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Effects of MoS_2 on mechanical and tribological properties of NiCr-based alloys①

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Abstract: Ni-Cr based alloys with a wide temperature range self-lubrication were made by hot-pressing the mixture powder of alloyed Ni-Cr powder, elemental Mo, Al, Ti and B powders and MoS_2 powder. The mechanical and tribological properties of these alloys when rubbing with Al_2O_3 ceramics and W18Cr4V high speed steel were measured in the temperature range of 20 ~ 700 ℃, and the mechanisms of self-lubrication and wear resistance were studied. The results showed that the alloy containing 10 % MoS_2 has the best combination of mechanical properties, antifriction and wear resistance. Over a wide temperature range from 20 ℃ to 700 ℃, when rubbing with Al_2O_3, its friction coefficient and wear rate are 0.19 ~ 0.3 and (1.1 ~ 1.5) 10^{-14} $m^3/(N\cdot m)$, respectively; when rubbing with the high speed steel, those values are 0.18 ~ 0.26 and (0.6 ~ 3.2) × 10^{-15} $m^3/(N\cdot m)$, respectively.

Key words: Ni-Cr based alloys; molybdenum disulfide; self-lubrication; tribological properties **Document code: A**

1 INTRODUCTION

With the rapid development of industries and advanced technologies, more and more mechanical devices are required to work in high temperature environments, for example, the turbine engines used in aviation and electrical industries, the radiator sealing systems of the automobile engines, and the mechanical devices in the atomic reactors. The conventional grease lubricating systems used in the high temperature environments no longer satisfy the present requirements, so it is urgent to develop materials with excellent self-lubrication from the room temperature to about 1 000 ℃. Sliney et al prepared several solid high temperature self-lubricating materials[1~4], three typical materials among which are PS101 (30 % Ni-Cr, 30 % Ag, 25 % CaF, 15 % Glass), PS200 (80 % Ni-Co-Cr_3C_2, 10 % Ag, 10 % BaF_2/CaF_2), and PS300 (80 % Ni-Cr-Cr_2O_3, 10 % Ag, 10 % BaF_2/CaF_2). They show excellent antifriction and wear resistance over a wide temperature range. Pertson et al studied the antifriction behaviors of oxide films and applied the antifriction principle of the autogenic oxide films to the development of high temperature self-lubricating alloys[5~10]. Because the oxide films form at relatively high temperature and play the roles of self-lubrication, they cannot lubricate the lubricating pairs effectively at room temperature. The S-bearing Ni-based alloys usually have self-lubrication over a wide temperature range[11~13], but their high temperature wear resistance and comprehensive mechanical properties need to be further improved. The authors utilize the synergistic anti-friction effects of oxides and sulfides to make self-lubricating NiCr-Base alloys, and examine the mechanical properties and tribological behaviors of the Ni-Cr based alloys containing strengthening elements Mo, Al, Ti and B and lubricating MoS_2 in the temperature range from 20 ℃ to 700 ℃.

2 EXPERIMENTAL

2.1 Material preparation

After fully mixing the alloyed Ni-20Cr powder with 0 %, 2 %, 4 %, 6 %, 10 %, 15 % or 20 % MoS_2 powder and Mo, Al, Ti and B powders, the mixture was cold pressed into d 45 mm × 15 mm disks. Disks containing different contents of MoS_2 were loaded in a graphite mould and separated by graphite slices each other. The samples were prepared by vacuum hot pressing in an FVPHP-R-10 vacuum hot-presser. The hot-pressing conditions are as follows: pressure 8.5 MPa, temperature 1 250 ℃, heating rate 20 ℃/min, holding time 20 min, argon protection after degassing to 10^{-5} Pa.

2.2 Property measurements

The antifriction and wear resistance tests were carried out in a MG-200 high temperature tribometer. The dimensions of the specimens are d 5 mm × 15 mm, the wearing pairs are Al_2O_3 disks (dimension d 52 mm × 8 mm, roughness Ra = 2.0 μm, hardness

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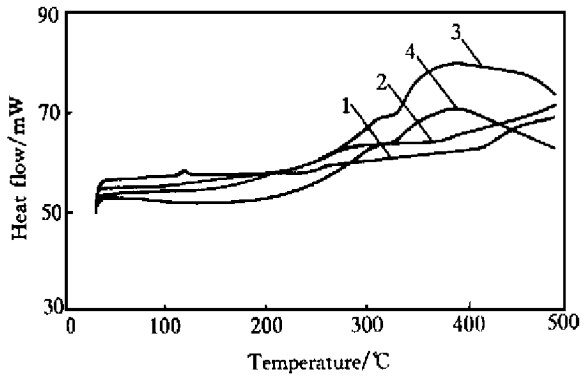

Fig.4 DSC curves of mixed powders after different times of ball milling
1 —0 h; 2 —4 h; 3 —10 h; 4 —10 h

tunity to diffuse to other side at a low temperature, stimulated by the crystal defects.

The most important interfacial reaction in Al-SiC system is $Al + SiC \rightarrow Al_4C_3 + Si$. Since Al_4C_3 is a brittle phase and has poor anticorrosion property, this reaction is often regarded harmful[9]. There are two reasons for the low level of interface reaction in our high-energy ball milling experiment. First, this reaction need a temperature as high as 650 ~ 700 ℃[5,10], however, the experimental temperature was not high enough for the reaction. Second, the solubility of Al_4C_3 in the Al matrix is quite small, in terms of the theory of chemical reaction balance, in order to produce more Al_4C_3, more Si should be removed or dissolved into the Al matrix. Since Al-30Si powders contain a large amount of Si, it is difficult for the reaction to proceed rightward. In other words, the reaction has been retarded due to both thermodynamics and kinetics.

As the hardness of SiC_p is far higher than that of Al-30Si alloy powder, after ball milling for a long time, some of SiC particles were pressed into alloy powder, which brings two advantages to MMC fabrication process. First, it can ease the wearability of the mould and improve shaping ability of the mixed powders. Second, since the wettability between the same type of materials is better than that of different one, it can promote sintering process to attain stronger bonding. In fact, some researchers have used high-energy ball milling to fabricate Al/SiC_p composites[11]. Considering the equipment condition and the cost, high-energy ball milling can serve as an effective reinforcement pre-treatment method in the fabrication of MMC.

5 CONCLUSIONS

1) Through high-energy ball milling, both Al-30Si alloy powders and their microstructure are obviously refined.

2) After high-energy ball milling, close-contacted interface is formed between the alloy powders and SiC_p without interfacial reaction. No reaction but relaxation of the powder can be detected by DSC.

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Hv1055) and as-quenched high speed steel disks(dimension d 45 mm × 10 mm, hardness HRC63). The upper pin specimen is fixed while the lower disk specimen rotates, and the pin slides on the disk and wears a scar of d 33 mm. The load is 98 N, and the sliding rate is 0.8 m/s. Before tests, the pin and disk surfaces were polished with 400# emery paper and cleaned with acetone. The sliding distance at each test temperature is 2.5 km, and the friction force was recorded with an X-Y continuous recorder. The average value of friction coefficient is taken as the friction coefficient at certain temperature and load. A balance with a precision of 0.1 mg was used to weigh the wearing mass loss. The structure of wear scars and debris were analysed by X-ray diffractometry, and the morphologies of the wear scars were observed by optic microscopy.

3 RESULTS

3.1 Effect of MoS_2 addition on physical and mechanical properties

The variations of density, hardness and bending strength with MoS_2 addition are presented in Fig.1. It can be seen that the density decreases with MoS_2 addition and the decreasing tendency is approximately linear. The change of hardness with MoS_2 is not violent and does not show obvious regularity. The bending strength decreases with increasing MoS_2 addition. The curve can be divided into two linear segments: the slope when the MoS_2 addition is below 10% is larger than that when the MoS_2 addition is over 10%, which shows that the decrease of the bending strength is more notable when the MoS_2 addition exceeds 10%.

3.2 Effects of MoS_2 addition on antifriction and wear resistance

The variations of the coefficient and wear rate with MoS_2 addition when rubbing with Al_2O_3 is presented in Fig.2. It can be seen that at the three test temperatures the friction coefficient shows a decreasing tendency with MoS_2 addition, and the decrease magnitude from 0% to 10% MoS_2 is larger than that from 10% to 20% MoS_2. At 20 ℃ and 400 ℃, the wear rate shows a decreasing tendency with MoS_2 addition in the range from 0% to 10%, but increases slightly instead when the MoS_2 addition increases further. At 700 ℃, the wear rate basically shows an increasing tendency except at 10% MoS_2, and especially the change of the wear rate is very fast at 10% ~ 20% MoS_2 addition. Considering the combination of the mechanical and the tribological properties, the alloy containing 10% MoS_2 is the best.

3.3 Effects of temperature and wearing pairs on tribological properties

Fig.3 shows the variations of friction coefficient

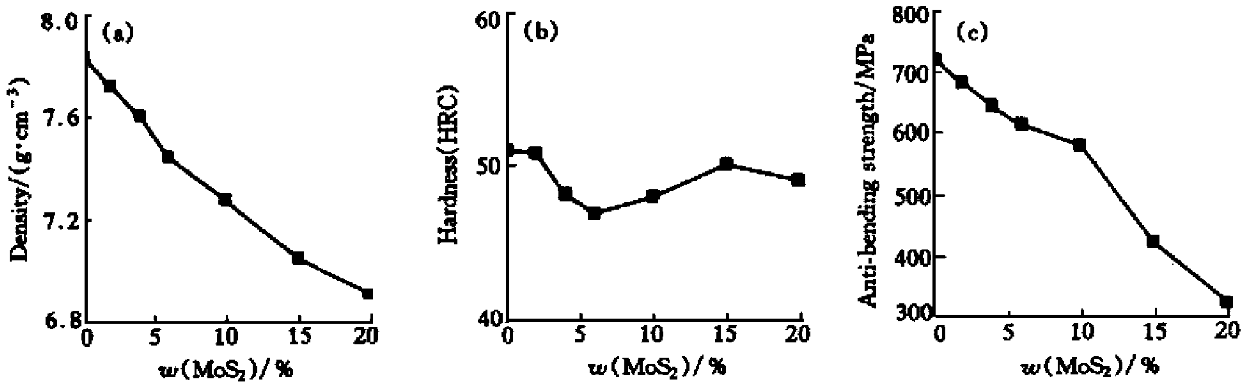

Fig.1 Variations of density, hardness and bending strength with MoS_2 addition for Ni-Cr based alloys

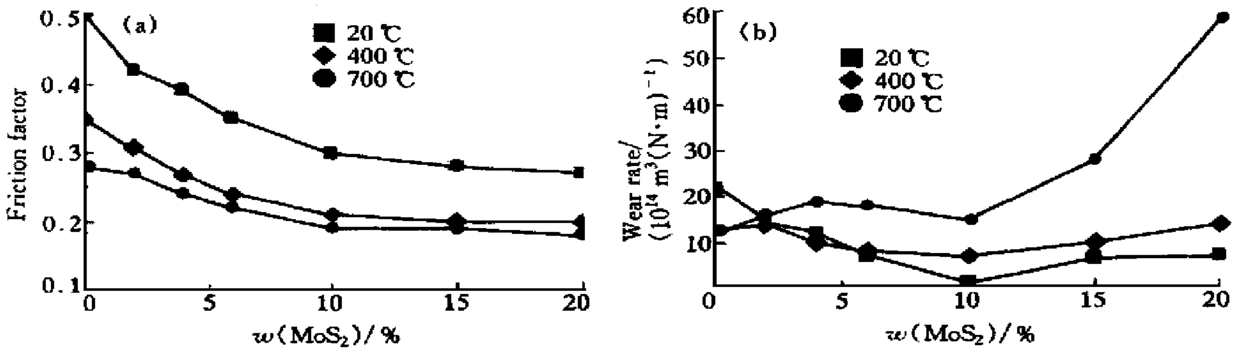

Fig.2 Variations of friction coefficient and wear rate with MoS_2 addition for Ni-Cr based alloys rubbing with Al_2O_3

and wear rate with temperature for the Ni-Cr alloy containing 10% MoS_2 rubbing with Al_2O_3 and high-speed steel. It can be seen that the friction coefficient decreases with increasing temperature for both rubbing pairs. When rubbing with the high-speed steel, the wear rate shows a decreasing tendency with temperature, whereas when rubbing with the Al_2O_3, it increases rapidly with temperature. In summary, the wear rate for the alloy/Al_2O_3 rubbing pair is larger than that for the alloy/high-speed steel rubbing pair by 1 ~ 2 orders of magnitude.

4 DISCUSSION

Fig.4 shows the wearing surface morphologies of the NiCr-10%MoS_2 alloy. It is clear that when rubbing with the high-speed steel, there forms on the wearing surface a bright glaze layer whose surface is covered with micro-cracks and there occurs peeling off of the glaze layer. This indicates that the wearing mechanisms can find expressions in the formation, propagation, fatigue rupture and peeling off of the glaze oxide films. When rubbing with Al_2O_3 under the same conditions, there does not form a glaze layer and the wearing surface is covered with groves caused by abrasive wear and scratches. Therefore the wear rate for the alloy/Al_2O_3 rubbing pair is larger than that for the alloy/high-speed steel by about 2 orders of magnitude.

Fig.5 shows the XRD patterns of the NiCr-10% MoS_2 alloy before and after rubbing with the high-speed steel and the wear debris. It can be seen from Fig.5(a) that the alloy is mainly composed of Ni(Cr, Mo, Al, Ti) solid solution, Ni_3Al, $Ni_3(Al, Ti)$, Cr_xS_y, MoS_2 and Mo_2S_3, and no elememtal Mo, Al and Ti phases are found, which shows that the alloying is full in the preparation of the alloys. After wearing at 600 ℃, the phase constituents of the surface layer comprise amounts of CrO, NiO and some transferred oxide Fe_2O_3 besides the Ni-based solid solution, Ni_3Al and a little residual MoS_2 and Mo_2S_3, while those of the debris mainly include the Ni-based solid solution, Ni_3Al, NiO and Fe_2O_3 phases. No S-Cr and S-Mo compounds are detected while there appear MoO_3 and Cr_2MoO_6, xNiO · MoO_3 · $y H_2O$. The comparison of Figs.5(b) with (c) indicates that the surface layer is mainly composed of CrO, and the content of Fe_2O_3 is far higher than that in the debris, while the content of NiO in the debris is far higher than that in the wear track. When rubbing with the high-speed steel, the wear surface layer of high-speed steel is mainly composed of $FeCr_2O_4$,

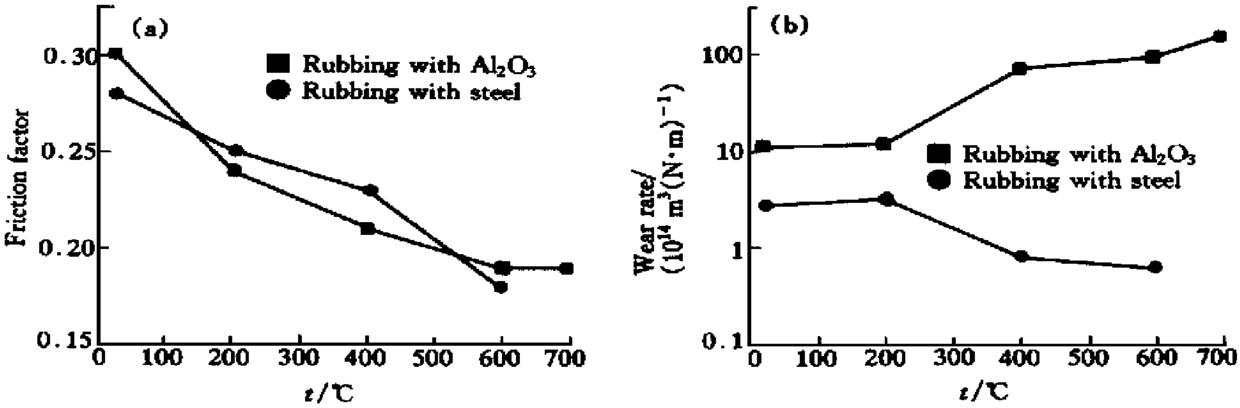

Fig.3 Variations of friction coefficient and wear rate with temperature

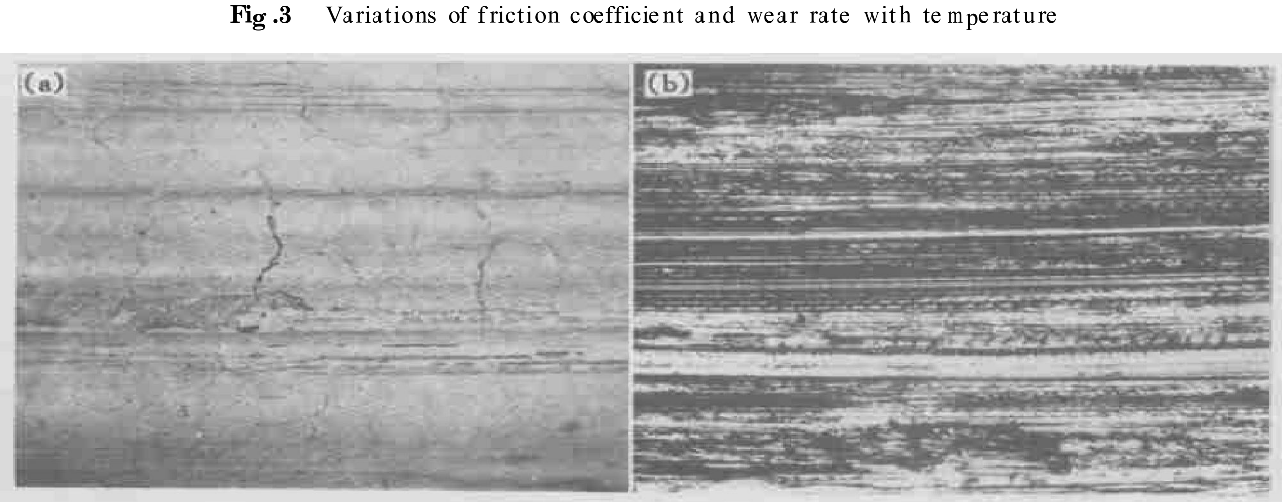

Fig.4 Wear scars of NiCr-10% MoS_2 alloy at 600 ℃
(a) —Rubbing with high-speed steel; (b) —Rubbing with Al_2O_3

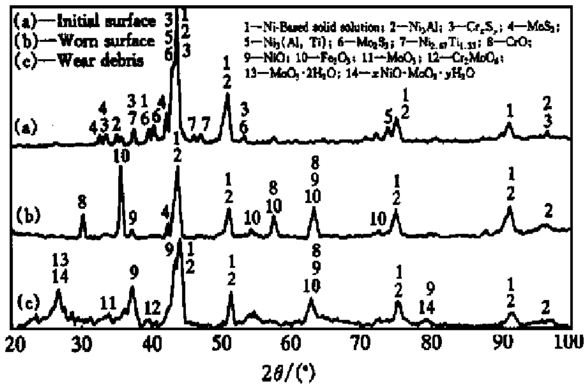

Fig.5 XRD patterns of NiCr-10 % MoS_2 alloy before and after wearing at 600 ℃ and debris

α-Fe and Fe_2O_3, and no Ni-bearing oxides are detected, which shows that there occurs selective transfer in the friction process. When rubbing with the Al_2O_3 ceramics, the phase constituents of the surface layer are the same as those of the matrix, and no oxides are detected; the phase constituents of the debris are the same as those when rubbing with the high-speed steel excluding Fe_2O_3.

The additions of Mo, Al, Ti and B elements play the role of solution strengthening, and the formation of Ni_3Al and $Ni_3(Al, Ti)$ further enhance the hardness and strength. Compared with the Ni-Cr-Mo-B-MoS_2 alloy[13], the additions of Al and Ti increase the strength, and the content of MoS_2 with good lubrication is raised from 4 % to 10 %. In the low temperature range (< 300 ℃), it is the sulfides (Cr_xS_y, MoS_2 and Mo_2S_3) that play the role of lubrication. When rubbing with Al_2O_3 at high temperature, the transferred oxides and the residual sulfides play the role of lubrication cooperatively. When rubbing with the high-speed steel at high temperatures, there forms a bright glaze layer of oxides on the rubbing surface. The synergistic effect of the oxides in the glaze layer, the residual sulfides and the oxides in the debris contributes to the further reduction of the friction coefficient.

5 CONCLUSIONS

1) Ni-Cr-Mo-Al-Ti-B-MoS_2 self-lubricating alloys with different contents of MoS_2 were prepared by P/M hot pressing. When the addition of MoS_2 is 10 %, the alloy has the best combination of mechanical and tribological properties.

2) At temperatures below 300 ℃, the sulfides play the main role of lubrication in the friction process; at higher temperatures, the synergistic effect of oxides and sulfides leads to the further reduction of the friction coefficient.

3) When rubbing with Al_2O_3 at high temperatures, the abrasive wear is dominant. When rubbing with the high-speed steel, a glaze layer was formed on the wear surface of alloys, and there are cracks, fatigue rupture and peeling off on the glaze layer.

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