

# High Temperature ‘Like-on-like’ Sliding of Nimonic 80A under Conditions of Limited Debris Retention

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## Abstract

A ‘like-on-like’ sliding study of Nimonic 80A was conducted using a ‘reciprocating-block (sample)-on-cylinder (counterface)’ configuration at 750°C and counterface sliding speeds of 0.314, 0.405, 0.485, 0.654 and 0.905 m.s<sup>-1</sup>. The collected data was compared with that from sliding a Nimonic 80A sample against a Stellite 6 counterface.

Similar behaviour was observed for both sliding combinations at 0.314, 0.405 and 0.485 m.s<sup>-1</sup> with protective ‘glaze’ layer formation observed, which was progressively retarded as sliding speed was increased. However, ‘glaze’ formation was delayed and retarded for Nimonic 80A ‘like-on-like’ compared to ‘Nimonic 80A versus Stellite 6’. This was attributed to the influence of Stellite 6-sourced Co (the contribution of which also decreased with increasing sliding speed) encouraging more rapid ‘glaze’ formation for ‘Nimonic 80 versus Stellite 6’ at 0.314, 0.405 and possibly also 0.485 m.s<sup>-1</sup>.

An abrasive oxidational wear regime was observed at 0.654 and 0.905 m.s<sup>-1</sup> for both systems. The debris for both material combinations consisted completely of Nimonic 80A-sourced NiO and Cr<sub>2</sub>O<sub>3</sub>, which showed poor sintering and ‘glaze’ forming tendencies at these higher sliding speeds and acted as the abrasive agent; there was no Co-indicated contribution from the Stellite 6 counterface for the ‘Nimonic 80A versus Stellite 6’ combination. A delay in transition to (abrasive) mild wear was again observed for Nimonic 80A ‘like-on-like’, though not as marked as at lower sliding speeds for (protective) mild wear. The delay at higher sliding speed was attributed to both surfaces consisting of thermally softened and thus easily removable Nimonic 80A, providing a higher level of abrasive NiO and Cr<sub>2</sub>O<sub>3</sub> debris than the ‘Nimonic 80A versus Stellite 6’ combination.

**Keywords:** high temperature wear, ‘like-on-like’, dissimilar materials, oxide ‘glaze’ layer, Nimonic 80A, Stellite 6

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## 1. Introduction

A preliminary investigation was conducted into the variation in behaviour during ‘like-on-like’ Nimonic 80A sliding wear, at 750°C and counterface surface sliding speeds of 0.314, 0.405, 0.485, 0.654 and 0.905 m.s<sup>-1</sup>. The same ‘block-on-cylinder’ configuration (a 45 x 5 x 5 mm block in reciprocating motion with a constant stroke of 12 mm, 3 times a minute, against a 50 mm diameter rotating counterface for a sliding distance of 4,522 m, load 7N) was used as in the previously studied ‘Nimonic 80A (sample) versus Stellite 6 (counterface)’ system [1-4]. Such a configuration does not readily encourage debris retention, especially at higher sliding speed.

One of the purposes of this investigation was to resolve differences in observed behaviour for high temperature ‘like-on-like’ sliding of Nimonic 80A [1-10]. Studies conducted at Northumbria University [1-4] suggest that the NiO and Cr<sub>2</sub>O<sub>3</sub> debris generated from Nimonic 80A (when slid against Stellite 6) doesn’t readily sinter together to form ‘glaze’

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(Version 1: 2003 – Nimonic 80A ‘like-on-like’ wear only; Version 2: 2007 – Comparison with ‘Nimonic 80A versus Stellite 6’ added.)

and instead assists wear by abrasion ('block-on-cylinder' configuration). Other research using a 'pin-on-disk' configuration [5-10] suggests ready formation of 'glaze' during 'like-on-like' sliding of Nimonic 80A. 'Like-on-like' sliding of Nimonic 80A was thus conducted using Northumbria University's 'block-on-cylinder' configuration to help further understand these differences and to see if there was a limiting sliding speed for 'glaze' formation. A brief comparison of sliding behaviour was also made between the Nimonic 80A 'like-on-like' and the 'Nimonic 80A versus Stellite 6' systems.

Note this investigation is incomplete with SEM micrographs and EDX data yet to be taken or compiled for the Nimonic 80A 'like-on-like' combination. However, given debris generated solely from Nimonic 80A elsewhere closely matches that of the source material and no other material is contributing to the debris for the 'like-on-like' wear pair, a standard Nimonic 80A debris composition can be assumed (~70% Ni, ~20% Cr; all compositions are given here in 'wt%'). 'Nimonic 80A versus Stellite 6' EDX data are included in this preliminary report, however, SEM micrographs are presented elsewhere [1-4]. Ideally, this study should be completed before the data is further utilised.

The nominal compositions of the Nimonic 80A (where used as a sample and counterface in this study) and the Stellite 6 (used only as a counterface for the 'Nimonic 80A versus Stellite 6' combination) are shown in Table 1.

## **2. Nimonic 80A 'like-on-like' sliding - summary**

### **2.1 Sliding wear at 0.314, 0.405 and 0.485 m.s<sup>-1</sup>**

At 0.314, 0.405 and 0.485 m.s<sup>-1</sup>, there was a period of initial severe wear that increased in severity with sliding speed, followed by a transition to mild wear and 'glaze' formation. Preliminary coefficient of friction data suggested this transition occurred after ~600 m sliding, when there was a change from early unsettled, highly erratic friction to a more settled steady state (Fig. 1).

Such 'glaze' was formed from Ni- and Cr-based oxide (XRD detected NiO and – in the debris – Cr<sub>2</sub>O<sub>3</sub>), generated initially by removal, breakdown and oxidation of metallic debris sourced from both sample and counterface. Due to high residency and low mobility (hence low ejection) at these lower sliding speeds, the normally abrasive NiO and Cr<sub>2</sub>O<sub>3</sub> debris had sufficient time to sinter together to form wear-protective 'glaze' layers. These

layers eventually separated sample and counterface surfaces and eliminated the early severe wear. However, the abrasive effects of the NiO and Cr<sub>2</sub>O<sub>3</sub> were not completely eliminated by this 'glaze' formation and fine grooves formed parallel to the sliding direction at all three sliding speeds.

Raising sliding speed increased debris mobility and reduced debris residency, such that:

- i) there was reduced time for the debris to sinter, and
- ii) there was also increased abrasive action.

'Glaze' formation thus became increasingly retarded at higher sliding speed and was less developed at 0.405 m.s<sup>-1</sup> and especially at 0.485 m.s<sup>-1</sup>, compared to 0.314 m.s<sup>-1</sup>. This reduced 'glaze' formation and increased abrasion was reflected by increased weight loss (Fig. 3).

## **2.2 Sliding wear at 0.654 and 0.905 m.s<sup>-1</sup>**

No 'glaze' was observed at 0.654 and 0.905 m.s<sup>-1</sup>, with only a thinly smeared oxide layer accompanying the fine grooves parallel to sliding direction generated by NiO and Cr<sub>2</sub>O<sub>3</sub> debris (as indicated by XRD) abrasive action. The poor sinterability of the mixed NiO and Cr<sub>2</sub>O<sub>3</sub> combined with increasing debris mobility (and hence abrasion) and reduced residency (hence increased ejection), was sufficient to completely suppress 'glaze' formation. Weight loss was thus higher at 0.654 and 0.905 m.s<sup>-1</sup> (Fig. 3).

A small reduction in weight loss was observed on increasing sliding speed from 0.654 m.s<sup>-1</sup> to 0.905 m.s<sup>-1</sup> (Fig. 3), as loose NiO / Cr<sub>2</sub>O<sub>3</sub> generation increased (due to greater frictional heating and mechanical action) and so did residency. However, increased oxide generation and residency did not result in 'glaze' formation and the reduction in wear at 0.905 m.s<sup>-1</sup> is attributable to greater separation due to this increased loose oxide production.

The preliminary coefficient of friction data indicated no clear transition from early unsettled friction to a more settled steady state at 0.654 and 0.905 m.s<sup>-1</sup> (Fig. 1). This may be explained by greater equipment vibration at these higher sliding speeds, masking any transition. This vibration could also explain the lower apparent friction at 0.654 and 0.905 m.s<sup>-1</sup> (also possibly at 0.485 m.s<sup>-1</sup>), due to reduced contact between sample and

counterface. Actual friction may have thus been much higher as commented on elsewhere for ‘Nimonic 80A versus Stellite 6’ [1-4] and separately for ‘Incoloy MA956 versus Stellite 6’ [11]. Such difficulties meant that at 0.654 and 0.905 m.s<sup>-1</sup>, a frictional assessment of the Nimonic 80A ‘like-on-like’ system was not possible with this preliminary data and no extra information could be obtained from it. It has also been suggested, however, that the increased oxide production at 0.905 m.s<sup>-1</sup> may at least be partially responsible for this lower friction [12].

### **3. Comparison of Nimonic 80A ‘Like-on-like’ Sliding Behaviour with ‘Nimonic 80A versus Stellite 6’**

The behaviour observed for the Nimonic 80A ‘like-on-like’ system mirrors that of the ‘Nimonic 80A versus Stellite 6’ system also studied at Northumbria University [1-4]. Protective mild wear with ‘glaze’ formation was observed at 0.314, 0.405 and 0.485 m.s<sup>-1</sup>, above which there was a transition to abrasive mild wear with copious oxide debris generation at 0.654 and 0.905 m.s<sup>-1</sup> (with at best a thinly smeared oxide layer on the finely grooved wear surface – these analogous observations included the slight reduction in weight loss at 0.905 m.s<sup>-1</sup>). However, the transition from early severe to later mild wear is more rapid for the ‘Nimonic 80A versus Stellite 6’ system, with a clear enhancement of early severe wear observed for the Nimonic 80A ‘like-on-like’ system.

The most pronounced physical evidence of Nimonic 80A ‘like-on-like’ extended severe wear was observed at 0.314 and 0.405 m.s<sup>-1</sup> (Fig. 2); weight loss data indicates higher loss for this combination (Fig. 3). The presence of Co-based material within the debris for ‘Nimonic 80A versus Stellite 6’, either as the dominant material (0.314 m.s<sup>-1</sup>) or as a lesser component (0.405 m.s<sup>-1</sup>), promoted extremely rapid formation of more wear protective ‘glaze’ layers with little chance for severe wear (Fig. 2) [1-4]. EDX indicated an oxide composition of ~35% Co, ~37% Cr and ~18% Ni at 0.314 m.s<sup>-1</sup> (XRD detected one or more of Cr<sub>2</sub>O<sub>3</sub>, CoCr<sub>2</sub>O<sub>4</sub> and Co<sub>3</sub>O<sub>4</sub> in the ‘glaze’, with high Co favoring the latter two phases [1-4]) and ~11% Co, ~25% Cr and ~55% Ni at 0.405 m.s<sup>-1</sup> (no clear phase could be determined by XRD). The rapid ‘glaze’ development is reflected in the speedier transition in friction from early unsettled state to later settled steady state in the presence of Co-based material (almost immediately at 0.314 m.s<sup>-1</sup> and after ~300 m at 0.405 m.s<sup>-1</sup> [3,4], compared to ~600 m for Nimonic 80A ‘like-on-like’ at both sliding speeds – Fig. 1).

Additionally, evidence of abrasive wear was either absent ( $0.314 \text{ m.s}^{-1}$ ) or much reduced ( $0.405 \text{ m.s}^{-1}$ ) where Co-based material was present, due to greater oxide debris incorporation in the 'glaze' layers and its consequent unavailability as loose abrasive material.

This extended severe wear was also evident at  $0.485$  (the highest test speed at which 'glaze' layers were observed),  $0.654$  and  $0.905 \text{ m.s}^{-1}$  (Fig. 2), with increased early-stage metallic damage indicating the delayed onset of mild wear (either protective at  $0.485 \text{ m.s}^{-1}$  or abrasive at  $0.654$  and  $0.905 \text{ m.s}^{-1}$ ). Why there continued to be a delay for Nimonic 80A 'like-on-like' sliding at higher sliding speeds is unclear, as the same oxides (XRD detected NiO and – in the loose debris –  $\text{Cr}_2\text{O}_3$ ) dominated for both Nimonic 80A 'like-on-like' and 'Nimonic 80A versus Stellite 6', with little or no significant contribution from the Stellite 6 for the latter system ( $0.485 \text{ m.s}^{-1}$  – EDX indicated ~2% Co, ~26% Cr and ~63% Ni in the limited glaze and similar levels in the debris;  $0.654$  and  $0.905 \text{ m.s}^{-1}$  – EDX indicated ~71% Ni and ~24% Cr /  $0.654 \text{ m.s}^{-1}$  or ~25% Cr /  $0.905 \text{ m.s}^{-1}$  and no significant Co in the smeared oxide on the sliding surfaces and loose oxide debris). There was some evidence of thermally induced plastic deformation for the Nimonic 80A 'like-on-like' system and it may be that continued abrasive removal and generation of even more debris was made easier for this system by both sliding surfaces consisting of thermally softened Nimonic 80A. With the Nimonic 80A versus Stellite 6 system, it was noticeable the Stellite 6 resisted thermal deformation).

However, in the absence of Stellite 6-sourced material ( $0.485$ ,  $0.654$  and  $0.905 \text{ m.s}^{-1}$ ), the delay in the severe wear / mild wear transition was less marked with significant wear now also occurring for the 'Nimonic 80A versus Stellite 6' system. This demonstrates the effectiveness of rapid protective 'glaze' formation in reducing notably early wear and the effect of oxide composition on this (i.e. the presence of Co on rapid 'glaze' formation in the generated debris at  $0.314$  and  $0.405 \text{ m.s}^{-1}$ ).

The high vibration encountered with the preliminary friction data at  $0.654$  and  $0.905 \text{ m.s}^{-1}$  (Fig. 1) made any assessment of transition distance for Nimonic 80A 'like-on-like' and comparison with that for 'Nimonic 80A versus Stellite 6' unfeasible at this time. A more rapid 'unsettled-early-friction-to-more-settled-steady-state' transition was, however, evident at  $0.485 \text{ m.s}^{-1}$  for 'Nimonic 80A versus Stellite 6' (~300 m [4] compared to

~600 m for Nimonic 80A 'like-on-like' – Fig. 1). It is possible that trace amounts of Stellite 6-sourced Co (~2%) may still enhance 'glaze' formation at 0.485 m.s<sup>-1</sup> for the 'Nimonic 80A versus Stellite 6' combination.

#### **4. Nimonic 80A 'like-on-like' Siding and Comparisons with Other Research**

By conducting 'like-on-like' sliding of Nimonic 80A using Northumbria University's 'block-on-cylinder' configuration, it has been shown that removing all traces of Stellite 6-sourced material does retard 'glaze' formation, however, it does not prevent its formation at lower sliding speeds.

In the absence of Stellite 6-sourced material, the key factor supporting or preventing 'glaze' formation for the Nimonic 80A 'like-on-like' system is that of debris residency at the wear interface and effect of sliding speed upon it. At lower sliding speeds (0.314, 0.405 and 0.485 m.s<sup>-1</sup>), 'glaze' formation occurs as residency is high enough to allow sintering of the NiO and Cr<sub>2</sub>O<sub>3</sub> oxides. At higher sliding speeds, there is insufficient residency for sintering to occur. This study indicates a limiting speed (at which ejection / reduced residency and sintering balance each other out) of between 0.485 and 0.654 m.s<sup>-1</sup>.

The 'block-on-cylinder' configuration used at Northumbria University [1-4] is a unidirectional sliding wear system that promotes debris mobility and ejection over retention. Debris is ejected without outside intervention as the counterface continuously rotates in one direction only at uniform speed; this ejection theoretically increases if higher sliding speeds are used. The reciprocating motion of the sample continually moves the contact point backward and forwards, further removing debris from the interface as it does so. No part of the sample can thus remain in continuous contact with the counterface unless reciprocation is switched off (examples of enhanced 'glaze' development when this happens are discussed elsewhere [1], for both Incoloy MA956 and Nimonic 80A as samples slid against an Incoloy 800HT counterface).

Other Nimonic 80A 'like-on-like' studies [5-10] were conducted using lower speed reciprocating sliding wear (a mean value for sliding speed of 83 mm.s<sup>-1</sup> was quoted) with a 'pin-on-disk' configuration; such systems also have a higher degree of debris retention, in which the debris generated is less mobile and remains resident in the contact area of the two sliding surfaces. Increased residency and reduced mobility allows more contact time

between debris particles for sintering and welding processes to occur, and comprehensive 'glaze' layers can thus develop. Such retention may possibly only be reduced by the introduction of an artificial removal mechanism, such as vibration or an air / gas flow to remove debris as it is generated.

Also, whilst the disk's point of contact changes as the pin moves backwards and forwards relatively against it, the same point of the pin is effectively in contact with the disk and the retained debris for the duration of sliding. There is thus a greater proportion of time for 'glaze' development to occur at this point of contact.

## 5. Summary of Results

1. Similar behaviour was observed for both sliding combinations at 0.314, 0.405 and 0.485 m.s<sup>-1</sup> with protective 'glaze' layer formation observed, which was progressively retarded as sliding speed was increased.
2. However, 'glaze' formation was delayed for Nimonic 80A 'like-on-like' compared to that for 'Nimonic 80A versus Stellite 6'. This was attributed to the influence of Stellite 6-sourced Co (the contribution of which decreased with increasing sliding speed) encouraging more rapid 'glaze' formation for 'Nimonic 80 versus Stellite 6' at 0.314, 0.405 and possibly also at 0.485 m.s<sup>-1</sup>.
3. An abrasive oxidational wear regime was evident for both systems at 0.654 and 0.905 m.s<sup>-1</sup>. The debris for both material combinations consisted completely of Nimonic 80A-sourced NiO and Cr<sub>2</sub>O<sub>3</sub>, which showed poor sintering and 'glaze' forming tendencies at higher sliding speed and acted as the abrasive agent; there was no contribution from the Stellite 6 counterface for the 'Nimonic 80A versus Stellite 6' combination.
4. A delay in transition to (abrasive) mild wear was again observed for Nimonic 80A 'like-on-like' at 0.654 and 0.905 m.s<sup>-1</sup> compared to Nimonic 80A versus Stellite 6, though not as marked as with (protective) mild wear at lower sliding speeds. The delay at higher sliding speed was attributed to both surfaces consisting of thermally softened and thus easily removable Nimonic 80A, providing a higher level of abrasive NiO and Cr<sub>2</sub>O<sub>3</sub> debris than the 'Nimonic 80A versus Stellite 6' combination (the Stellite 6 notably resisting thermal deformation).

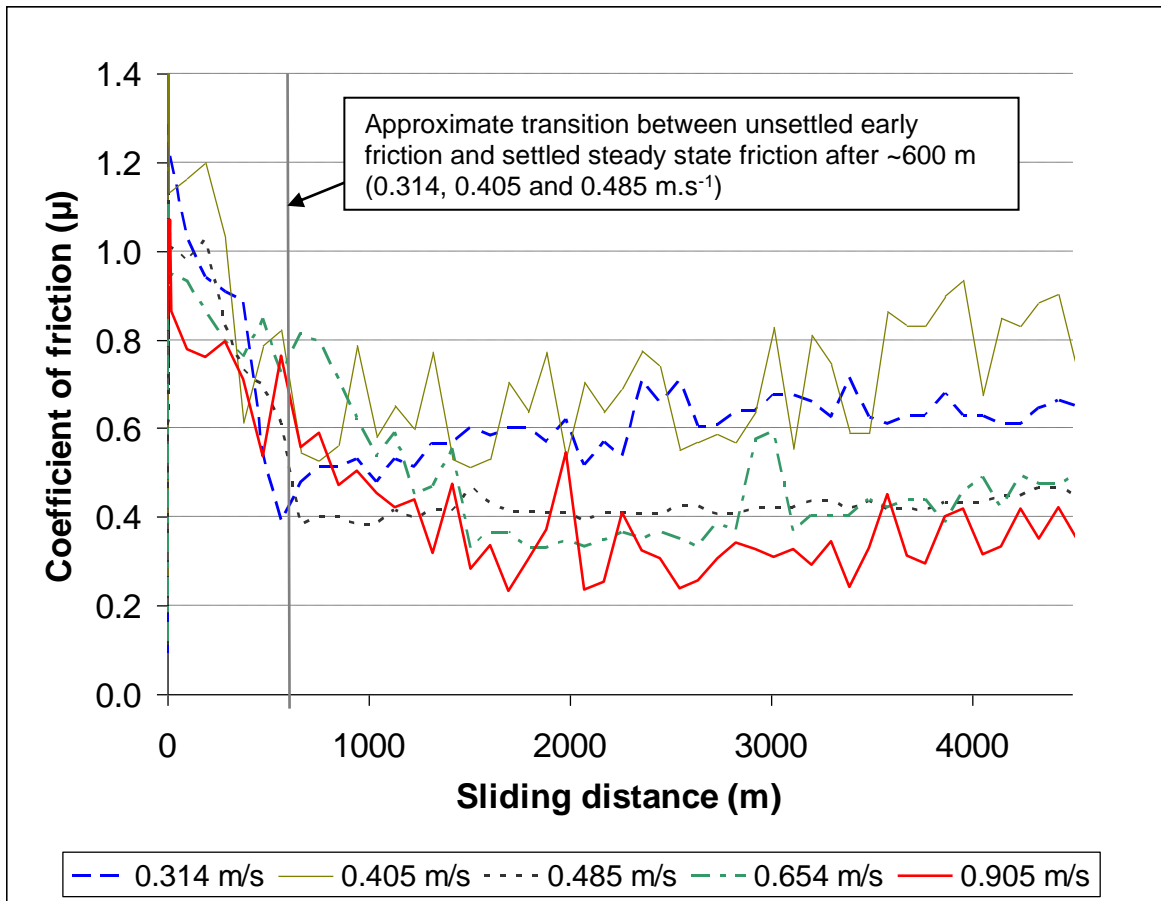
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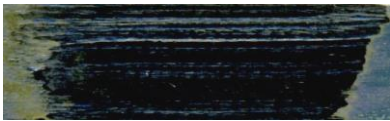

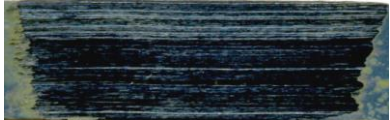

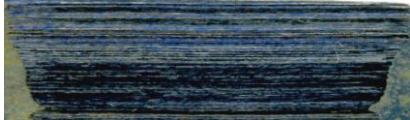



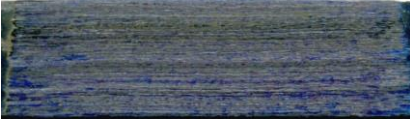



|    | Nimonic 80A (sample and also counterface for 'like-on-like') | Stellite 6 (counterface only) |
|----|--|-------------------------------|
| Ni | 75.8   | 2.5 (maximum)                 |
| Cr | 19.4   | 27                            |
| Ti | 2.5  | -                             |
| Al | 1.4  | -                             |
| Fe | 0.7  | 2.5 (maximum)                 |
| Si | 0.1  | 1                             |
| C  | 0.08   | 1                             |
| Co | -  | 60                            |
| W  | -  | 5                             |
| Mn | -  | 1                             |

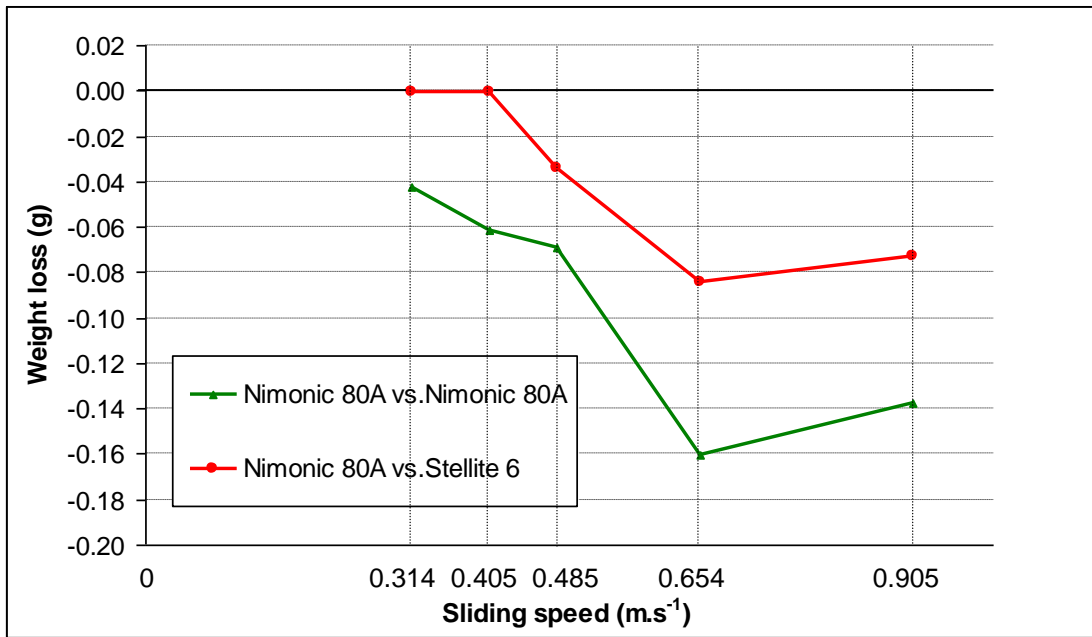
**Table 1:** Nominal compositions of alloys (in wt.%)



**Fig. 1:** Variation of coefficient of friction with sliding distance for like-on-like sliding of Nimonic 80A (load 7N, sliding distance 4,522 m)

| Sliding speed (m.s <sup>-1</sup> ) | Surface condition  | Nimonic 80A – like-on-like  | 'Nimonic 80A versus Stellite 6 (counterface)'  |  |
|------------------------------------|--|---|--|--|
| 0.314                              | 'Glaze' formation progressively retarded with increasing sliding speed | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris), some abrasion and debris production      | <br>Mainly CoCr <sub>2</sub> O <sub>4</sub> , some Ni/Cr-based oxide, no abrasion and little loose debris production          |  |
| 0.405                              |  | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris), moderate abrasion and debris production  | <br>Phase not determined (oxide Ni/Cr-based with some Co), little abrasion or loose debris production                         |  |
| 0.485                              |  | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris), moderate abrasion and debris production | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris) dominant, trace Co-based oxide, moderate abrasion and debris production |  |
| 0.654                              |  | No 'glaze' (smeared oxide plus loose debris)  | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris), very heavy abrasion and debris production                               | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris) only, heavy abrasion and debris production |
| 0.905                              |  |   | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris), very heavy abrasion and debris production                               | <br>NiO (+ Cr <sub>2</sub> O <sub>3</sub> in debris) only, heavy abrasion and debris production |
| 15 mm                              |  |   |  |  |

**Fig. 2:** Optical micrographs for Nimonic 80A slid against Nimonic 80A (like-on-like) and also Nimonic 80A slid against Stellite 6 (load 7N, sliding distance 4,522 m) – phases present in debris and 'glaze' layers also shown



**Fig. 3:** Weight change versus sliding speed for ‘like-on-like’ sliding of Nimonic 80A and also ‘Nimonic 80A versus Stellite 6’ (load 7N, sliding distance 4,522 m)