Table 1 Composition and main properties of the chosen nickel－base alloy powders

trademark	C/ mass%	B/ mass%	Si/ mass%	Cr/ mass%	Fe/ mass%	Ni/ mass%	relax density /g·cm^{-3}	liquidity /s(50g)	density /g·cm^{-3}	melting point /℃	micro-hardness /HRC
Ni25	≤0.2	1.0～2.0	3.0～4.5	－	≤8	rest	≥3.5	<20	－	1040	25～30
Ni60	0.6～1.0	2.5～4.5	3.0～5.0	14～17	≤15	rest	4.1	18.1	7.5	1027	55～62

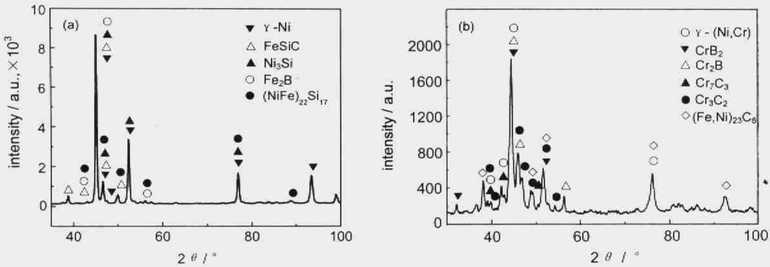

Fig.1 XRD result of different coatings by spray welding (a)Ni25 alloy coating, (b)Ni60 alloy coating

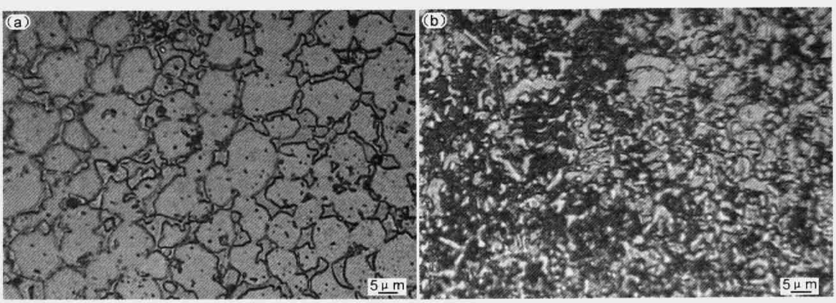

Fig.2 Microstructure of different coatings by spray welding (a)Ni25 alloy coating, (b) Ni60 alloy coating

3 结果与讨论

3.1 喷焊层的组织与结构

由X射线衍射分析(图1)可知,Ni25喷焊层主要由$\gamma-Ni$、Fe_2B、Ni_3Si、FeSiC、$(Ni\ Fe)_{22}Si_{17}$等组成,Ni60喷焊层主要由$\gamma-(Ni,Cr)$、$(Fe,Ni)_{23}C_6$及Cr的碳化物和硼化物等组成[5]. Ni25喷焊层的显微组织为典型的胞状晶(图2a)[6],基体为含Ni、Fe、Si的$\gamma-Ni$固溶体,晶间组织为Fe_2B、FeSiC和Ni_3Si,其中Fe_2B为一种硬质相,由图可以看出,该喷焊层组织较粗大,硬质相弥散度较小;Ni60喷焊层的显微组织由枝晶状的镍基固熔体和枝晶间大量细小颗粒状化合物的共晶组织组成(图2b). 从成分上分析,Ni60喷焊层C、Si、Fe的含量有所增加,同时又加入了Cr,化合物增多且更加弥散. 其基体为含Si、Ni、Cr的镍基固熔体γ相,硬质相为黑色点状$(Fe,Ni)_{23}C_6$及Cr的碳化物和硼化物,该喷焊层组织细小,硬质相的弥散程度较高[7].

3.2 涂层的显微硬度

显微硬度测试结果(图3)指出,两种喷焊层的显微硬度值均高于基体,Ni60喷焊层硬度较高,平均值为930 HV,数据分布较分散,说明喷焊层硬度不均匀;Ni25喷焊层显微硬度值比基体略高,平均值为260 HV,数据分布较集中,说明整个喷焊层硬度较均匀;另外,两种喷焊层在各自喷焊层与基体的界面附近硬度值均有所下降.

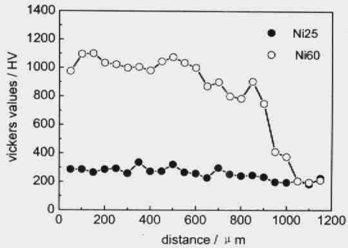

Fig.3 Curves of the coatings Vickers hardness values from the surface to the interface

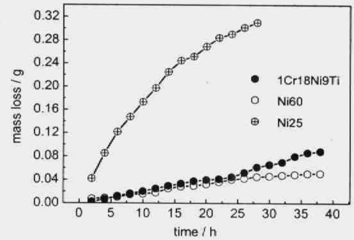

Fig.4 Curve of mass loss against time

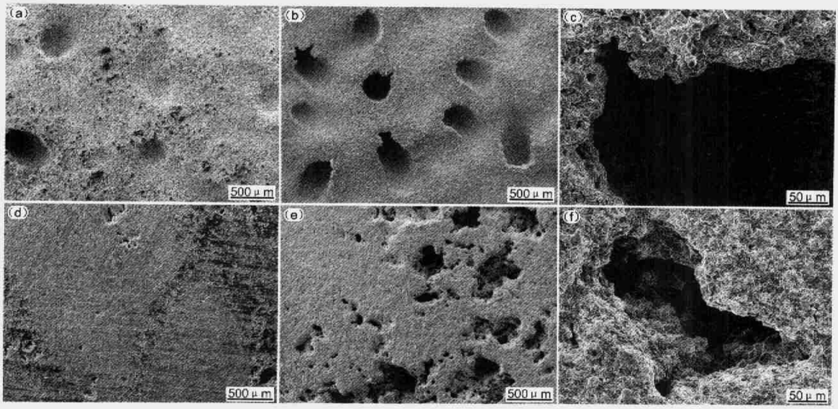

Fig.5 SEM micrographs of different coatings (a)Ni25 coating, 8 h;(b、c) Ni25 coating, 20 h;(d)Ni60 coating, 8 h;(e、f)Ni60 coating, 20 h

Ni60 喷焊层中硬质相的含量高于 Ni25 喷焊层,并且其硬质相的弥散度较好.大量硬质相的存在,阻碍了晶粒生长,因此晶粒较 Ni25 细小;综合以上几个方面原因,Ni60 的高硬度是固溶强化、弥散强化、细晶强化的综合结果.

3.3 涂层的抗气蚀性分析

图4 为基体、Ni25 喷焊层和 Ni60 喷焊层的绝对失重与时间关系.可知,Ni25 喷焊层的气蚀破坏较严重,27 h 气蚀后,其重量损失分别是基体和 Ni60 喷焊层的 5.8 倍和 7.1 倍.而 Ni60 喷焊层和基体的重量损失在试验 24 h 之前非常接近,24 h 之后,基体损失逐渐增多,在 38 h 试验结束后,其重量损失为 0.0884 g,是 Ni60 损失量的 1.7 倍.

总体上看,Ni25 喷焊层的破坏程度远大于其他两组,基体的气蚀破坏程度大于 Ni60 喷焊层,尤其在 26 h 之后,该趋势更加明显.

图 5 为 Ni25 及 Ni60 喷焊层气蚀后的 SEM 图.可知,Ni25 喷焊层在气蚀试验开始后 2 h 左右,喷焊层表面颜色变暗,失去原有金属光泽;气蚀累计 4h 后,局部产生麻点;累计 8 h(图 5a),有明显气蚀坑出现,试样在气蚀坑出现后破坏速度逐渐加快,该气蚀坑接近圆形,靠试样中心方向有一倾斜面,坑内光洁,但深浅不一;随着时间的延长,20 h 后,原有气蚀坑不断加深变大,坑孔边缘出现缺口(图 5b、5c);气蚀过程中不断产生新的麻点、气蚀坑,直至最后整个喷焊层表面均匀布满气蚀坑.该喷焊层气蚀坑的特点是面积较大,深度较浅.

Ni60喷焊层气蚀最初阶段有极少量气蚀针孔

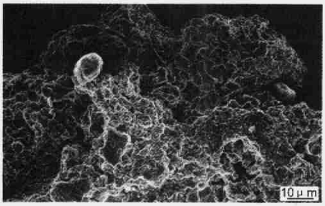

Fig.6 Cracks on the edge of the cavitation erosion hole of the Ni25 coating

产生,试验4 h左右表面逐渐失去光泽,出现“发乌”现象,累计8 h后,表面原有气蚀针孔加深变大,小的针孔彼此相连长大,成为气蚀坑(图5d);随着时间的延长,在其他部位又有新的针孔产生,新产生的针孔尺寸相当(图5e).该喷焊层产生的气蚀坑形貌与Ni25喷焊层有明显不同,在大的气蚀坑内部包含有更小的气蚀坑[8],单个气蚀坑面积较小,深度较深,坑的表面不规则,在扫描电镜下看不清洞内的形态(图5f).Ni60喷焊层气蚀坑比较集中,只在局部产生较严重破坏,其他部位只有少量气蚀针孔产生.

Ni25喷焊层表面在气泡溃灭的冲击作用下,发生弹性变形和塑性变形,由于相邻两相的晶体结构不同,造成变形不协调,相界附近形成位错塞积,在相界局部形成高应力场,如此反复作用,当位错塞积达到一定程度,应力峰值达到某个临界值时,在相界上就会产生裂纹[9,10].

裂纹从相界处产生,在气蚀过程中成为气蚀源,并以一定的倾斜角度向内部扩展,形成裂缝;各个方向的裂缝相互交汇贯通,导致喷焊层颗粒沿晶剥落[11~13],成为气蚀孔洞或气蚀坑;而气蚀孔洞和气蚀坑的形成又成为新的气蚀源,加速喷焊层的破坏[14].在高倍SEM像图上可以清楚的看到喷焊层表面布满细小的裂纹,裂纹在气蚀坑周围集中,并形成较长的裂缝,气蚀坑边缘的颗粒即将剥落(图6).

与Ni25喷焊层破坏机理相似,气蚀初期,Ni60喷焊层裂纹产生于相界处.涂层的表面硬度对其抗气蚀性能有重要影响[15],由于该喷焊层中硬质相弥散度相对较好,晶界增多,位错滑移受阻,裂纹在扩展中所受阻力增大,因此Ni60喷焊层表现出较好的抗气蚀性能.

4 结论

(1)在相同的气蚀条件下,Ni60喷焊层的抗气蚀性能比Ni25喷焊层有很大提高.

(2)Ni25喷焊层的裂纹主要萌发于晶界处,因此强化晶界、细化组织是提高材料抗气蚀性能的主要途径.

(3)Ni60喷焊层存在大量含铬硼化物和碳化物等硬质相,导致喷焊层晶界较多、硬度较高,且硬质相弥散度较好,形成了“骨架”以抵御气蚀破坏,有利于提高抗气蚀性能.

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CAVITATION EROSION RESISTANCE OF SPRAY WELDING NICKEL-BASED COATINGS

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Abstract: Ni-based alloy coatings were made by spray welding on surface of the mild steel(1Cr18Ni9Ti). The microstructure and performance of the coatings were investigated by optical microscope, X-ray diffraction, Vickers hardness, scanning electron microscope(SEM) and vibratory cavitation apparatus. The results show that the Ni60 coating has much higher hardness and finer structure than Ni25 coating and 1Cr18Ni9Ti. In addition, the vibratory cavitation results show that the mass loss increases with increasing test time. These results indicate that the cavitation erosion resistance of Ni60 coating is much better than that of the Ni25 coating, due to higher hardness and finer structure. Furthermore, the cavitation erosion mechanisms were studied also in the end of this paper. The results showed that higher hardness and finer structure can increase the vibratory cavitation resistance of coatings.

Key words: cavitation erosion, spray welding, microstructure, mechanism