Study on preparation methods of copper-based composites

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Abstract: Copper matrix composites are generally used as friction disc materials of the water pump clutch due to their excellent mechanical properties, but they also experience severe wear and relative slip between the friction disc and the impeller ring at a high velocity. To investigate the influence of the different structures of the composite on wear performance, this paper discussed the copper-based composites with three process methods, by contrast, the process method of low-pressure preloading and sintering, then perform a high-pressure could effectively improve the densification, hardness and wear resistance.

1. Introduction
The switchable water pump (SWP) is a component to cool the engine, and significantly affects the service lifetime of the engine. Inside the SWP, there is a device with a similar structure to the wet clutch of the automobile, it is named SWP clutch here. The friction disc and impeller ring are made and used in the application of the SWP clutch. The SWP clutch generally operates with a higher speed and a lighter load in comparison to that of the wet clutch mounted in the automobile [1]. Specifically, the SWP clutch normally operates at a wide range of temperature from -30 °C to 120 °C and pressure from 0 to 0.66 MPa. Generally, the friction disc is connected to the drive shaft, and the impeller ring is connected to the driven shaft [2]. When the temperature of the engine is up to 80 °C, the friction disc and the impeller ring engage and the power is transferred to the driven shaft, leading to the rotation of the impeller and resultant coolant circular motion rapidly to cool the engine. It is found that the achievement of the power transferred course is relied on the engagement and disengagement of the two discs, which is significantly affected by the applied normal pressure, the dynamic coefficient of friction, the velocity, and the temperature of the clutch plates [3]. The friction coefficient of the contacted surface that experiences a severe wear after a long-time cycle and dynamic contact would be considerably reduced, generating a relative slip between the two discs and attendant decline of the torque transmission, especially for the application of a high velocity of the engine. Thus, it can be derived that the wear resistance is considered as a crucial factor in obtaining a high-performance SWP clutch.

A number of research efforts have focused on the friction behavior and wear resistance of the materials for the applications of the wet clutch [4, 5]. Among them, copper and its alloys, generally exhibit a higher thermal conductivity in comparison to other alloys, have performed the combined properties, e.g., high strength, high thermal conductivity and low coefficient of thermal expansion and wear resistance, favoring the sufficient dissipation of the heat generated during friction [6]. Su et al. [7] have produced the copper-based composite with self-lubricated graphite for wet clutch and the excellent lubricating performances have obtained, attributing to the formation of lubricating and
transferring films during friction. Ma et al. [8] have disclosed that there is a critical speed where a transition of the friction and wear regimes of the composite formed of the copper-graphite composite with a pin-on-disc configuration, implying an enhancement of the wear properties. Powders were loaded into a graphite mold and sintered in an Ar atmosphere at 900 °C for 1 h under a pressure of 25 MPa to fabricate copper matrix composites reinforced with graphene, the coefficient of friction of the composite is stable with increasing the applied load [9]. Akbarpour et al. [10] have studied that the effect of SiC nanoparticles on tribological properties of copper matrix composites were plasma spark sintered in a vacuum atmosphere, indicating that the addition of 4 vol% silicon carbide to copper matrix reduced the wear track depth and with lower plastic deformation during dry sliding wear test. It can be found that the friction properties of the copper-based composites are useful for the SWP wet clutch.

However, the structure is a main factor to influence the properties of copper-based composite, and generally the powder sintered process and the relevant parameters selected could determine the necessary structure. To data, the wet clutch and the brake pads with a considerably low wear loss are highly required in the applications of the SWP wet clutch. In the press study, the copper-based composites with various process methods were prepared through powder sintering to obtain an increased micro-hardness and a reduced wear loss, and give priority satisfying preconditions of SWP wet clutch.

2. Experimental procedures

The copper-based composites consist of copper, iron, silica, graphite and the other elements. Different types of the powder with a same average size of 80 μm were employed in the present study. The QM-ISP04 planetary ball mill (Nanjing Nanda instrument Co., Ltd, Nanjing) was applied to mix the composite powders in ZrO2 ceramic jars duration of 4 h with a speed of 200 rpm which to prepare for fabricating the composite samples. The fabrication process included three methods. Method A: Mixed composite powder was pressed into the small-sized pieces with a pressure of 800 MPa at room temperature by the DY-30 tablet press machine, then with the vacuum furnace sintered in an Ar atmosphere at 800 °C for 1 h. Method B: Mixed composite powder was pressed into the small-sized pieces with a pressure of 400 MPa at room temperature by the DY-30 tablet press machine, then loaded into a graphite mold and sintered in an Ar atmosphere at 800 °C for 1 h under a pressure of 135 MPa. Method C: Mixed composite powder was pressed into the small-sized pieces with a pressure of 400 MPa at room temperature by the DY-30 tablet press machine, then with the vacuum furnace sintered in an Ar atmosphere at 800 °C for 1 h. Subsequently, the sintered samples were pressed under a larger pressure of 800 MPa, and then with the vacuum furnace sintered in an Ar atmosphere at 500 °C for 2 h to anneal. Finally, all the samples with a diameter of 10 mm and a thickness of 5 mm were obtained.

The surface morphologies of the as-produced composites were characterized by the MicroXAM 3D non-contact three-dimensional morphometer (ADE, USA). The Vickers micro-hardness of the samples was measured with an automatic turret micro-hardness tester (HY-1000, China) under a load of 0.3 kg with the holding time of 10 sec.

The friction tests were carried out using the Friction wear testing instrument (UMT-2, USA) with a ball-on-plate manner. The GCr15 ball with a diameter of 4 mm and a polished end-face was used as the friction pairs of the copper-based composite. The reciprocated amplitude was settled as 1 mm, and the friction tests achieved in the glycol coolant at room temperature with an applied load of 5 N, and an operated speed of 900 rpm for 1 h. The coefficient of friction (COF) of the composite was automatically recorded during friction test. The worn samples were ultrasonically rinsed with alcohol and dried with nitrogen gas, subsequently, the wear extent was measured by the non-contact three-dimensional morphometer.
3. Results and Discussion

3.1 Surface morphologies

Fig. 1 illustrates the three-dimensional surface morphologies and incidental surface roughness of the copper-based composites with various process methods. It was apparent that the different process methods could significantly affect the surface quality of the composites. Method A: the mixed powders with a pressure of 800 MPa at room temperature then were put into the vacuum furnace sintered in an Ar atmosphere at 800 °C for 1 h, the surface with a large amount of shallow zone that was identified as the produced pores was obtained (Fig. 1a), implying a relatively high surface roughness of 0.496 μm (Fig. 1d). Method B: the mixed powders with a pressure of 400 MPa at room temperature, then loaded into a graphite mould and sintered in an Ar atmosphere at 800 °C for 1 h under a pressure of 135 MPa. was used, the surface appeared to be smooth, except for limited fluctuation in a certain area (Fig. 1b), demonstrating a considerably reduced surface roughness of 0.32 μm (Fig. 1d). Method C with a pressure of 400 MPa at room temperature then sintered at 800 °C for 1 h. Subsequently, the sintered samples were pressed under a pressure of 800 MPa, then annealed at 500 °C for 2 h, the surface was observed with the presence of less asperities, due to the porosity resulting from the first sintering was reduced under the second pressure load (Fig. 1c). As a result, the minimal surface roughness of 0.2608 μm was measured (Fig. 1d), indicating a good surface quality of the composite fabricating with method C.

![Fig. 1. The characterized 3D morphologies showing the surface features of the copper-based composites with various process methods: (a) method A, (b) method B, (c) method C, and (d) presenting the specific surface roughness of the composite with various process methods.](image)

3.2 Vickers micro-hardness

Fig. 2 shows the Vickers micro-hardness indentation morphologies and attendant hardness of the copper-based composites with various process methods. It could be found that the measured Vickers micro-hardness of the composites fluctuated in the range from 84.05 HV to 92.8HV and to 125.76 HV.
as varying the applied process methods A, B and C. As process method A, for only once press and sintering, presenting more pores leads to poor compactness and lower hardness (Fig. 2d). Process method B chose the second time to press at a high temperature, it could appropriately improve the compactness of the composites. It showed that the value of micro-hardness increased to 92.8HV and the indentation turned to small (Fig. 2b and 2d). However, since graphite mold also produced thermal expansion at a high temperature, the pressure could not be sufficiently transferred to the sample, which would limit the increase in the compactness of the sample. Process method C preloaded with a small load, and then pressed with a larger load after sintering, which effectively eliminated the pores generated after sintering, thereby fully improving the compactness of the sample, and the micro-hardness reached 125.76HV with a small size of the indentation (Fig. 2c and 2d). Therefore, reasonable to conclude that the Vickers micro-hardness of the composite is significantly affected by the combined factors, including the compactness and the homogeneous microstructure.

3.3 Wear morphologies and volume

Fig. 3 gives the characterized 3D morphologies showing the worn surface features of the copper-based composites with various process methods and attendant wear extent and volume. Wear test of the copper-based composites with the various process methods sliding against the counterpart GCr15 in the glycol solution for 1h. It could intuitively found that the wear extent of the copper-based composites involving the width and depth of worn cracks. The values of wear volume exhibited the considerable differences. For the copper-based composite with process method A, the wear volume with a relatively large value of $13.490 \times 10^{-3} \text{mm}^3$ was measured. Pressing under a high temperature as process method B, the wear volume of the composite decreased to $10.911 \times 10^{-3} \text{mm}^3$. For process method C, the wear volume of the composite rapidly decreased to $7.001 \times 10^{-3} \text{mm}^3$, due to preload with
less pressure, then increasing the pressure after sintering, which can effectively eliminate the generated pores by sintering. Process method A and method B presented a relatively large amount of wear volume, attributed to the high porosity level and the low Vickers micro-hardness of the composites, indicating a poor wear resistance. Normally, an increase in hardness of the composite is favorable to obtain a lower wear volume [11]. The composite with process method C exhibited a lower wear volume due to its high Vickers micro-hardness, revealing a high wear resistance.

Fig. 3. The characterized 3D morphologies showing the worn surface features of the copper-based composites with various process methods: (a) method A, (b) method B, (c) method C, (d) wear extent and volume.

4. Conclusion
The wear resistance of copper-based composites with the various process methods was investigated with a ball-on-plate friction test under glycol coolant. The influence of materials with various process methods on surface roughness, micro-hardness, and the wear resistance of the composites were discussed. From our work, the major conclusions can be drawn as follows:

1) The copper-based composites were fabricated by powder sintered process, and the process method A, B, and C all could obtain the composites with uniform composition.

2) Process method C preloaded with a small load, and then pressed with a larger load after sintering, which effectively eliminated the pores generated in the course of sintering, thereby fully improving the compactness of the composite. The composite also exhibited a lower wear volume due to its high Vickers micro-hardness that revealed a high wear resistance.

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