

The Effect of Molybdenum on Cavitation Erosion and Corrosion Resistance of Fe-Cr-C-Si Hardfacing Alloys

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The cavitation erosion behavior of Fe-Cr-C-Si-xMo ($x = 0, 3$ and 6 wt.%) hardfacing alloys were investigated for up to 50 hours by using 20 kHz vibratory cavitation erosion test equipment. With increasing Mo contents, $M_{23}C_6$ and M_6C carbides were formed instead of Cr-rich M_7C_3 and $M_{23}C_6$ type carbides observed in the interdendritic region of the Mo-free Fe-Cr-C-Si hardfacing alloy. This microstructural change was responsible for the improvement of mechanical properties such as hardness and cavitation erosion resistance of the Mo-added Fe-Cr-C-Si hardfacing alloy.

KEY WORDS: cavitation erosion, corrosion, Mo, microstructure

I. Introduction*

Co-based Stellite alloys have traditionally been used as hardfacing materials for nuclear power plant valves owing to their superior high corrosion, wear and cavitation erosion resistance^{1),2)}. However, the need to avoid the use of Stellite alloy has emerged since it is the main source of ^{60}Co , which is the largest contributor to occupational radiation exposure. As the most effective way to reduce ^{60}Co contamination many ^{60}Co -free hardfacing alloys, such as Fe-base and Ni-base alloys have been investigated to replace Stellite³⁾.

High corrosion, cavitation erosion and wear resistance are generally required for hardfacing materials in nuclear power plants^{4),5)}. It has been found that the cavitation erosion resistance and corrosion are dependent on the stacking fault energy and the martensite phase transformation in austenitic Fe-based alloys and carbide types⁶⁾.

Alloying Fe with Cr and various quantities of C, W and Mo produces a family of alloys which can have excellent resistance to corrosion and/or cavitation erosion by the formation of M_7C_3 and $M_{23}C_6$ ⁷⁾. The carbide precipitation strengthening is a desirable feature; Cr also plays a strong role through the formation of a series of varying Cr-C ratio carbides such as M_7C_3 . Alloying elements like W, Mo, and V are added to Fe for solid solution strengthening^{8),9)}. If these metals are added in excess of their solubility, formation of carbides like MC, $M_{23}C_6$ and M_6C is likely to occur.

But, detailed relationships between microstructures and mechanical properties such as hardness and cavitation erosion resistance in the Mo-added Fe-Cr-C-Si alloys have not been established until now¹⁰⁾.

Throughout this paper, the effect of Mo on cavitation erosion resistance of Fe-based alloys is investigated. The procedure outlines how cavitation erosion resistance was measured by the cumulative weight loss of the Mo added Fe-based alloy compared to that of Stellite 6.

II. Experimental Details

Since there is no difference in the cavitation erosion characteristics of specimens prepared by casting, cast ingots of Stellite 6 and the Fe-Cr-C-Si-xMo ($x = 0, 3$ and 6 wt.%) alloys were used. The chemical compositions of the specimens were analyzed using an optical emission spectrometer (Table 1).

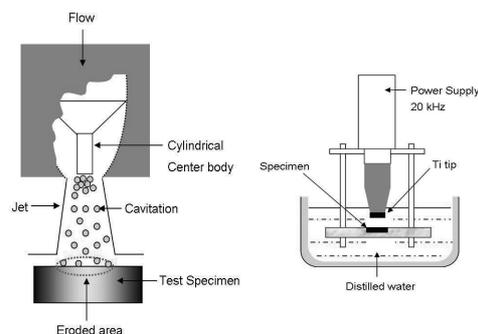


Fig. 1 Schematic representation for vibratory cavitation erosion test equipment

The cavitation erosion experiment is schematically represented in Fig. 1, which conforms to ASTM Standard G32-92 with the samples in unattachment mode¹¹⁾. The peak-to-peak amplitude and the vibration frequency used were $15 \pm 1 \mu m$ and 20 ± 2 kHz, respectively. The apparatus used a commercial ultrasonic oscillator. The weight loss was measured at regular intervals during the test for up to 50 hours and converted to the material loss per unit area ($mg \cdot cm^{-2}$) and then plotted against time.

The microstructures of Fe-Cr-C-Si-xMo ($x = 0, 3$ and 6 wt.%) alloys were observed using optical microscopy and field-emission scanning electron microscopy. Then the chemical compositions of dendrite and precipitates in the Fe-Cr-C-Si-Mo alloys were analyzed using Electron Back Scattered diffraction Pattern. Subsequently, a Rikagu diffractometer was employed for the X-ray diffraction (XRD) studies of the precipitates formed in the Fe-based hardfacing

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alloys with continuous scan speed of 5°/min at an operating voltage of 100kV, using Cu-K_α radiation (λ=1.54056 Å).

Table. 1 Nominal elemental composition of the hardfacing alloys. (wt.%)

Element	Co	Fe	Cr	Si	Mo	C
Stellite 6	60	2.1	29	0.8	0.59	1.3
Mo-added Fe alloy	-	76.3	19.9	0.9	0	1.7
	-	75.3	19.9	1.0	2.98	1.7
	-	74.3	20	0.9	6.01	1.7

III. Results and Discussion

The cumulative weight loss of Fe-Cr-C-Si-xMo (x = 0, 3 and 6 wt.%) alloy and Stellite 6 were measured doing the cavitation erosion test every 3 hour for a period of 50 hours. The results are presented as a function of the exposure time in Fig. 2.

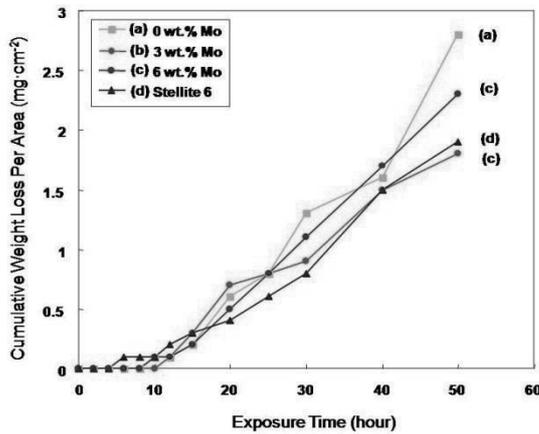


Fig. 2 Compares the cumulative weight loss of Stellite 6 and Mo-added Fe-base alloys as a function of exposed; (a) 0 wt.% Mo (b) 3 wt.% Mo (c) 6 wt.% Mo (d) Stellite 6

The respective cumulative weight losses of 0, 3 and 6 wt.% Mo added alloys and Stellite 6 were roughly 3.2, 1.8, 2.3 and 1.9 mg·cm⁻² after 50 hours of exposure. In the case of 3 wt.% Mo added alloy had similar cavitation erosion characteristics compared to that of Stellite 6.

Alloying iron with Cr and various quantities of C, W and Mo produces a family of alloys which can have excellent resistance to corrosion and/or erosion¹²⁾. It was concluded that the Fe-based alloy containing M₂₃C₆ and M₆C carbides has better cavitation erosion resistance than that containing M₇C₃. It is known that the cavitation erosion resistance is not affected by the carbide type, but complexly by the hardness, size, distribution and volume fraction of carbide.

It is not easy to identify the carbide types from the simple comparison of XRD peaks and Joint Committee on Powder Diffraction Standards (JCPDS) values since the wide solubility limits of most carbides exist. The precise value of lattice parameter will vary between compositional changes and processing. The phase identification in the Mo-free alloy and molybdenum-added alloys was carried out by comparing the data on the lattice parameters of each phase based in

standard JCPDS cards and the lattice parameter of each phase estimated from XRD peaks¹³⁾.

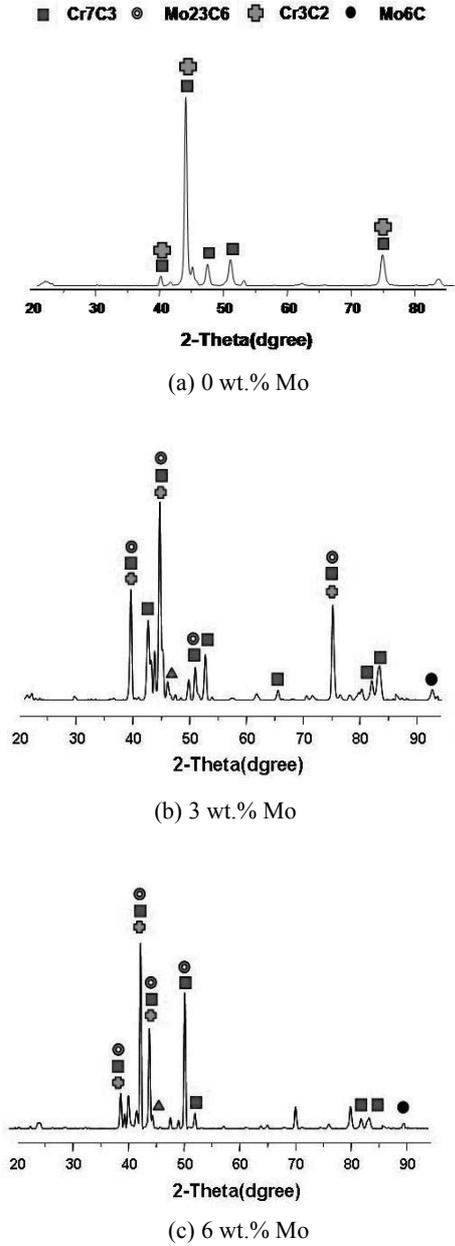


Fig. 3 XRD is after the intergranular corrosion of all the tested Mo added alloys

Fig. 3 (a), (b) and (c) show the XRD patterns taken from the surface of Fe-based alloys with varying Mo contents to investigate how the types of carbides change with Mo contents. The addition of Mo in Fe-based alloy suppresses the formation of M₇C₃ type carbide. This transformation on carbide structure is similar to the previous result that Cr-rich carbides transform from M₇C₃ to M₂₃C₆ and M₆C in a Fe-Cr-C-Si alloy with Mo content above 3 wt.%. That is, with an increase in Mo content, the M₂₃C₆ and M₆C type carbides were formed instead of Cr-rich M₇C₃ carbides.

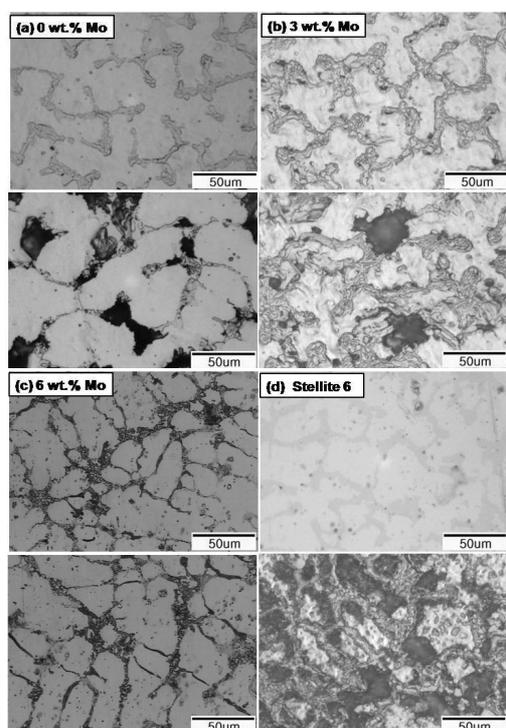


Fig. 4 Optical microscope of cavitation erosion surfaces of Mo added alloy; (top) before test (bottom) 20 hours after test

The surface morphology of all the tested alloys was observed using an optical microscope (top) before and (bottom) after the exposure to cavitation for 20 hours which is shown in **Fig. 4**. It can be confirmed with the naked eye that the material losses of the low-Mo alloys are less than high-Mo alloys. Mo-addition above 3 wt.% was observed to increase the cavitation erosion resistance of the Fe-based alloy. As shown in **Fig. 3**, since the more finely distributed $M_{23}C_6$ carbide than M_7C_3 carbide prevented propagating the cracks caused by cavitation erosion, it is considered that microstructure with $M_{23}C_6$ carbide has improved the cavitation erosion resistance.

As illustrated in **Fig. 5**, Mo improved the polarization behavior of Fe-Cr-C-Si-xMo ($x = 0, 3$ and 6 wt.%) in the saline medium. Although both Mo-free and Mo-added alloys exhibited poor polarization behavior and were even anodically active, the addition of Mo positively affected the corrosion current density and potential. With increasing Mo content, the corrosion current density decreased and the corrosion potential moved toward the noble direction. Since Mo remained in the austenite phase as solute atoms during the solidification, the composition of the matrix may be chemically improved. It is considered to be reason for the increased corrosion potential with Mo addition.

Consequently, the increased corrosion potential was beneficial to the corrosion resistance of the alloy due to reduction of potential difference for carbides. In addition, the decrease of the corrosion current density indicated the dissolution rate of the metallic ions.

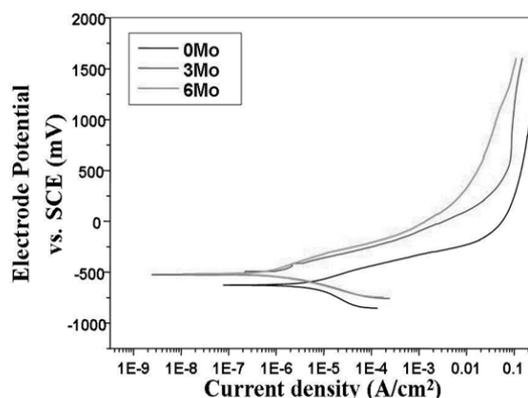


Fig. 5 Polarization curves of the alloys in the saline medium

IV. Conclusions

With an increase in Mo content, the $M_{23}C_6$ in the interdendritic region and M_6C type carbides at the interface of dendrites were formed instead of Cr-rich M_7C_3 carbide observed in the interdendritic region of the Mo-free Fe-based hardfacing alloy.

In addition, with increasing Mo content, the size of Cr-rich carbide formed in the interdendritic region decreased, but that of $M_{23}C_6$ and M_6C type carbides formed at the interfaces of dendrites increased as the refinement of Fe-rich dendrites. The addition of Mo improved the cavitation erosion resistance of Fe-based hardfacing alloys. It was concluded that the Fe-based alloy containing $M_{23}C_6$ and M_6C carbides has better cavitation erosion resistance than that containing M_7C_3 . And with increasing Mo, the corrosion current density decreased and the corrosion potential moved toward the noble direction. Since Mo remained in the austenite phase as solute atoms during the solidification, the composition of the matrix may be chemically improved. It is considered the reason for the increased corrosion potential with Mo addition.

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