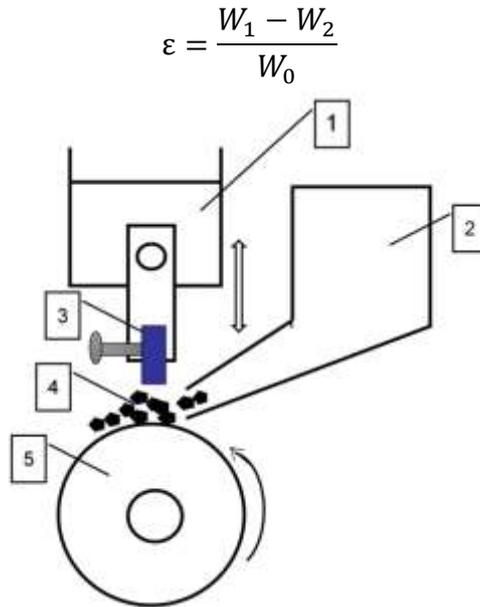


Fig. 3 (a) Schematic diagram of impact wear test rig, 1 Dropping hammer, 2 Stand funnel, 3 Test Specimen, 4 Quartz sand, 5 Lower specimen; (b) Size of upper specimens (c) SEM morphology of quartz abrasive particles.

3. Results and discussion

To prepare of particle reinforced metal matrix wear-resistant composites, the hardness and density of composites (macroscopic), as well as the uniformity, microstructure and interface properties exhibited by composites (microscopic) reflect the properties exhibited by composites to a large extent. The effects of NbCp mass fraction, sintering temperature and holding time on NbCp/Fe60 were investigated. A better process was achieved in the preliminary exploratory experiment, as presented in Table 4.

Table 4 Better process parameters of NbCp/Fe60

NbC (wt. %)	Sintering temperature/(°C)	Holding time/(h)
0	1190	1
1~15	1175	1

The correlation between sintering temperature, NbC content and holding time was explored. When the sintering temperature was low, the underfiring phenomenon occurred. At a high sintering temperature, serious sample melting phenomenon occurred, thus resulting in excessive shrinkage of the material, which became difficult to form and hindered the preparation of composite materials. The various specimens are presented in Fig. 4.

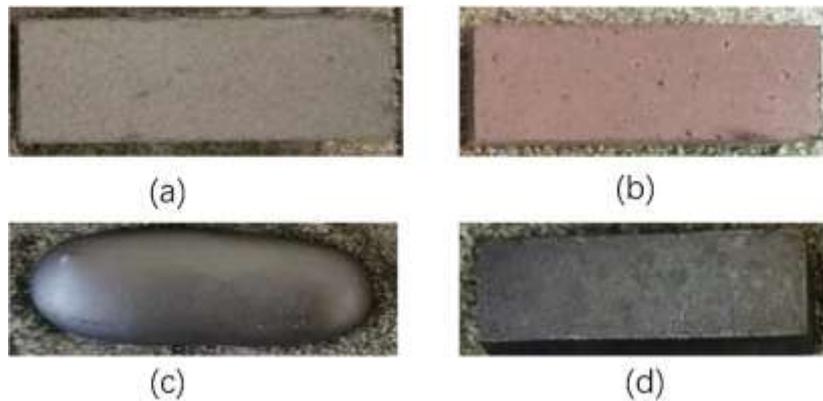


Fig. 4 Specimen topography; (a) Pressed blank specimen (b) low sintering temperature specimen (c) sintering temperature excessive specimen (d) better sintering specimen

Through the above test, the apparent density of the sintered pure Fe60 specimen was measured as 7.81g/cm^3 , significantly close to the density of Fe60p before sintering 7.85g/cm^3 , which further revealed that the above preparation process was more reasonable. The coefficient of growth of the density of the NbC composite with different amounts relative to the density of the matrix and the change law with the mass fraction of NbCp were obtained (Fig. 5).

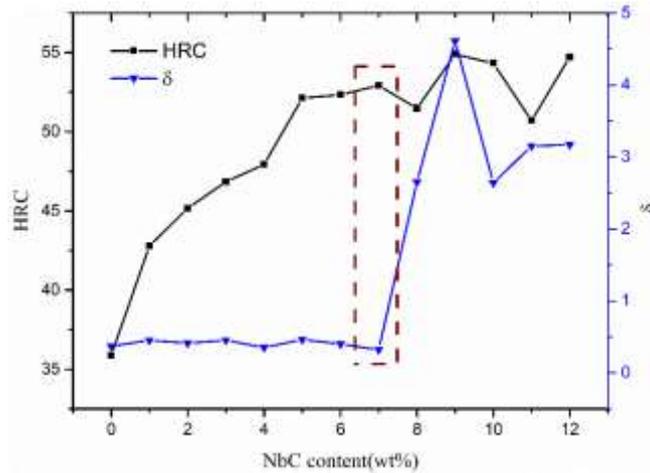


Fig. 5. Effect of mass fraction of NbC on hardness of composites and variance

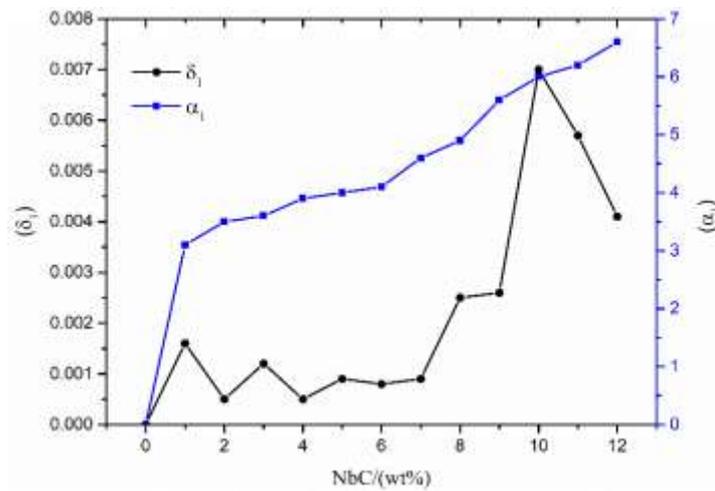


Fig. 6. Effects of NbC mass fraction on density growth coefficient and fluctuation

Fig. 5 presents the Brinell hardness of sintered sample with pure Fe60 matrix, which was relatively low. After the addition of NbCp, the hardness of composite material was significantly improved compared with that of pure Fe60. Under the mass fraction of lower than 7%, the hardness of NbCp/Fe60 increased with the increase in the NbCp mass fraction. When the NbC mass fraction was higher than 7%, the hardness changed irregularly. When the mass fraction of NbC was lower than 7%, the hardness fluctuation (variance) of NbCp/Fe60 is relatively small and the uniformity became high. When the mass fraction of NbCp was higher than 8%, the variance value of the composite increased, the hardness of the composite increased, the

uniformity was reduced, and agglomeration phenomenon might occur in the microstructure. As depicted in Fig.6, when the mass fraction of NbC was lower than 7%, the density reduction rate of the composite increased with the increase of the mass fraction of NbC, thus suggesting that adding NbCp into the pure Fe60 matrix could reduce the density of the material. When the mass fraction of NbCp was higher than 7%, the density reduction rate of the composite material increased dramatically, thus suggesting that the density of the composite material was low. As a result the poor compactness and a large fluctuation phenomenon were found, which further demonstrated that the structure of the material was not uniform, and agglomeration occurred. The performance parameters of 7%NbCp samples were generally good, as shown in box in Fig. 5.

The reasons for the above phenomenon are as follows. The hardness of NbCp enhanced phase was significantly higher than that of Fe60 matrix, and the NbCp with higher hardness was dispersed in the Fe60 matrix to achieve the strengthening effect of the second phase. Adding NbCp to Fe60 could hinder the grain growth, improve the microstructure, enhance the deformation resistance of Fe60 matrix, and increase the hardness of composites. The addition of carbide ceramic particles could refine the matrix grain and enhance the hardness and bending strength of iron matrix composites. Besides, the addition of carbide ceramic particles could significantly refine the grain size and enhance the mechanical properties exhibited by composites^[22]. Fe atoms were replaced by Cr, Ni and other alloying elements to form replacement solid solution. The solid solution effect resulted in lattice distortion of the matrix, and

atoms should to overcome greater energy in the process of movement, to enhance the hardness of materials. With the increase in the NbC mass fraction, the content of NbC particles in the composite increased, and the hardness of the composite was enhanced. When NbC mass fraction was excessively high, NbCp content was too much, there was a serious impediment to the end in the process of sintering atom diffusion in solid flow, viscous flow and diffusion, thus leading to the local small area of the component of metal matrix composites uneven. As a result, the composite particle agglomeration was enhanced to a certain extent, so the microstructure of the composite became uneven, and the hardness was volatile. The density of NbCp(7.79g/cm³) was lower than that of Fe60p(7.85g/cm³), so the overall density of the composite was lower than that of the matrix Fe60p. When joining excess NbC (mass fraction was higher than 7%), excessive NbCp could inhibit the formation of the liquid phase sintering. The formation of the liquid phase could usually enhance the densification of the composite, lower porosity, thus resulting in a decline in the hardness of the composite material, Besides, it would easy to have a reunion phenomenon, thus resulting in sharp composite density drop with the increase of the mass fraction of NbC. Furthermore, the above irregular phenomenon, confirmed that sintering composites could not be desirable at this time.

SEM and XRD were adopted to analyze the microstructure and XRD of the sintered composites, as illustrated in Fig. 7.

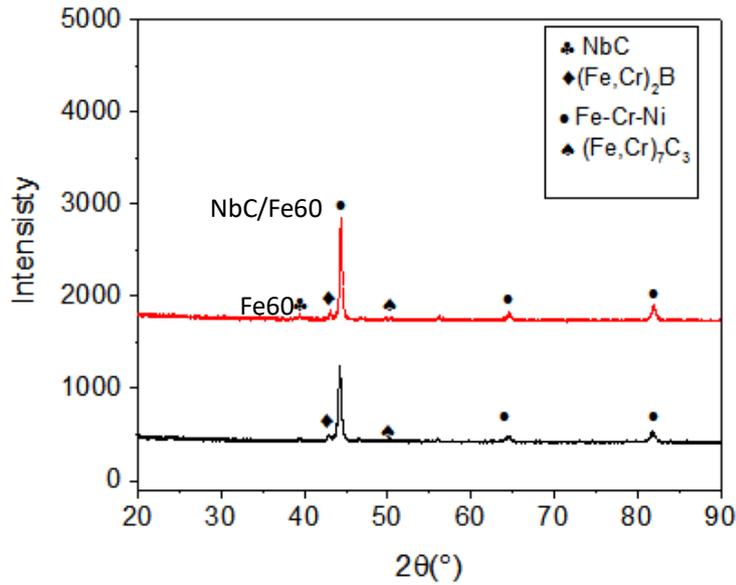


Fig. 7 Metallographic structure and XRD analysis of the Fe60 and NbC/Fe60.

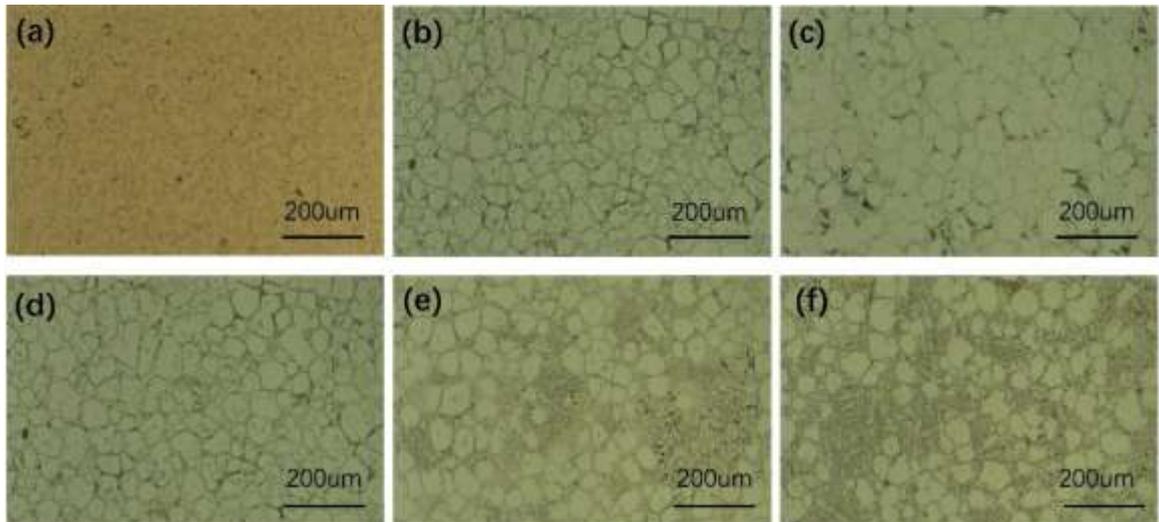


Fig. 8 (a)Fe60 (b)1%, (c)2%, (d)7%, (e)8%, (f)9%. (g)XRD curves of Fe60 matrix and NbC/Fe60

As depicted in Fig. 7 the sintered specification of pure Fe60 and the sintered specimen of NbCp/Fe60 were similar, the main phase composition was Fe-Cr-Ni solid solution, $(Fe, Cr)_2B$ [23] and $(Fe, Cr)_7C_3$ [24], where Fe-Cr-Ni solid solution represents a α -(Fe-Cr-Ni) solid solution. The formation mechanism is: the α -Fe of the body-centered cubic structure occurred austenization during the sintering process with increasing temperature, and it was transformed into a γ -Fe of the surface-centered cubic structure. Ni, Cr and other alloying elements atoms replaced the Fe atoms in the

γ -Fe lattice to form a displacement solid solution. Subsequently, at the cooling stage, with the furnace cooling to ambient temperature process to form a α - (Fe-Cr-Ni) solid solution. As depicted in the figure, after sintering, carbides and borides with high hardness (e.g., Cr_7C_3 and FeB) were precipitated in the Fe60 matrix, thus promoting the sintered pure matrix specimen to have a certain hardness, which was also the main reason for choosing it as the wear-resistant material matrix. After the addition of NbCp particles and the sintering process, the composite material or generate a new phase, did not have any chemical reaction, and NbC was not decomposed.

From the microstructure observation of the composite material, Fig. 8 reveals that in the Fe60 matrix, the grain distribution was uniform, whereas the grain size was larger and there were few less precipitates in the grain. After the addition of NbCp, the number of grains increased, the grain size decreased, and the precipitates in the grain increased. The presence of carbides reduced grain boundary mobility and strengthened the Fe60 matrix. Before the NbC mass fraction reached 8%, the NbC distribution was basically uniform, with only a small amount of agglomeration. Under the mass fraction of higher than 7%, considerable agglomerations occurred in the microscopic tissues, resulting in uneven distribution of the microscopic structures of the composite materials and large fluctuations in the hardness of the surface of the materials.

To analyze the elemental distribution and element content of pure Fe60 matrix and NbCp/Fe60 were selected as the study objects. As depicted in Fig. 9, the surface element distribution was relatively uniform, the precipitate contained numerous Cr

elements, As revealed by the XRD analysis results, the precipitate also contain contained considerable Cr_7C_3 , which were basically distributed along the grain boundary. In the Fe60 matrix, small area scanning analysis was conducted for the in-grain and out-grain respectively, as presented in Fig. 10 and Table 5.

The data of microscopic structure diagram and energy spectrum analysis suggested that the content of Out-of-grain Cr element in the Fe60 matrix was low, while the content of in-grain Cr element significantly increased. The precipitates in the in-grain contained B element, while the content of out-grain B element was low. It was therefore revealed that the precipitates inside the crystal included $(\text{Fe}, \text{Cr})_2\text{B}$, while the precipitates outside the crystal were solid solutions formed by substituting Fe atoms with Ni, Cr and other elements.

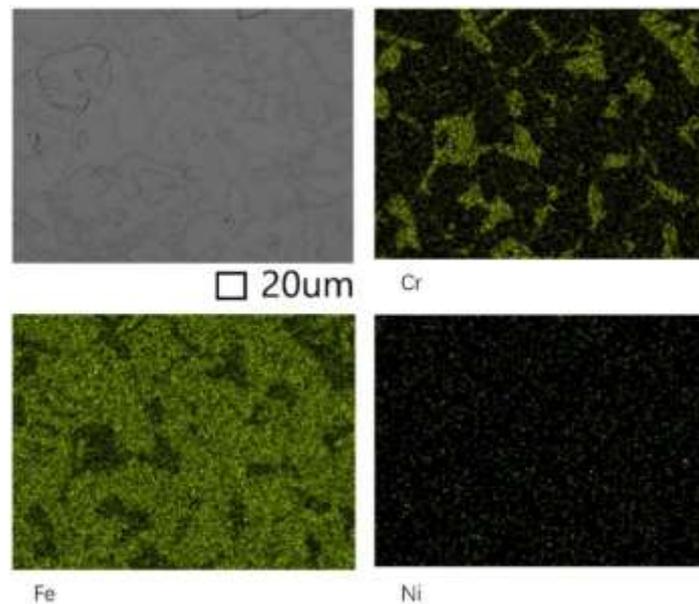


Fig. 9 Elemental composition analysis of Fe60 matrix

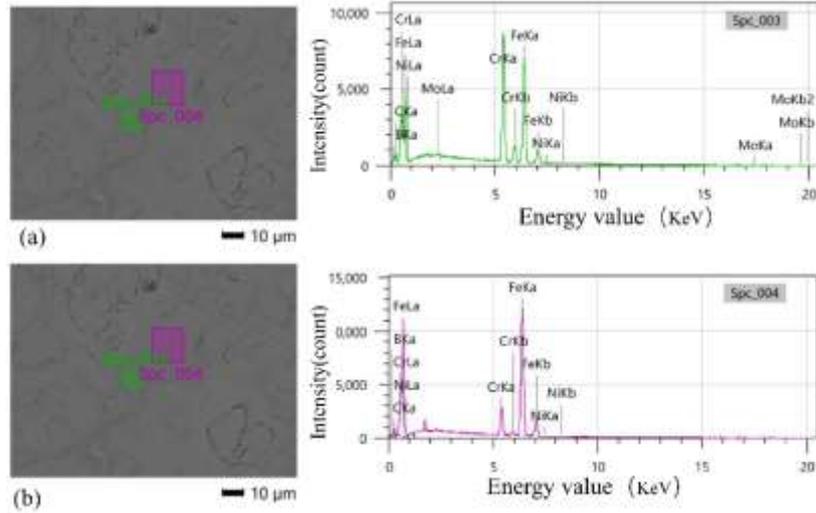


Fig. 10 Fe60 matrix element analysis; (a) Exocrystalline precipitation of Fe60 matrix, (b) inocrystalline precipitation of Fe60 matrix

Table 5 Content of main elements in and out of grain in Fe60 matrix

Element	Exocrystalline precipitation of Fe60 matrix		Inocrystalline precipitation of Fe60 matrix	
	Wt%	at%	Wt%	at%
B	7.6	25.81	1.52	2.32
C	4.86	14.88	4.79	18.64
Cr	36.09	25.48	10.43	9.37
Fe	51.38	33.79	82.77	69.28
Ni	0.07	0.04	0.49	0.39

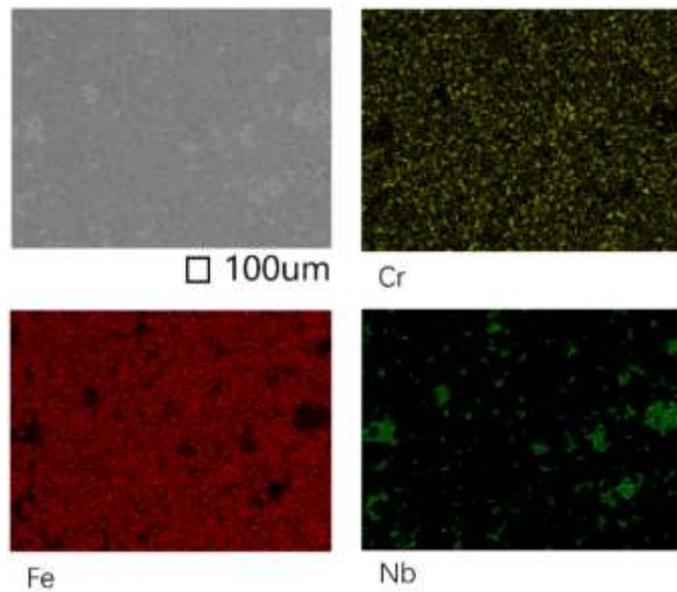


Fig. 11 Fe60 matrix element analysis

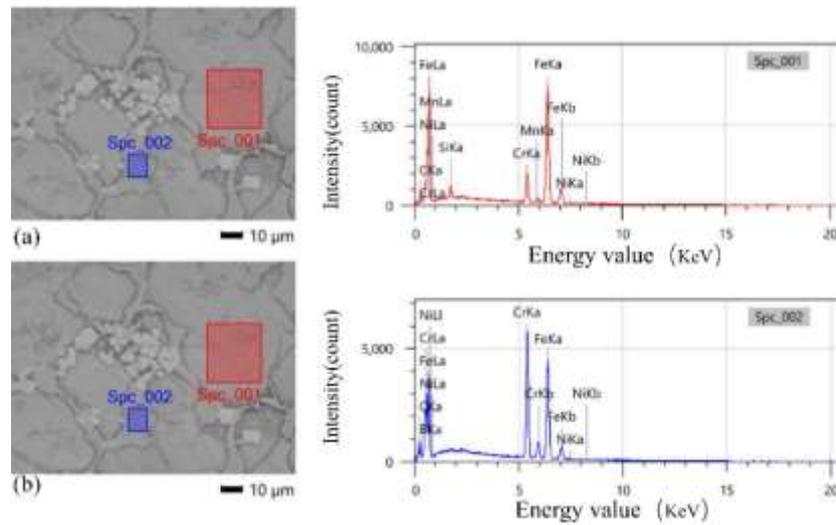


Fig. 12 Fe60 matrix element analysis: (a) Exocrystalline precipitation of NbCp/Fe60
(b) inocrystalline precipitation of NbCp/Fe60

Table 6 Content of main elements in and out of grain in NbCp/Fe60

Element	Exocrystalline precipitation of NbCp/Fe60		Inocrystalline precipitation of NbCp/ Fe60	
	Wt%	at%	Wt%	at%
B	6.64	24.37	0.45	0.51
C	2.94	9.7	2.7	11.75
Cr	35.4	27.11	11.74	9.43
Fe	54.23	38.51	84.02	77.9
Ni	0.65	0.32	0.54	0.38

As depicted in Fig. 11, although slight agglomeration occurred in few parts, the added NbCp was uniformly distributed in the Fe60 matrix as a whole. Fig. 12 and Table 6 reveal that the addition of NbCp could effectively reduce the grain size, and the elements in and out of the gain of Fe60 matrix and NbCp/Fe60 were almost the same, whereas the element content was very different. More Fe-Cr-Ni solid solutions precipitated outside the NbCp/Fe60 gain grain, while the FeCrB precipitated relatively less in the gain, thus interrupting the continuous state of the grain boundary to a certain extent. Besides, the grain was significantly refined. The precipitates

outside the large flake crystals decreased. The nailing of NbCp inhibited grain growth, thus resulting in the grain refinement of NbCp/Fe60. During the grain growth, NbCp was located at the front of the solid-liquid interface, and part of the NbCp was not captured by the growing grain. Since the thermal conductivity of NbC was smaller than that of the matrix, the particles in the front of the solid-liquid interface would hinder the solidification heat transfer, thus affecting the temperature gradient of the solid-liquid interface. Moreover, the particles at the solid-liquid interface hindered the diffusion of solute at the dendrite front and changed the concentration gradient of solute. NbC particles hindered the grain growth by affecting temperature gradient and solute concentration gradient at the front of solid-liquid interface, thus leading to grain refinement. Accordingly, when NbCp was added to Fe60 matrix, NbCp largely played a fine grain strengthening and dispersion strengthening role in Fe60.

Energy spectrum line scanning analysis was conducted on the binding sites of NbCp and matrix in and outside of the NbCp/Fe60 crystal. As depicted in Fig. 13, no new substances were generated when the Fe60 matrix with Fe, Cr and Ni as the main elements reacted with the enhanced phase with Nb and C as the main elements. As revealed by the results, NbCp was bonded with iron matrix by good mechanical action.

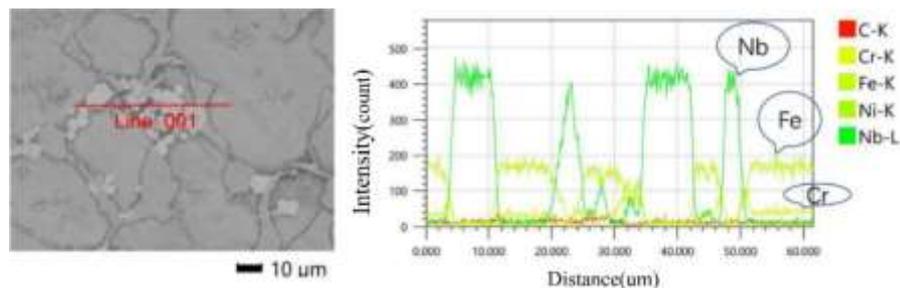


Fig. 13 Result of EDS line of NbCp/Fe60

4 Impact wear property and wear mechanism

4.1 Impact wear property

After the wear test of sintered samples, the correlation of Fig. 14 was obtained.

According to the chart, the following rules were obtained:

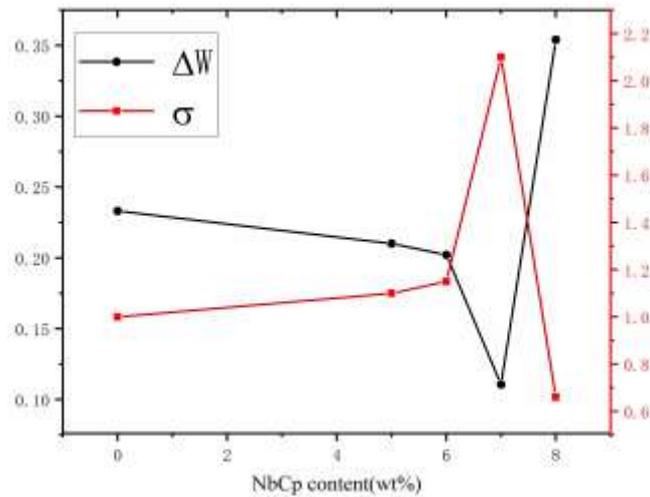


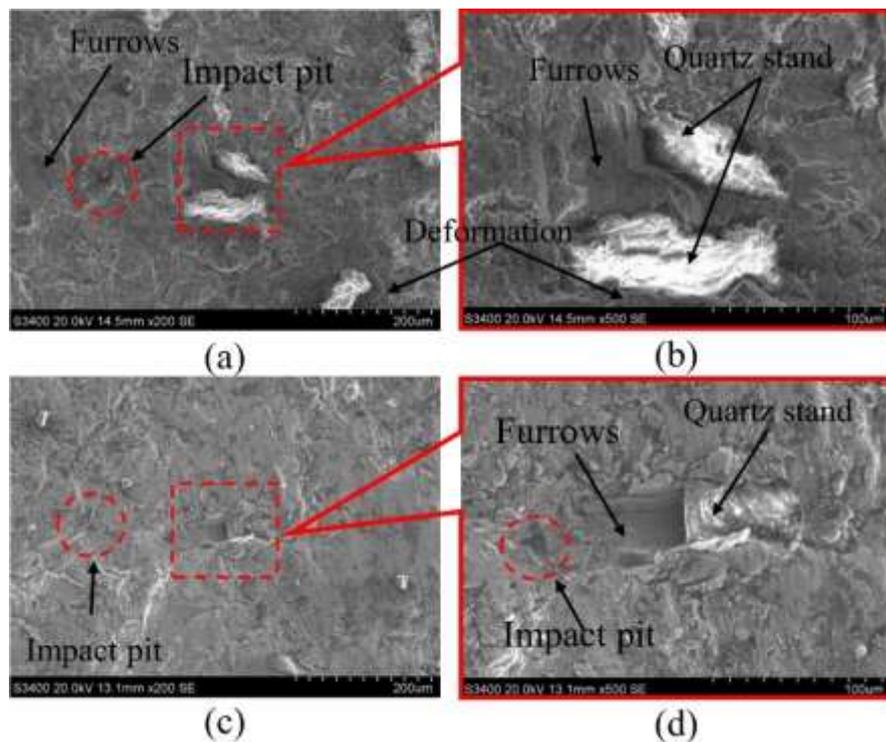
Fig. 14 Effect of mass fraction of NbC on wear loss and relative wear resistance

Fig. 14 shows the wear loss of Fe60 matrix is larger, thus suggesting that the wear resistance of Fe60 matrix is poor. It was found that the hardness of Fe60 matrix is only 38.88HRC, which affects its wear resistance to a certain extent. When the NbC content was lower than 7%, wear loss decreases with the increase of the NbC content, thus suggesting that NbC plays a strengthening role in the matrix after the addition of Fe60 matrix. Because the hardness of the NbC reinforced phase is much higher than that of the Fe60 matrix, the NbC particles with high hardness are dispersed in the Fe60 matrix to strengthen the effect in the second stage, and will hinder the grain growth, refine the grain, improve the deformation resistance of the Fe60 matrix and improve the overall hardness of the composite to a certain extent. After testing, the hardness of the composite materials with 5%NbC, 6%NbC and 7%

NbC are 51.12HRC, 52.34HRC and 54.92HRC respectively, It is 1.31 times, 1.34 times and 1.41 times of matrix Fe60 respectively; When the mass fraction of NbC is 8%, the wear amount increases sharply, thus suggesting that the wear resistance is not significantly improved, and NbC does not play a good strengthening role after after the addition of Fe60 matrix. Because the mass fraction of NbC is too large and the content of NbC is too large, it significantly hinders the diffusion and viscous flow of Fe atoms in solid flow during sintering. This leads to the uneven composition of local small area and agglomeration of composite reinforcement particles to a certain extent, which significantly reduces the properties exhibited by the composites. The wear resistance of composites with 5%NbC, 6%NbC and 7% NbC are 1.1,1.15 and 2.1.

4.2 Impact wear property

The wear morphology of the samples after the impact abrasive wear test is analyzed, as illustrated in Fig. 15.



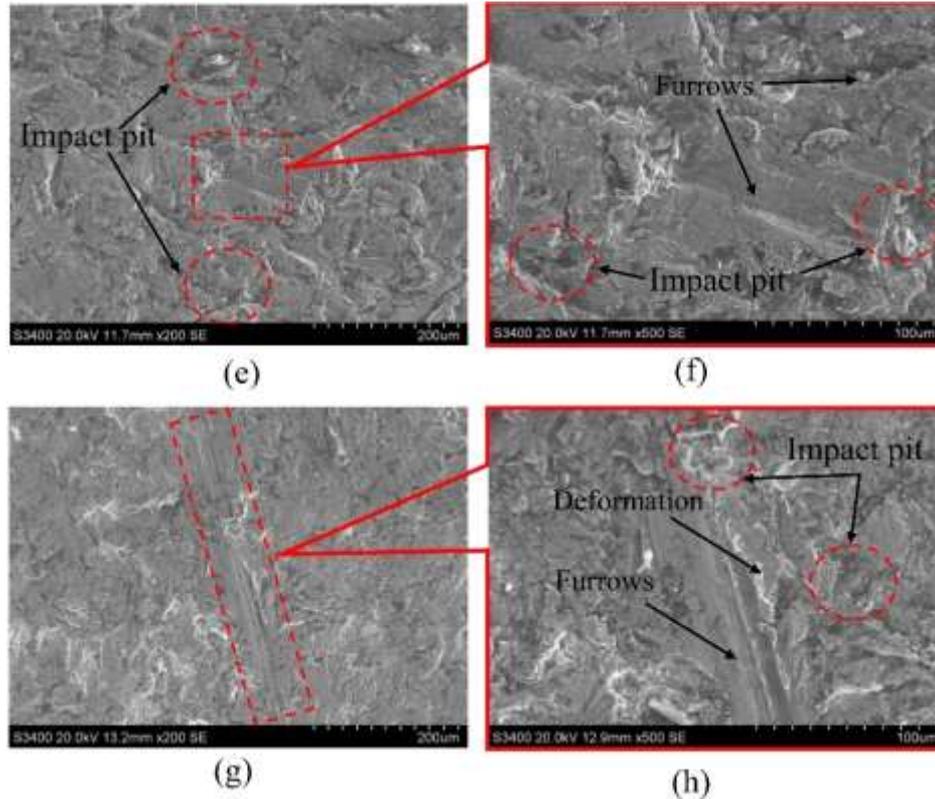


Fig. 15 (a), (c),(e),(g) and (i) are respectively the wear morphologies of Fe60, NbC(5%)/Fe60, NbC(6%)/Fe60, NbC(7%)/Fe60 and NbC(8%)/Fe60. b, d, f, h and j are the corresponding morphologies after magnification of 500 times

As depicted in Fig. 15, the surface had furrows and pits. When the abrasive was on the surface of the material, grooves were formed on the abrasive particles in the direction of shear stress to repeatedly cut the surface of the material. Under the repeated impact of the impact hammer, the deformation on both sides of the groove would make the surface be squeezed, resulting in the reduction of the compressive strength and impact toughness of the material, thus forming cracks. During subsequent impact, the cracks gradually extended and joined. Lastly, the impact crater was formed from the surface of the matrix. For some sharp quartz sand, under the action of vertical impact force, it will directly stab into the material body, and the material is integrated. At this point, hardening of the surrounding material caused the

furrow to stop or change direction. However, quartz sand and material belonged to mechanical combination, easy to loosen in the subsequent wear process, leaving sharp pits from the material. As depicted in Fig. 15(b), the grooves and pits in the figure were significantly deeper, due to the low hardness of Fe60 matrix, which cannot effectively resist impact and wear. The impact abrasive wear mechanisms of Fe60 matrix were primarily micro-cutting, impact plastic deformation and fatigue spalling, which are typical abrasive wear mechanisms. Fig. 15(b), 15(d) and 15(f) show that the impact pits on the Fe60 wear surface, largely furrows, were significantly reduced after the addition of NbC because NbC as dispersed and distributed at grain boundaries. When impacted, the cracks extended to grain boundaries and were deflected due to the NbC-based pinning effect. The cracks should absorb more energy to destroy the reinforced particles, so there were fewer impact craters but more furrows, primarily microcutting. As depicted in Fig. 15(i), the number of impact craters and furrows increased again, since too much NbC caused NbC caking in the sample. Although NbC dispersed at the grain boundary to strengthen the matrix, due to the high melting point of NbC, there was no physical or chemical bond between the reunited NbC particles, resulting in reduced bonding strength between NbC particles. When subjected to the impact of impact hammer and the ploughing effect of abrasive particles, the shear stress of abrasive particles was higher than the binding force between NbC particles, NbCp resulting in agglomeration are plowed out of the surface in one piece, reducing the impact resistance of the material surface and forming impact pits on the surface. At this time, the main wear mechanism is the fall

off of the whole reinforcing particle, resulting in serious wear of the material. Thus, agglomeration of reinforced particles must be avoided when preparing particle reinforced metal matrix composites.

5. Conclusions

(1) NbC particles can hinder the grain growth and achieve the effect of grain refinement. Accordingly, fine grain strengthening is the main strengthening mechanism when the grains are completely distributed on the grain boundary.

(2) Under the mass fraction of 7%, the sintering temperature is 1175°C, and the microstructure of NbC/Fe60 composite is uniform, higher hardness, higher relative density. The impact abrasive wear performance is higher than Fe60. When the NbC mass fraction is 5%-8%, the impact abrasive wear performance of NbC/Fe60 composites first increases and then decreases with the increase in the NbC mass fraction. Under the mass fraction of 8%, the composite begins to aggregate and the performance is significantly reduced.

(3) The impact abrasive wear mechanisms of NbCp/Fe60 composites are largely micro-cutting or micro-ploughing, impact plastic deformation and fatigue spalling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplement

The datasets generated and/or analysed during the current study are not publicly available due [REASON WHY DATA ARE NOT PUBLIC] but are available from the corresponding author on reasonable request.

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