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Inconel 617 and Stellite 6 alloys for tooling in thixoforming of steels

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Abstract: Thermal fatigue and high temperature wear are the two principle failure mechanisms for thixoforming dies. Samples of Inconel 617 and Stellite 6 alloys were submitted to thermal cycling under conditions which approximate thixoforming of steels and to sliding wear tests at 750 °C. The experimental results thus obtained were compared with those of the X32CrMoV33 hot work tool steel. The Inconel 617 and Stellite 6 samples are much more resistant to oxidation and to softening than the hot work tool steel, providing a superior resistance to thermal fatigue cracking. The wear resistance of the Inconel 617 and Stellite 6 alloys at 750 °C is also markedly superior. The adhesive oxides growing slowly on Inconel 617 and Stellite 6 alloys sustain the wear action without spalling and are claimed to be responsible for the superior wear resistance of these alloys at 750 °C.
Key words: steel; thixoforming; tooling; thermal fatigue; wear

1 Introduction

Lack of suitable high temperature die materials is the major impediment that denies the benefit of commercialization of semi-solid forming for high melting point alloys in spite of its potential to provide lightweight for forged steel parts[1−2]. Thixoforming tools ought to last thousands of forming cycles for industrial application. While very affordable, the conventional hot work tool steels were proved to be entirely inadequate[1, 3−7].

Suitable replacements for hot-work tool steels, able to withstand the steel thixoforming environment for an economically acceptable life have been investigated in recent years[8−18]. Superalloys which are generally employed for high temperature applications are among potential candidates. With a dispersion of hard carbide particles in a cobalt-rich solid solution matrix, cobalt-base alloys are exceptionally good for applications requiring resistance to oxidation and wear[20−23]. Stellite 6, in particular, retains its hardness, resists oxidation and offers an excellent resistance to thermal shock, wear and corrosion over a wide temperature range[24]. Ni-base alloys are also attractive high temperature materials owing to an excellent oxidation resistance, creep strength and phase stability at high temperatures[25−28]. Inconel 617, a Ni-based superalloy, was reported to exhibit superior thermal fatigue resistance in demanding tooling applications[29]. The present work was undertaken to explore the potential of Inconel 617 and Stellite 6 alloys for tooling applications in steel thixoforming. These alloys were tested in thermal fatigue and high temperature wear, claimed to be the principle failure mechanisms for thixoforming dies. Their performance was compared with that of X32CrMoV33 steel widely used in the manufacture of conventional forging dies.

2 Experimental

The chemical compositions of the Inconel 617 and Stellite 6 alloys and the hot work tool steel tested in the present work are given in Table 1. The thermal fatigue test was designed to approximate the conditions encountered in steel thixoforming. This test involved cyclic heating and cooling of prismatic samples (25 mm×25 mm×20 mm) between the peak die cavity surface temperature and the temperature the die was pre-heated to that before the forming operation. The controlled parameter during thermal cycling was the temperature of the front face of the sample, heated by an oxyacetylene flame to 750 °C within about 30 s (Fig.1). Cooling was performed by forced air, adjusted so as to bring the surface temperature to around 450 °C, during the next 30 s. Thermal fatigue damage was assessed

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Table 1 Chemical compositions of X32CrMoV33, Inconel 617 and Stellite 6 alloys (mass fraction, %)

Alloy	C	Si	Mn	Cr	Mo	Ni	Co	V	W	Fe
X32CrMoV33	0.281	0.190	0.200	3.005	2.788	0.221	<0.010	0.413	0.020	92.63
Inconel 617	0.080	0.945	0.513	21.88	8.177	53.861	10.872	−	−	2.850
Stellite 6	1.089	1.099	1.154	28.272	0.004	2.802	58.241	0.009	4.512	2.660

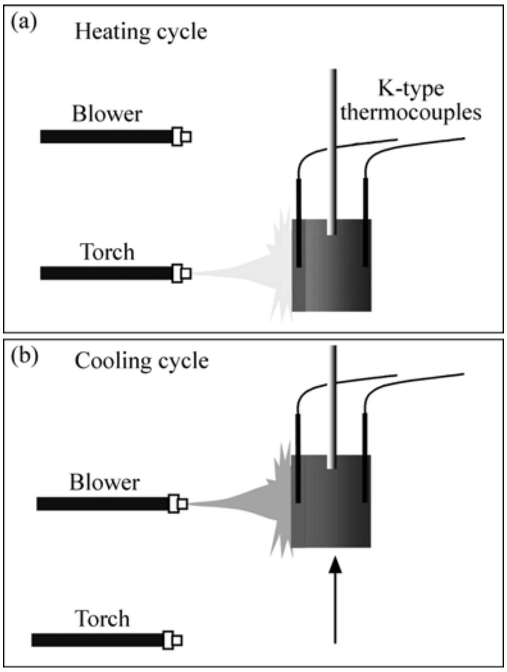

Fig.1 Schematic diagram of thermal fatigue test: (a) Heating cycle; (b) Cooling cycle

qualitatively using stereo and optical microscopy.

A commercial ball-on-disc type tribometer was used to investigate the high temperature wear properties of Inconel 617 and Stellite 6 alloys and X32CrMoV33 hot work tool steel. Wear tests were carried out at 750 °C with a sliding speed of 0.025 m/s, under 5 N load for 60 min. A *d*10 mm alumina ball ran over disk samples along a circular path having a diameter of 30 mm. The disc surfaces were ground with 1 000 mesh grit sandpaper and were ultrasonically cleaned in acetone and dried before each test. Wear tracks were investigated with an optical profilometer, an optical microscope and a scanning electron microscope. Wear quantification was done by measuring the volumetric loss of the worn area. XRD analysis with Cu K_α radiation and step size of 0.02° was also used to identify the oxides formed on the worn surfaces. The hardness of the samples was measured in Vickers units with a load of 9.8 N (HV_1) before and after the wear test.

3 Results and discussion

Thermal cycling produced thick oxide scales on the front face of the X32CrMoV33 hot work tool steel soon after the test started (Fig.2). These scales spalled off with continued thermal cycling, due to a thermal expansion mismatch. The thermal fatigue test of the X32CrMoV33 hot work tool steel was thus terminated after 1 500 cycles due to severe surface degradation. Deep, branched thermal fatigue cracks, decorated with thick oxides were noted once the surface scales were removed (Fig.2(c)). The surface scales were believed to promote crack initiation while the thick oxides inside the cracks exerted a wedging effect which helped to open the cracks wide and thus encouraged propagation. Besides severe oxidation, the conventional hot work tool steel suffered loss of mechanical strength upon thermal cycling (Fig.3). Hardness at the front face, measured to be HV442 before the thermal fatigue test, dropped to approximately HV275 after only 400 cycles. A surface layer 10 mm deep was adversely affected by thermal exposure. The temper resistance of the X32CrMoV33 hot work tool steel apparently failed to sustain the temperatures thixoforming dies experienced during forming operations.

The response to thermal cycling of the Inconel 617 and Stellite 6 alloys was markedly different. Slight colouring was the only evidence for oxidation on the front face of the Inconel 617 and Stellite 6 samples (Fig.2(b) and (c)), suggesting that they were much more resistant to oxidation than the hot work tool steel. Both alloys suffered very few and relatively shallow cracks after as many as 5 000 thermal cycles. These cracks were readily removed after light grinding of the surface. Softening upon thermal cycling was relatively modest in Inconel 617 and Stellite 6 (Fig.3). The average hardness at the front face, HV306 before the test, dropped to HV268 after 1 500 cycles and remained more or less constant for the rest of thermal cycling in Inconel 617. Likewise, the hardness of the Stellite 6 sample, measured to be HV430 before thermal cycling dropped to HV337 after the first 1 500 cycles. The heat-affected surface zones were relatively thinner.

Two- and three-dimensional topography images of the samples submitted to sliding wear tests are illustrated in Fig.4. The widest and the deepest wear track, and thus the highest volume loss occurred in the hot work tool steel (Fig.5). The surface of the hot work tool steel disc sample deteriorated not only inside but also outside the wear track, due to the extensive oxidation as evidenced

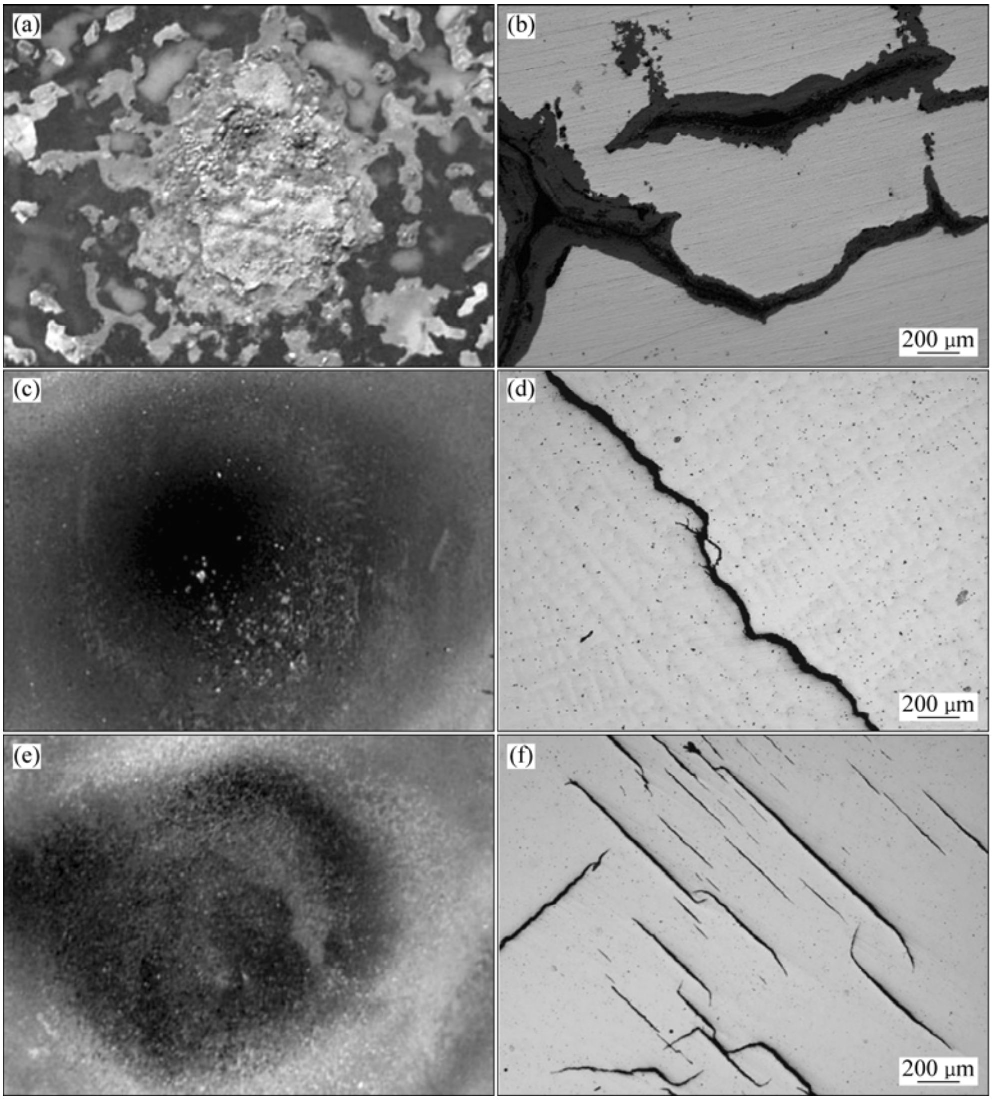

Fig.2 General views of front faces (a, c, e) and thermal fatigue cracks on front faces (b, d, f): (a, b) X32CrMoV33 steel after 1 500 cycles; (c, d) Inconel 617 after 5 000 cycles; (e, f) Stellite 6 after 5 000 cycles (Thermal fatigue cracks on front faces are revealed after metallographic polishing; (b) shows section approximately 1 mm from front face)

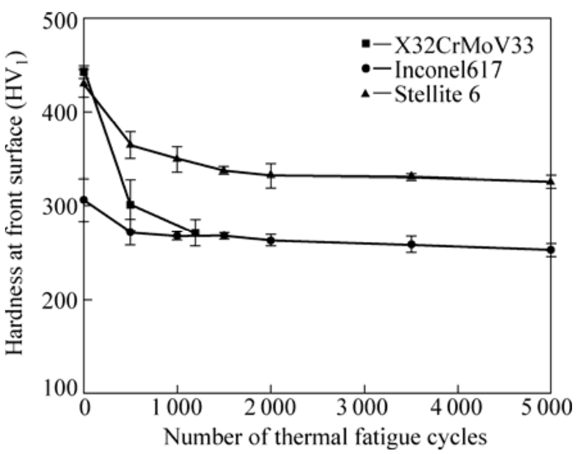

Fig.3 Change in hardness of X32CrMoV33 hot work tool steel, Inconel 617 and Stellite 6 samples with increasing number of thermal fatigue cycles

in the transverse section micrograph of the wear track (Fig.6). Thick oxide scales apparently failed to sustain the wear loading and fractured to produce oxide debris in the wear track. Abrasive wear with grooving in the sliding direction, a very thick oxide layer and an appreciable quantity of debris accumulated at the edges of the track were the basic wear features for the hot work tool steel (Fig.7). Oxidation, fresh surface generation via fracture and removal of the surface oxides inside the wear track and reoxidation of the fresh surface were claimed to be responsible for the substantial wear loss suffered by the hot work tool steel. Wear resistance of the X32CrMoV33 tool steel was impaired also via loss of mechanical strength. X32CrMoV33 tool steel responded to thermal exposure at 750 °C with a sharp hardness drop (Fig.8).

The width and the depth of the wear tracks were

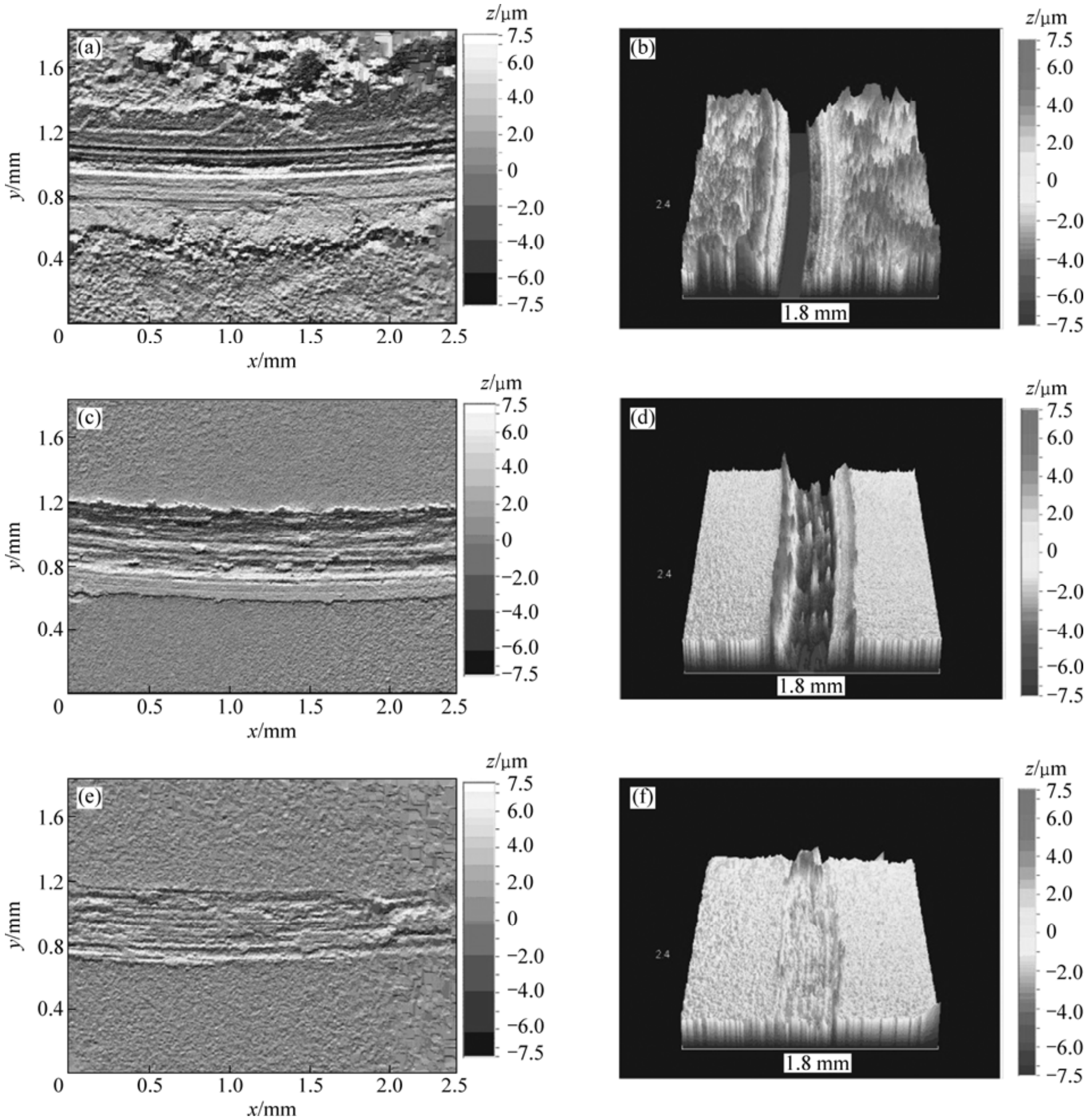

Fig.4 2D (a, c, e) and 3D (b, d, f) topography images of wear tracks in X32CrMoV33 steel (a, b), Inconel 617 (c, d) and Stellite 6 alloy (e, f) samples in dry sliding ball-on-disc wear tests at 750 °C

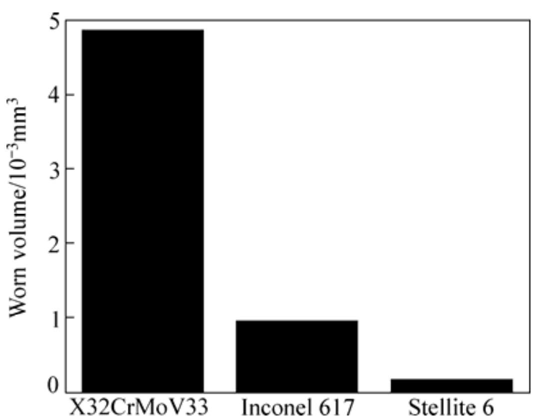

Fig.5 Ball-on-disc dry sliding wear test results

much smaller in the Inconel 617 and Stellite 6 alloys (Fig.4). While the oxides on the Inconel 617 and Stellite 6 samples were too thin to be resolved with an optical microscope, the increased oxygen signal intensities across the wear tracks of the Inconel 617 and Stellite 6 disc samples confirmed a mild oxidation. Generation of fresh surface and defects due to abrasion via sliding wear and subsequent reoxidation might be responsible for the relatively higher oxygen levels inside the wear tracks. The oxide debris was compacted into a glazed layer[30−32]. While the glazed layer was continuous in the Inconel 617 alloy along the periphery of the wear track, it was in the form of discontinuous patches inside

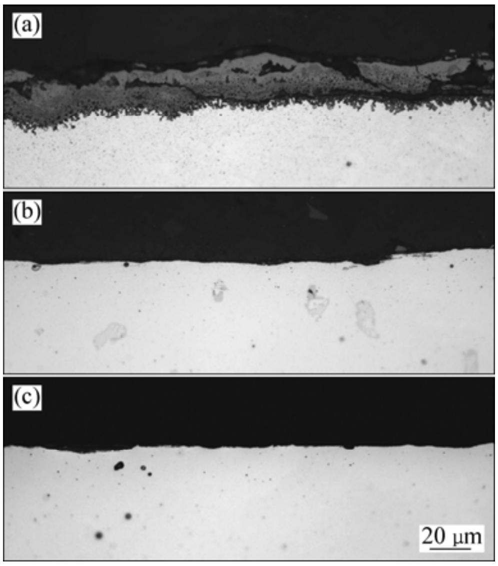

Fig.6 Micrographs taken from transverse cross section of wear tracks in X32CrMoV33 hot work tool steel (a), Inconel 617 (b) and Stellite 6 (c) alloy disc samples

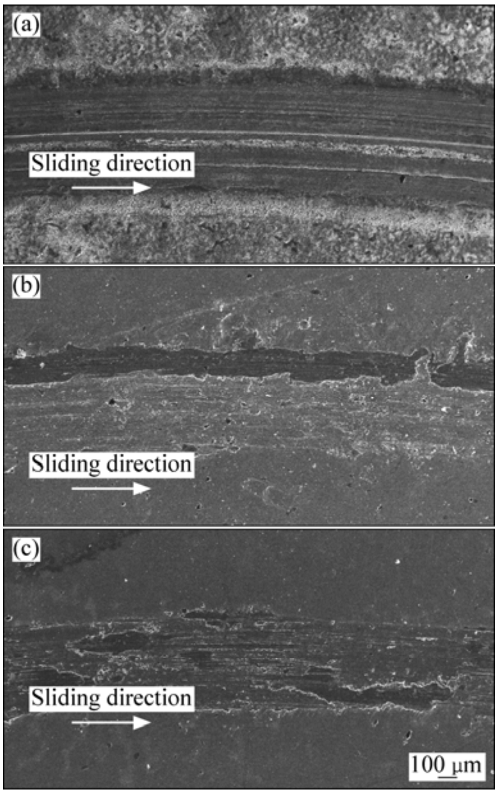

Fig.7 SEM micrographs of wear tracks in X32CrMoV33 hot work tool steel (a), Inconel 617 (b) and Stellite 6 (c) alloys

the wear track in the Stellite 6 alloy. It was also worth mentioning that Inconel 617 and Stellite 6 alloys retained their hardness at 750 °C and were thus much more resistant to abrasion (Fig.8). These observations were consistent with the wear volume loss measurements which clearly showed Inconel 617 and Stellite 6 alloy to be most resistant to sliding wear at 750 °C (Fig.5).

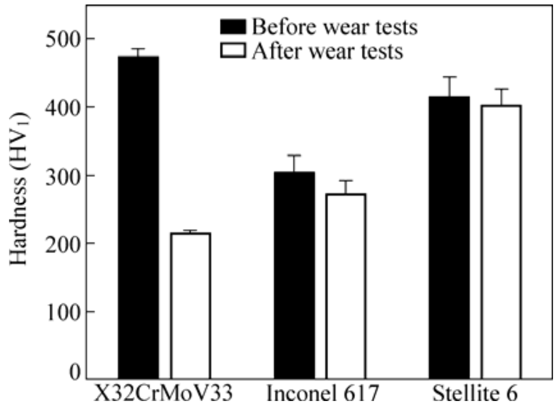

Fig.8 Hardness of X32CrMoV33 hot work tool steel, Inconel 617 and Stellite 6 alloys before and after wear tests

The performance of the three alloys tested in the present work was closely linked with their oxidation behaviour and mechanical strength at 750 °C as reported in Refs.[33−34]. The thick surface oxide layer on the tool steel samples was found by XRD analysis to consist of Fe_3O_4 and Fe_2O_3 (Fig.9(a)). The poor adherence and limited ductility of these oxides promoted the failure of the oxide scale, impairing both thermal fatigue and wear resistance at elevated temperatures[35−36]. The adhesive and highly plastic Cr_2O_3 film, identified to be the predominant oxide on the surface of both Inconel 617 and Stellite 6 samples (Fig.9(b)), on the other hand, sustained the thermal stresses abrasion and was claimed

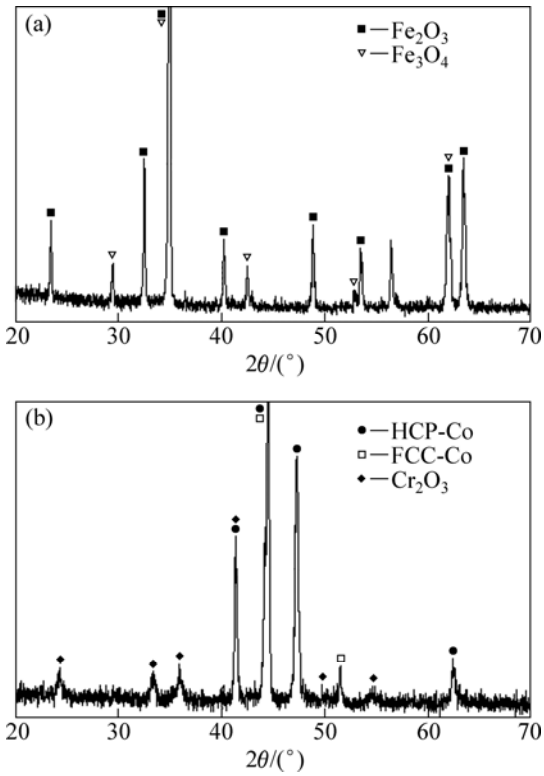

Fig.9 XRD patterns of surface layer on tool steel (a) and Inconel 617 and Stellite 6 (b) samples

to be responsible for the improved performance of these alloys at 750 °C as suggested in Ref.[35−38].

4 Conclusions

Samples of Inconel 617 and Stellite 6 alloys were submitted to thermal cycling between 750 °C and 450 °C. The Inconel 617 and Stellite 6 samples were found to be much more resistant to oxidation and temper softening than the hot work tool steel, providing a superior resistance to thermal fatigue cracking with few and relatively shallow cracks after as many as 5 000 thermal cycles. The high temperature wear resistance of the hot work tool steel was far from satisfactory. Extensive oxidation co-occurring with abrasion at 750 °C led to substantial material loss basically due to the lack of an adhesive oxide scale, sufficiently ductile to sustain the abrasive action without extensive cracking or spalling. Fe_3O_4 failed to survive in the abrasion conditions and is readily detached from the surface. The adhesive and highly plastic Cr_2O_3 on Inconel 617 and Stellite 6 alloys, on the other hand, sustained the sliding wear action without spalling and was claimed to be responsible for the improved wear resistance of these alloys at 750 °C. It was concluded that Inconel 617 and Stellite 6 alloys could be used for the manufacture of thixoforming dies or as hard facing coatings on conventional hot work tool steels.

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