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Effects of alloy additions on the fatigue properties of cast Co–Cr–Mo alloy used for surgical implants

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As the second part of the present study, the effects of modifying the composition of the Co–Cr–Mo alloy with additions of nickel and some trace elements aluminium, titanium and boron, have been investigated. A great improvement in the fatigue crack growth resistance of the cast alloy is obtained by nickel additions to the base alloy, mainly because of a significant increase in the alloy's stacking fault energy. In addition, the fatigue fracture ductility is observed to be improved strikingly with the nickel additions. Much smaller facets and better ductility with a mixed fatigue crack propagation mode, as compared to the base alloy, are observed in the alloys with low nickel content level, and in the alloys with high nickel content level, localized ductile fatigue striations are observed. It is also indicated that minor additions of such elements as aluminium, titanium and boron can be used to improve further the fatigue crack growth resistance resulting from the elimination of some microstructural casting defects.

1. Introduction

In the first part of this study [1] the experimental details of modifying the composition of the Co–Cr–Mo based surgical implant alloy with additions of nickel and some trace elements aluminium, titanium and boron are described and the effects of alloy additions on the microstructures and the transient mechanical properties of the as-cast alloys are evaluated. It is found that the contribution of nickel additions to the improvements in mechanical properties observed are mainly attributed to the changes in stacking fault energy (SFE) of the matrix, because the SFE is affected significantly by adding nickel to a cobalt-based alloy [2], while the contribution of minor additions of the trace elements to the improvements in mechanical properties mainly resulted from the elimination of some microstructural casting defects.

However, an implantable structural material involves more than just having adequate transient mechanical properties. A very important mechanical factor, particularly for a weight-supporting orthopaedic replacement device, is the cyclic nature of the mechanical stressing which many implants experience [3–10]. Therefore, fatigue resistance is of great importance for the alloys used as implant appliances.

The Co–Cr–Mo alloy is normally used in the as-cast condition and as such suffers from wide variability in mechanical properties and generally low mechanical integrity. This is because of random casting defects such as shrinkage cavities and a coarse nonuniform grain size which tend to reduce the alloy's tensile and fatigue properties. The fatigue strength (10^7 cycles) of the as-cast Co–Cr–Mo alloy is reported to be very low, about 250 to 300 MPa [10], with respect to its tensile yield stress. Furthermore, investigations concerning the fracture features of cast Co–Cr–Mo alloy indicated that brittle faceted fatigue fracture is the dominant fracture mode in which a crystallographically oriented fracture appearance is observed [3, 4, 11–13]. These shortcomings in the fatigue properties often lead to premature failure of implants manufactured from cast Co–Cr–Mo alloy.

In our previous investigation concerning the improvements in mechanical properties of the as-cast Co–Cr–Mo alloy by controlling the casting conditions [14, 15], it was shown that a higher fatigue threshold value and a lower fatigue crack growth rate at the same applied stress intensity factor range level can be obtained in the rapidly cooled cast alloy which shows a fine equiaxed grain structure, compared to the results obtained in the conventionally investment cast alloy which normally shows a coarse dendritic structure. However, this does not seem to result in substantial improvements in the fatigue fracture morphologies, and a brittle faceted fatigue fracture appearance is still observed in the fine-grained alloy. In this paper, the second part of the present study, the effects of alloy additions on the fatigue properties, both the fatigue crack growth resistance and the fatigue fracture ductility, of the as-cast Co–Cr–Mo alloy are discussed with specific attention to the role of SFE in improving the alloy's fatigue behaviour.

2. Materials and experimental procedure

Cast Co–Cr–Mo alloy, commercially known as Vitallium or H.S. 21 and its modified versions with alloy additions of nickel and some trace elements aluminium, titanium and boron were studied. The chemical compositions of the alloys are shown in Table I.

TABLE I Composition of as-cast alloys used in the present study

Alloy no.	Chemical composition (wt %)										
	Cr	Mo	Ni	C	Fe	Si	Mn	Co	Ti	Al	B
1	29.07	6.69	–	0.16	0.06	0.05	0.10	bal.	–	–	–
2	27.59	6.49	4.28	0.15	0.06	0.05	0.09	bal.	–	–	–
3	26.24	6.13	9.03	0.15	0.06	0.05	0.09	bal.	–	–	–
4	28.84	6.35	–	0.16	0.06	0.08	0.10	bal.	0.12	0.11	0.01
5	27.40	6.23	4.50	0.16	0.06	0.08	0.10	bal.	0.11	0.11	0.01
6	25.71	5.98	9.48	0.15	0.05	0.07	0.09	bal.	0.11	0.11	0.01

Alloys were prepared by vacuum induction melting and cast in sand moulds with air cooling. Specimens were mechanically tested and structurally examined in the as-cast condition.

Individual castings used for mechanical testing specimens were cast with dimensions 85 mm × 20 mm × 30 mm. The as-cast alloys exhibited a typical microstructure, namely a cored cobalt-rich fcc matrix with a considerable amount of interdendritic precipitates and few grain-boundary precipitates [1]. A directional, coarse dendritic cast structure was obtained both in the base alloy and in the modified alloys.

Fatigue crack propagation tests were conducted using an Instron testing machine (Model-1342) on standard three-point bend specimens [16] with S = 64 mm, W = 16 mm, B = 8 mm and a total specimen length L = 80 mm machined from the original castings, in laboratory air at room temperature. A 3 mm notch was made by spark cutting in advance and the fatigue precracking of the specimens was carried out in the same fixtures in which they were fatigue tested. Cyclic frequency of 20 Hz and sine waveform were used at a load ratio (R) of 0.1. A seven-point incremental polynomial method [17] was used for determining the constant-load-amplitude fatigue crack growth rates and stress intensity factor range values.

Fresh fatigue fracture surfaces were examined in Philips SEM505 scanning electron microscope. After fatigue testing, specimens were sectioned perpendicular to the fracture surfaces for metallographic examination and beneath the fracture surfaces for transmission electron microscopy study. Metallographic specimens were prepared by electrolytic etching with 60% HNO_3 + 40% distilled water by volume, 10 to 25 sec at 5 V. Transmission electron microscopy was performed using disc specimens of 3 mm diameter. They were finally thinned by jet polishing in an electrolyte of 10% perchloric acid + 20% ethanol + 70% butanol by volume, at temperatures between −20 and −30° C and at a potential of 30 V. The specimens were examined in Philips EM301 transmission electron microscope operating at 100 KV.

3. Results and discussion

The results of fatigue tests, relationships between fatigue crack growth rates and applied stress intensity factor ranges, for the base alloy and the modified alloys, are shown in Fig. 1. It is indicated that a great improvement in the fatigue crack growth resistance of the cast alloy has been achieved by modifying the composition of the base alloy with additions of nickel and the trace elements.

Corresponding to the applied stress intensity factor range levels during the fatigue testing in the present study, considerably lower fatigue crack growth rates, as compared with those obtained in the base alloy (alloy 1) and the modified alloy without nickel additions (alloy 4) under the same testing conditions, are obtained in the modified alloys with nickel additions, and this improvement is increased with the increase of nickel content in the alloys.

The results of fatigue testing show that minor additions of such elements as aluminium, titanium and boron may be used to improve further the fatigue crack growth resistance. The alloys with minor additions of these trace elements (about 0.1 wt % respectively) show a lower fatigue crack rate than the alloys without the trace element additions at the same applied stress intensity factor range level. This situation is found to exist in the alloys both with the base composition and with the compositions modified by nickel additions.

The appearances of the fatigue fracture surfaces of the base alloy and the modified alloys are shown in Figs 2 to 4, which sequentially correspond to the various nickel content levels in the alloys. The fatigue fracture morphologies are observed to change strikingly with the nickel additions and with the

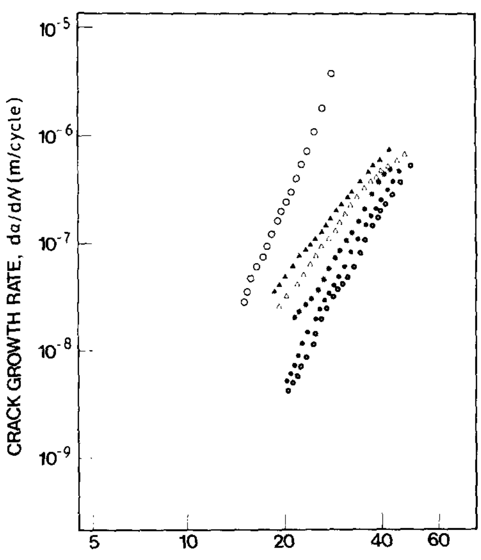


Figure 1 Fatigue crack propagation behaviour of the as-cast alloys showing the effects of alloy additions on the fatigue crack growth resistance in a Co–Cr–Mo based alloy, at constant amplitude. Alloys: (○) 1, (△) 2, (★) 3, (▲) 4, (●) 5, (◉) 6.

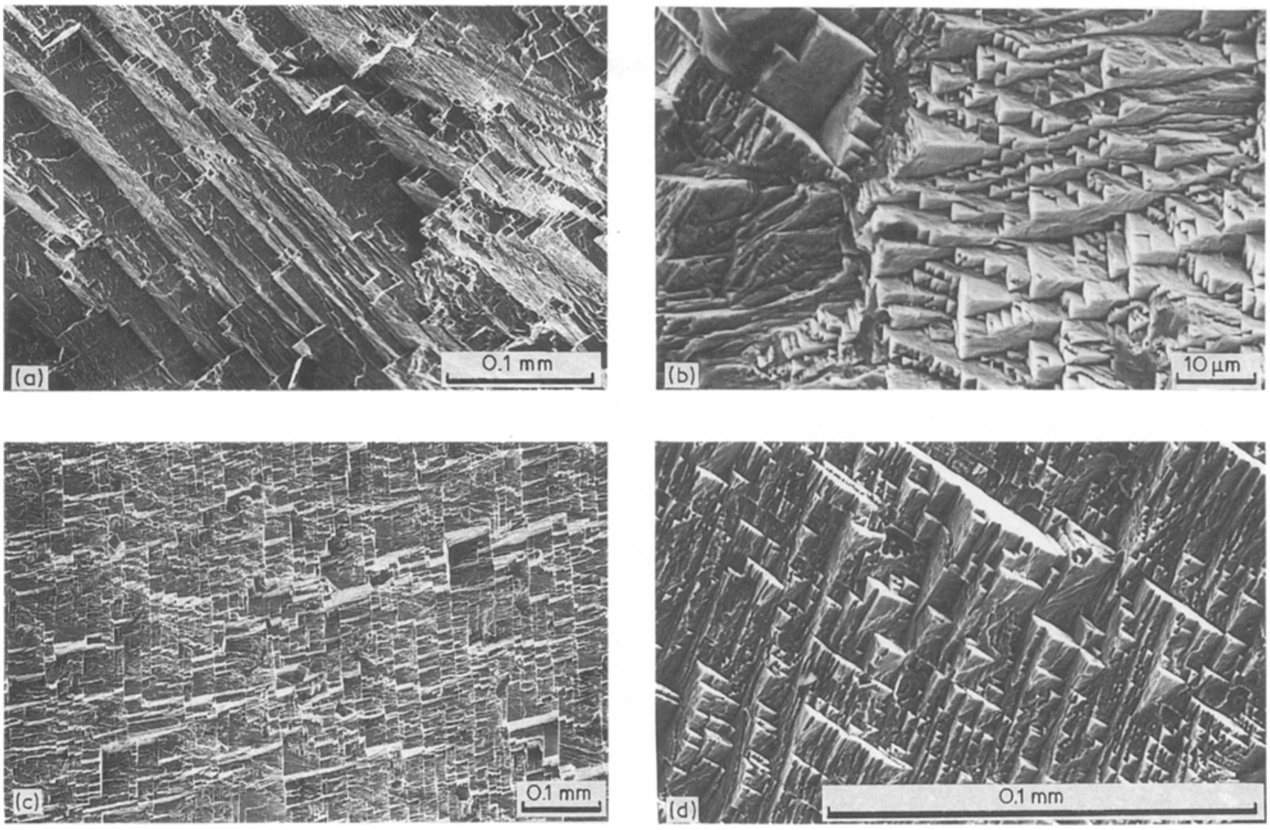


Figure 2 Scanning electron micrographs of the fatigue fracture surfaces showing the fracture appearances in alloy 1, (a) to (c), and in alloy 4, (d), which are the alloys with no nickel additions.

increase of nickel content in the alloys. However, the additions of the trace elements, aluminium, titanium and boron, seem to have no significant effects on the fatigue fracture features.

As reported in our previous studies [11, 14, 15], the base alloy exhibits a typically brittle fatigue fracture appearance in which crystallographically faceted fractures are found to be the dominant fatigue fracture feature. Fig 2a shows a SEM fractograph of the base alloy corresponding to a very low crack growth rate, where highly angular crystallographic facets are observed. Well-developed faceted fatigue fractures including the characteristics of a block structure with steps, large facets with three or four plane orientations (indicating the alternate $\{1\,1\,1\}$ planes in f c c structure) and abrupt height changes, as well as stair-step morphologies on the fine scales, as shown in Fig. 2b, are commonly observed in this alloy. Brittle striation-like fatigue fracture appearance, which is presumably associated with the presence of locally cyclic strain-induced f c c to h c p martensitic transformation [18], is observed in a region of the fatigue fracture surface of the base alloy corresponding to a high crack growth rate, as shown in Fig. 2c. A similar fatigue fracture appearance with faceted fracture feature, as observed in the base alloy, is also observed in the modified alloy with only minor additions of trace elements but no nickel additions (alloy 4), as seen in Fig. 2d.

For the alloys with about 4 to 4.5 wt % nickel (alloys 2 and 5), much smaller fatigue fracture facets and much better fracture ductility with a mixed fatigue crack propagation mode, as compared to the base alloy, are observed. In Fig. 3, the fatigue fracture appearances observed in alloys 2 and 5 are shown.

With the increase of nickel content in the alloys, up to about 9 to 9.5 wt % in the present study, the fatigue fracture ductility is further improved. As shown in Figs 4a and b, localized ductile fatigue striations are

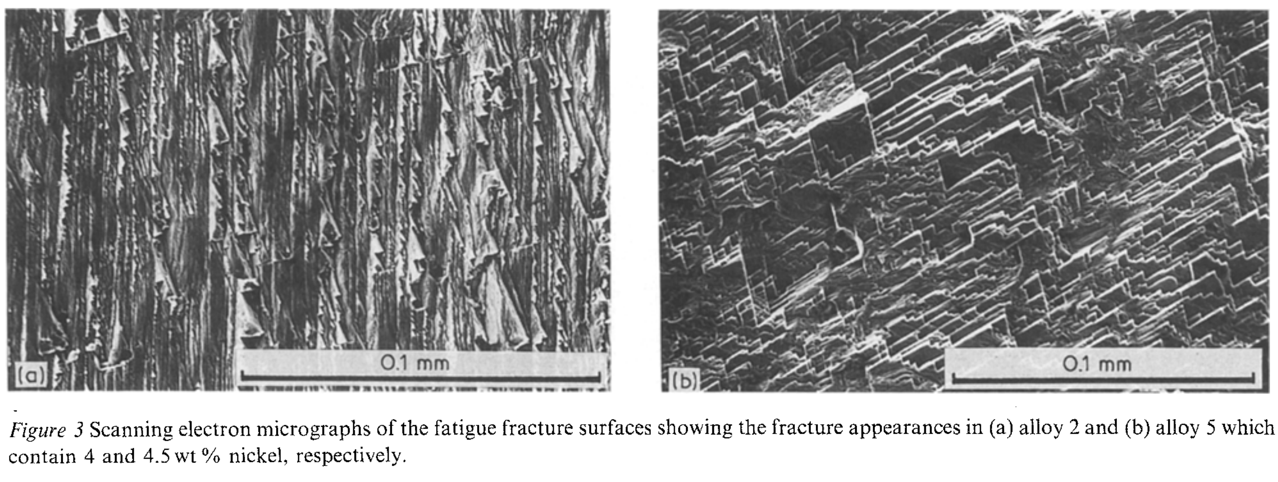
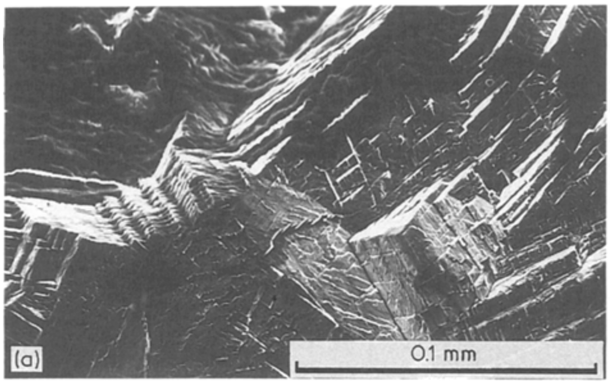
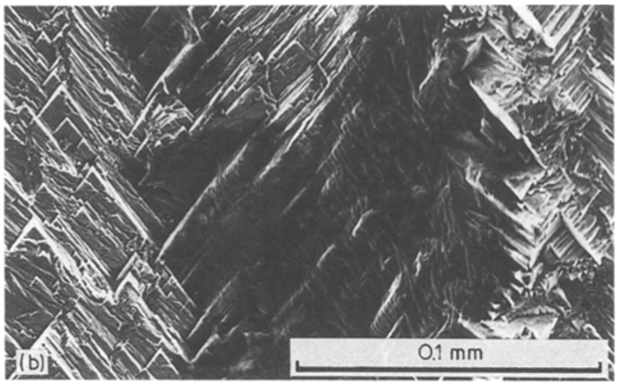


Figure 3 Scanning electron micrographs of the fatigue fracture surfaces showing the fracture appearances in (a) alloy 2 and (b) alloy 5 which contain 4 and 4.5 wt % nickel, respectively.





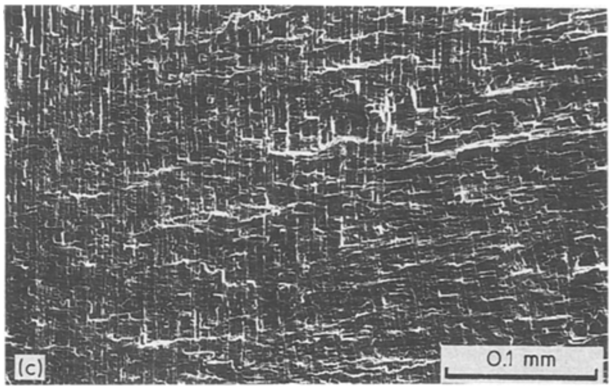


Figure 4 Scanning electron micrographs of the fatigue fracture surfaces showing the fracture appearances in (a) alloy 3 and (b, c) alloy 6 which contain 9 and 9.5 wt % nickel, respectively.

observed in alloys 3 and 6. A region of fatigue fracture surface observed in alloy 6 showing a ductile striation-like fatigue feature with a quite large dimension, which consists of many very small facets, is shown in Fig. 4c.

The changes in fatigue crack propagation mode, which indicate the differences in fatigue fracture morphology, caused by alloy additions in the present study are also revealed by optical microscopy examination. Fig. 5 shows the polished and etched side views of fatigue fracture surfaces of the base alloy (alloy 1) and a modified alloy with 9 wt % nickel (alloy 3), respectively. It is apparent that the fatigue crack growth is associated preferentially with specific crystallographic planes, here $\{1\,1\,1\}_{fcc}$ planes which are indicated by parallel arrangement of 60° angle difference between two orientations of the fatigue crack facets, in the cast Co–Cr–Mo alloy with base composition, as shown in Fig. 5a. However, these typically crystallographic plane faceted fatigue fracture characteristics are seldom seen in the alloys with nickel additions, especially in the alloys with high nickel content, as shown in Fig. 5b.

Transmission electron microscopy study [18] of the fatigued specimens reveals the effects of alloy additions on the cyclic strain induced microstructure changes during fatigue. Fig. 6 shows TEM micrographs of the fatigue tested specimens which are sectioned close to fracture surfaces in alloys 1, 2 and 6, respectively. It is proved that the cyclic strain during fatigue causes an initial martensitic transformation from f c c phase to a heavily faulted h c p structure in the base alloy and in the modified alloy with no nickel addition, as shown in Fig. 6a where an associated selected-area diffraction pattern is included, and no such transformation has been observed in the modified alloys with nickel additions, both the low nickel content alloys and the high nickel content alloys. In the nickel-added alloys, only a high density of stacking faults and the intersections of stacking faults, which are partly produced during solidification processes and partly induced by cyclic strain during fatigue, can be observed. The density of stacking faults in the f c c matrix is observed to decrease with the increase of nickel content in the alloys, as shown in Figs 6b and c.

The contribution of modifying the composition of the Co–Cr–Mo alloy with additions of nickel and the trace elements aluminium, titanium and boron to the improvement in the alloy's fatigue properties is of significant importance. In all cases, the modified alloys

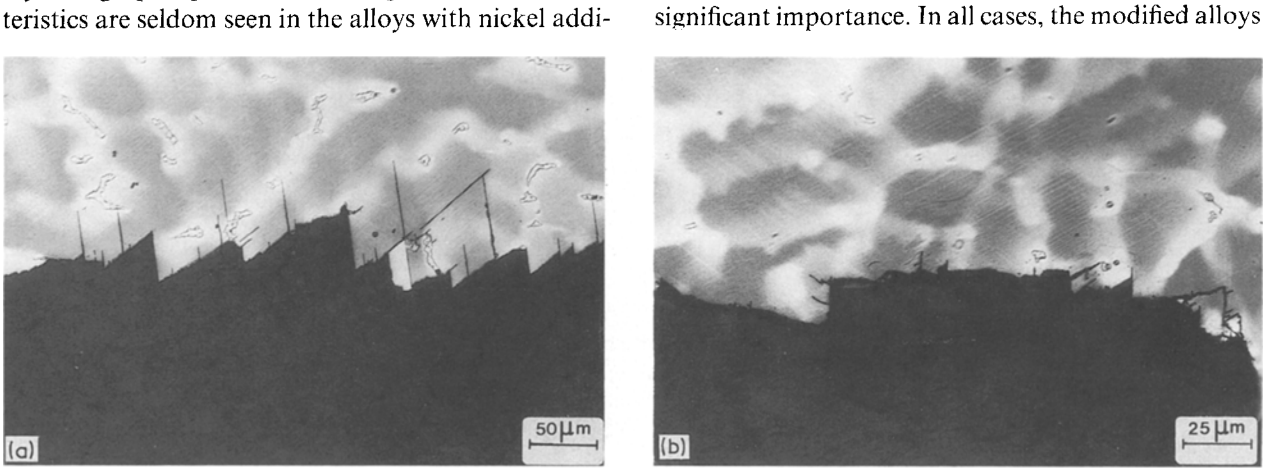


Figure 5 Optical micrographs of the side views of the fatigue fracture surfaces showing the effects of nickel additions on the fatigue crack propagation mechanism, (a) alloy 1 and (b) alloy 3.

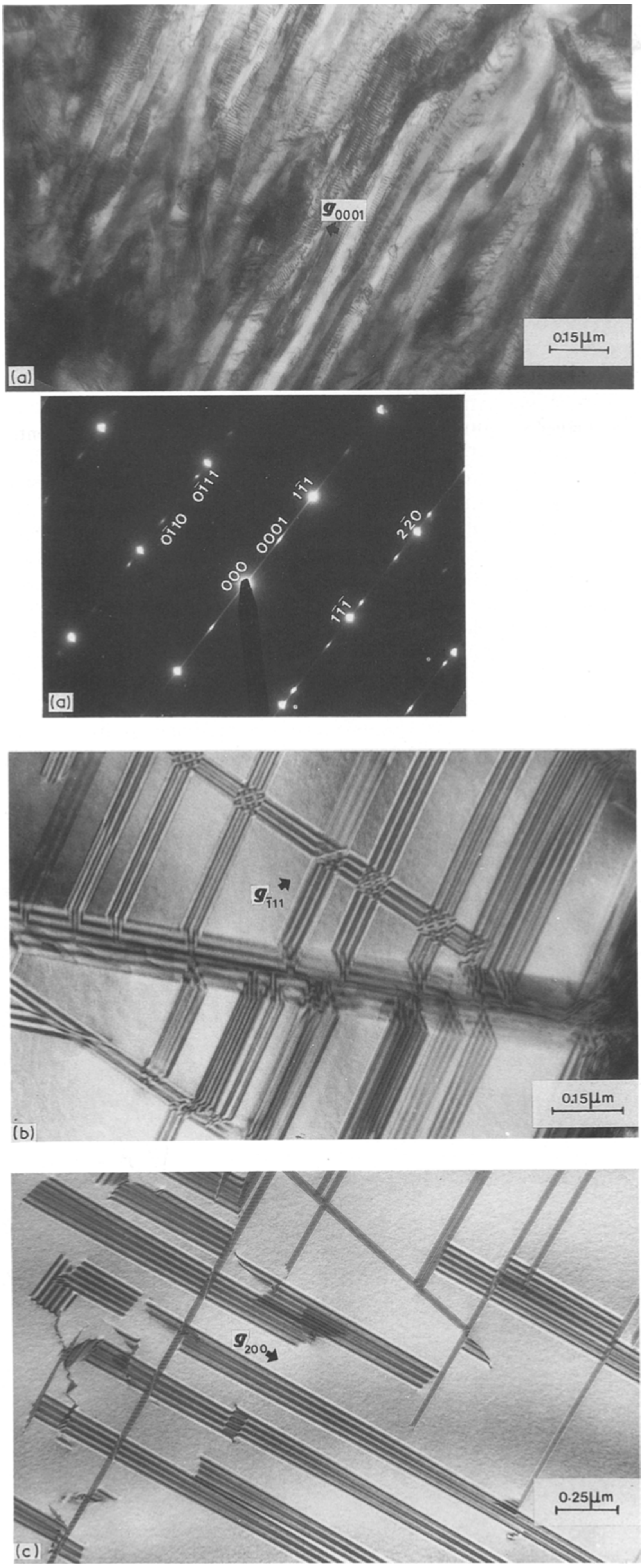


Figure 6 Transmission electron micrographs of the fatigue-tested specimens showing the effects of nickel additions on the cyclic strain-induced microstructures developed during fatigue. (a) Strain-induced martensite in alloy 1, (b) and (c) dense f c c stacking faults and the intersections of stacking faults in alloys 2 and 6, respectively.

show a much lower fatigue crack growth rate than the base alloys at the same applied stress intensity factor range level. Therefore, it would be reasonable to expect that the modified alloys possess a higher fatigue limit value than the base alloy; furthermore, a higher ratio of fatigue strength to tensile yield strength, especially for the nickel-containing alloys which show a lower tensile strength. The variations in the ratio of fatigue strength to tensile yield strength of the alloys are responsible for the changes in fatigue crack propagation mode and the fatigue fracture appearance. Alloys with a lower ratio of fatigue strength to yield strength are prone to faceted fatigue fractures [19]. This is probably a result of the fact that a high stress or strain at the crack tip in the alloys with a lower ratio of fatigue strength to yield strength cannot be accommodated by appropriate deformation processes because slip on specific crystal planes is restricted by some fine microstructural defects such as stacking faults, especially in the f c c materials with low SFE; therefore, a critical cleavage stress may be reached at the fatigue crack tip under a low applied load and faceted fractures occur.

The effects of nickel additions on the fatigue properties of this cobalt-base alloy are mainly determined by the fact that the SFE in this alloy system is strongly dependent upon the nickel content of the alloy. In Tisone's investigation [2], it is reported that for an alloy with about 60 at % cobalt, the SFE increases from 20 erg cm^{-2} to 40 erg cm^{-2} by 10 at % nickel replacement. Nickel additions to the base alloy result in a significant increase of the alloy's SFE, which leads to a substantial decrease of the density of dissociated dislocations, stacking faults and twins so as to facilitate the dislocation slip deformation processes in the f c c matrix during fatigue. With the increase of alloy's SFE, faceted fatigue fracture as well as cyclic strain-induced f c c to h c p martensitic transformation are eliminated. All of these factors which are known to be associated with the alloy's SFE promote the alloy to have a higher fatigue crack growth resistance with a better fatigue fracture ductility.

The effects of minor additions of the trace elements such as aluminium, titanium and boron on the fatigue crack growth resistance of this cobalt-base alloy are mainly results of the improvements in casting structure, where the microstructural casting defects such as shrinkage porosity, interdendritic segregation, non-metallic inclusions as well as coarse grain size can be minimized by minor additions of these elements; in particular a reduction in grain size is obtained. However, additions of the trace elements seem to have no significant effects on the fatigue fracture ductility and the cyclic-induced f c c to h c p martensitic transformation in the cast Co–Cr–Mo alloy. Faceted fatigue fractures and the strain-induced martensitic phase are also observed in the modified alloy with the trace element additions but with no nickel addition.

4. Conclusions

A significant improvement in fatigue properties of the alloy is obtained by modifying the composition of the Co–Cr–Mo alloy with additions of nickel and some trace elements such as aluminium, titanium and boron. The response of the fatigue properties to the additions of nickel can be understood in terms of the effects of stacking fault energy on the fatigue properties of the cast alloy, because nickel additions to the base alloy increase the alloy's stacking fault energy value strikingly and the observed changes in the alloy's fatigue properties are known to be associated with the stacking fault energy of the alloy. The effects of the trace element additions on the fatigue properties are mainly results of the elimination of microstructural casting defects.

Nickel additions render the alloy a higher fatigue crack growth resistance with a better fatigue fracture ductility. With the additions of nickel, faceted fatigue fractures are eliminated and much more ductile fatigue fracture appearances, such as localized ductile fatigue striation morphologies, are observed. Furthermore, the cyclic strain induced f c c to h c p martensitic transformation during fatigue is restricted and the density of dissociated dislocations, stacking faults as well as twins is decreased by the additions of nickel to the base alloy.

Further improvement in the fatigue crack growth resistance is achieved by minor additions of some trace elements aluminium, titanium and boron. However, the trace element additions do not result in changes in the nature of the alloy's fatigue behaviour which is dominated by the stacking fault energy of the alloy, such as faceted fatigue fractures and the cyclic strain-induced f c c and h c p martensitic transformation in the as-cast Co–Cr–Mo base alloy.

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