# ON THE ABRASION RESISTANCE OF Ni-HARD 4[1]

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**Abstract**

White cast iron (WCI) alloys have been increasingly used in the mining and mineral processing industries, where a combination of high abrasion resistance and moderate impact resistance is required. Ni-Hard 4 is a class of WCI alloys which contains 8-10 wt% Cr and 4-6 wt% Ni. In this work, the two-body abrasion of Ni-Hard 4 alloys worn on three abrasives, namely, silicon carbide, corundum and flint has been investigated, using a pin abrasion test. To obtain different alloy's matrices and hardnesses, specified heat treatments were carried out. Hardness measurements, before and after the abrasion tests, were made. Carbide volume fraction and retained austenite contents in the matrix were measured. The dominant wear mechanisms were identified by scanning electron microscopy. The abrasion resistance results have been discussed in terms of bulk hardness and microstructure features. Due to a high intensity of plastic deformation during wear tests, the influence of strained matrices on the abrasion resistance has been also discussed. Since the bulk hardness of Ni-Hard 4 alloys cannot be safely used as an indicator of abrasion resistance, a general model "Equivalent Hardness" was developed to describe better the abrasion resistance.

**Keywords**: Ni-Hard 4; Work hardening; Equivalent hardness; Abrasion.

## SOBRE A RESISTÊNCIA À ABRASÃO DE Ni-HARD 4

**Resumo**

Ferros fundidos brancos têm sido cada vez mais utilizados nas indústrias de mineração, onde uma combinação de alta resistência à abrasão e moderada resistência ao impacto é necessária. Ni-Hard 4 é uma classe de ferros fundidos brancos que contém teores de 8-10% Cr e 4-6% Ni. Neste trabalho, o desgaste abrasivo a dois corpos de Ni-Hard 4 foi investigado utilizando-se para isso três abrasivos, são eles: carbeto de silício, alumina e sílica. Tratamentos térmicos especificados foram realizados para obter diferentes matrizes e durezas. As medidas de dureza foram feitas antes e após os ensaios de abrasão. A fração volumétrica de carbonetos e austenita retida na matriz foram medidas. Os mecanismos de desgaste dominantes foram identificados através de microscopia eletrônica de varredura. Os resultados de resistência à abrasão são discutidos em termos de dureza global e constituintes da microestrutura. Devido a uma alta intensidade da deformação plástica durante os testes de desgaste, a influência das matrizes encruadas sobre a resistência à abrasão também é discutida. A medida que a dureza global de Ni-Hard 4 não pode ser utilizada com segurança como um indicador de resistência à abrasão, um modelo geral de "dureza equivalente" foi desenvolvido para melhor descrever a resistência à abrasão.

**Palavras-chave:** Ni-Hard 4; Encruamento; Dureza equivalente; Resistência à abrasão.

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## 1 INTRODUCTION

Of the many different modes of wear, abrasive wear, which accounts for more than 50% of all wear problems,(1-3) has been recognised as the most severe and the most commonly encountered by industry. This type of wear occurs when hard particles or protuberances interact with a material surface, removing debris from it by mechanical action.(4)
To resist abrasive wear, white cast iron (WCI) alloys are usually used. These alloys have been found in many technical situations such as in coal pulverising, crushing and grinding of ores, manufacture of slurry pumps and different parts of earth-moving equipments.(5-8)
Ni-Hard 4 is a class of WCI alloys(8-11) which contains 8-10 wt% Cr, 4-6 wt% Ni and 1.8-2% Si. It is designed to give a microstructure of eutectic $M_7C_3$carbides embedded in a metallic matrix that, in the as-cast condition, is free from pearlite, predominantly austenitic one. But, after destabilisation heat treatments, the matrix is predominantly martensitic. The carbon content is designed to give a eutectic or slightly hypoeutectic composition. The carbon content determines the eutectic carbide volume fraction. Usually, the carbon content is kept between 2.8% and 3.2% as a compromise between abrasion resistance and fracture toughness.
The majority of the carbon enters the carbide phase,(12) together with iron, chromium, and other carbide forming elements present. A higher carbon content results in higher abrasion resistance but lower the fracture toughness of the material, and vice versa.
The high level of chromium (8-10 wt%) contributes to the hardness and abrasion resistance as well as to corrosion resistance. The majority of chromium combines with carbon in the carbide, so that its concentration in the matrix is quite low.(12) It has been therefore recognised that additional elements such as nickel are required to improve hardenability of larger section sizes. The nickel content provides the necessary combination of toughness, strength, and hardenability. It is added to avoid a pearlite formation during cooling in the as-cast condition. Higher Ni content will overstabilise the austenite on cooling to room temperature.
For a given wear system, the alloy microstructure plays an essential role in determining the wear resistance. It is thought that the volume fraction of eutectic carbides is responsible for a good abrasion resistance.(13,14) Many other factors, such as, carbide nature (type, hardness, form, morphology, and distribution), matrix hardness, and the mean free path of the matrix between the carbides also affect the abrasion resistance.(13,14) The alloy microstructure may be varied through alloy selection, processing route, and heat treatments.
In this work, the abrasion behaviour of three Ni-Hard 4 specimens has been studied. The alloys were varied by changing chemical compositions and solidification parameters, and they were then subjected to heat treatments.

## 2. EXPERIMENTAL PROCEDURES

### 2.1 Materials

The chemical compositions of tested Ni-Hard 4 alloys are listed in Table 1.

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**Table 1**: Chemical composition of Ni-Hard 4 specimens

| Ni-Hard 4 | Composition (wt.%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Ni | Mo | S | P |
| A | 2.90 | 1.68 | 0.58 | 9.02 | 5.24 | 0.14 | 0.026 | 0.047 |
| B | 2.86 | 1.78 | 0.52 | 8.78 | 5.12 | 0.19 | 0.024 | 0.037 |
| C | 3.56 | 1.62 | 0.73 | 9.38 | 5.21 | 0.13 | 0.027 | 0.042 |

The chemical compositions of both A and B specimens seem to be nearly the same. According to British Standard, BS. 4844 Part 2 [9], these alloys fall into grade 2D. However, casting parameters used to solidify these specimens were different. Alloy C falls into grade 2E [9] in which the carbon content is higher than of the others. Besides, the same casting parameters used to produce the specimen B were employed.

### 2.2 Heat Treatments

Ni-Hard 4 alloys can be used in as-cast condition, but their service life may be improved if they are heat-treated.(15) The heat treatments applied were hardening and tempering. Hardening was carried out at 820°C for four hours and then air cooling to room temperature.(10) To relieve internal stresses and obtain different matrices and hardness levels, tempering was carried out at three temperatures, namely, 300°C, 450°C and 550°C for four hours and then air cooling to room temperature.(10) The heat treatments for Ni-Hard 4 alloys were rarely designed to modify the morphology of the eutectic carbides. However, when these alloys are heat-treated at very high temperatures, it may be led to globalize eutectic carbides, thereby, improving the fracture toughness.

### 2.3 Quantitative Analysis

The carbide volume fractions of Ni-Hard 4 specimens were determined by computerised image analysis using Quantimet 520. For each specimen, at least 50 fields were imaged and the average was used. The retained austenite contents in the matrix were determined by the X-ray diffractometer (Philips Crystallox) using the technique described by Kim.(16) For each specimen, at least five measurements were averaged.

### 2.4 Hardness Measurements

Vickers hardness measurements were made under a load of 294 N. For each specimen, at least seven hardness indentations were made, and the mean was presented. Microhardness testings were carried out under a load of 0.49 N. These tests were done on the constituents of the polished and lightly etched pins used for the abrasion. The matrix and the carbide microhardness values were averaged from at least 15 and 30 measurements each. To evaluate the matrix microhardness after the abrasion test, each worn pin was lightly polished with 1 µm diamond paste for about 10-15 s to obtain a smooth surface without destroying the deformed layer related to wear. A light etching with 5% natal revealed the matrix and carbide phases; then at least 20 hardness indentations were made on the matrix and the average was used.

## 2.5 Abrasive Wear

The pin abrasion test, which is generally regarded as indicating the resistance to high stress abrasion, is shown in Figure 1. A flat cylindrical specimen 6 mm in diameter was loaded with 37.2 N and moved back and forth at a sliding speed of 4.78 $mm.s^{-1}$ in a non-overlapping pattern across fresh abrasive paper. During sliding, the specimen was rotated simultaneously around its axis at 47.8 rpm to eliminate intense wear of the leading edge. Before any measurements were made, each specimen was given a full run-in under the same condition.
Before and after the wear test, each specimen was ultrasonically cleaned with alcohol for not less than 5 min and then dried using blasts of warm air. Wear was measured by weight loss taking an average of at least three runs. The weight losses were determined on an electronic balance to an accuracy of $10^{-4}$ g. The abrasion rate (W) was calculated using the following equation:

$$W = \frac{\Delta m}{\rho \times A \times S} \qquad (1)$$

where $\Delta m$ is the weight loss, $\rho$ the specimen density, *A* the cross-sectional area of the worn specimen, and *S* the wear length. The abrasion resistance was expressed as the reciprocal of the abrasion rate. The maximum coefficient of variation in the abrasion resistance results was less than 3%. The reference material used was low alloyed steel with tempered martensite possessing a bulk hardness of 310 HV 30.

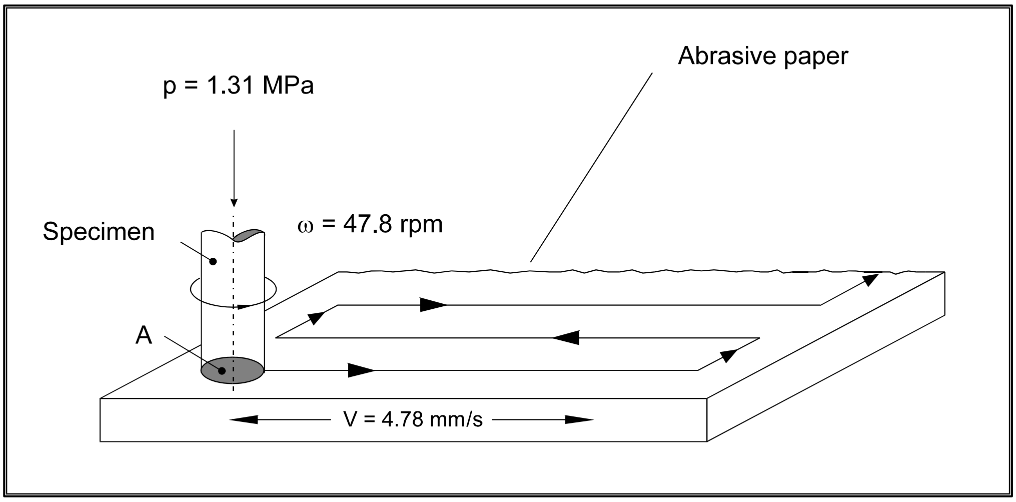


**Figure 1**: Schematic illustration of the pin abrasion test.

## 2.6 Abrasive Particles

The ability of abrasive particles to remove wear debris from a determined material is affected by a number of factors. These include hardness, size, shape, density, crushing strength and chemical properties of the abrasive. It is recognised that hard particles, such as silicon carbide (SiC) and corundum ($Al_2O_3$), produce faster wear rates and little difference in wear rates among any of white cast irons. However, the use of a relatively soft abrasive, such as flint (silica) gives significant differences in wear rates.

In this work, three abrasive papers, namely, silicon carbide (2600 HV0.05), corundum (2050 HV 0.05), and flint (900 HV 0.05) were used. It is known that the wear rate of a given material increases with the size of abrasive particles until a threshold value; above this value, it remains almost constant with increasing the size.[17] Therefore, the abrasive size was chosen so that the wear rate is independent of it. The average diameter (size) of the abrasives used was 200 um (80 mesh).

## 3 RESULTS AND DISCUSSION

### 3.1 Microstructure

The microstructures of Ni-Hard 4 specimens in as-received condition were characterized through a scanning electron microscopy (SEM) and shown in Figures 2-4. Generally, the microstructure is composed of an $M_7C_3$ eutectic carbide network with a metallic matrix that is a mixture of martensite, retained austenite and secondary carbides. Eutectic carbides of the specimen B are smaller than those of A. This is due to the casting parameters used. The smaller eutectic carbides may improve the fracture toughness and reduce the abrasion resistance.
The volume fractions of eutectic carbides for the specimens A and B were measured as 27.2% and 25.9%, respectively, and the microhardness of these carbides were measured as 1297 and 1237 HV 0.05. When the carbon content was increased (specimen C), both volume fraction of eutectic carbides (33.4%) and its hardness (1573 HV 0.05) were increased.
According to Maratray's formula[18] for calculating carbide volume fraction of white cast irons (CVF); $CVF\% = 12.33\ C\% + 0.55\ Cr\% - 15.2.$ The carbide volume fractions of specimens A, B, and C were calculated as 25.5%, 24.9% and 33.6%, respectively. It can be seen that the experimental and calculated values seem very close, validating the Maratray's formula in calculating carbide volume fraction for Ni-Hard 4 alloys.

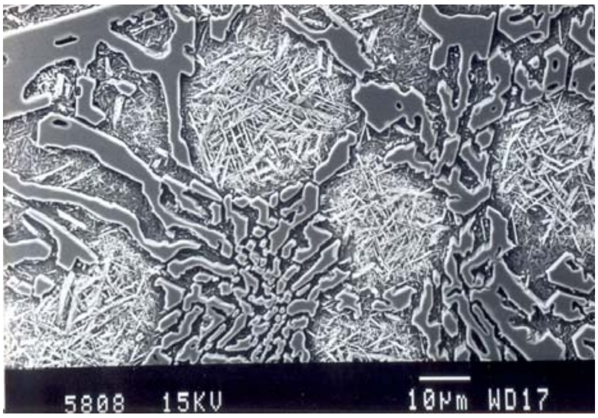


**Figure 2**: SEM micrograph of Ni-Hard 4 alloy, specimen A.

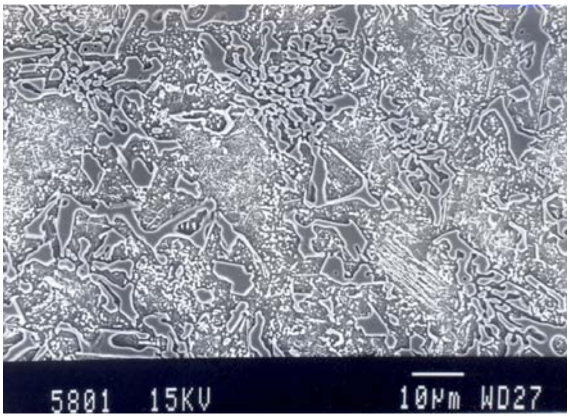


**Figure 3**: SEM micrograph of Ni-Hard 4 alloy, specimen B.

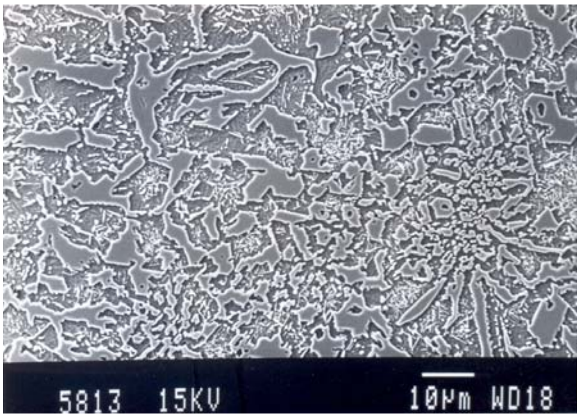


**Figure 4**: SEM micrograph of Ni-Hard 4 alloy, specimen C.

### 3.2 Abrasion Resistance

Figure 5 shows the abrasion resistance of Ni-Hard 4 specimens worn on silicon carbide (SiC), corundum ($Al_2O_3$), and flint ($SiO_2$) as a function of the hardness ratio ($H/H_a$), where $H$ is bulk hardness of the material and $H_a$ the hardness of the abrasive particles. The abrasion resistance slightly increases up to an $H/H_a$ value of about 0.8, and so it increases rapidly over this value.

Generally, when different microstructures of Ni-Hard 4 specimens (produced by heat treatments) were abraded on SiC and $Al_2O_3$, small differences in their abrasion resistance were recorded. These results can be attributed to the hardness of abrasive particles. Both abrasives SiC (2600 HV 0.05) and $Al_2O_3$ (2050 HV 0.05) are able to cut the microstructure constituents (matrix and carbide), thereby resulting in a high wear rate (low wear resistance). However, there were significant differences in abrasion resistance of these specimens when worn on flint. This also refers to the hardness of the abrasive particles, where a flint with 900 HV 0.05 is not hard enough to cut $M_7C_3$ carbides, but it can cut the matrix, as seen in Figure 6.

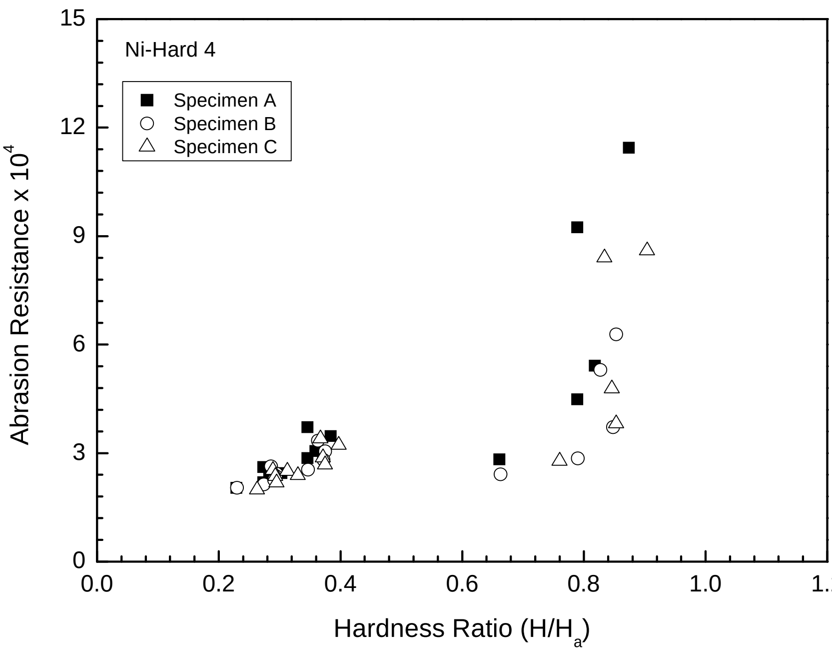


**Figure 5**: Abrasion resistance of Ni-Hard 4 specimens worn on silicon carbide, corundum, and flint a function of hardness ratio.

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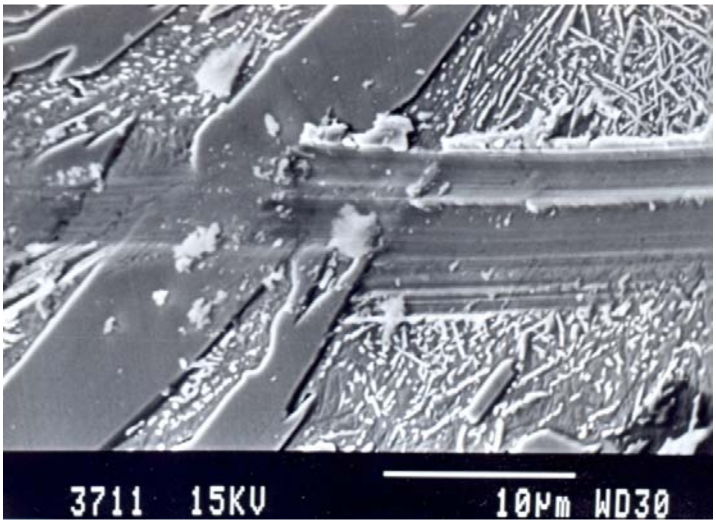


**Figure 6**: SEM micrograph of worn surface of Ni-Hard 4, specimen A, 80 mesh flint, stress =1.31 MPa, abrasion distance = 20 mm without rotation.

Figure 7 shows that the abrasion resistance of Ni-hard 4 specimens worn on flint abrasive paper decreases with the tempering temperature. The as-hardened microstructures exhibit the highest wear resistance, while the lowest abrasion resistance is obtained in as-tempered microstructures at 550°C. This behaviour may be analysed using Figures 8 and 9. As seen, the as-hardened specimens possess the highest values of bulk hardness and retained austenite content, whereas, the as-tempered specimens the lowest ones. Retained austenite content in the matrix may enhance abrasion resistance due to its ability to deform and work-harden as a result of wear conditions. Besides, the distribution and morphology of retained austenite may be played an essential role in this regard.(19,20)

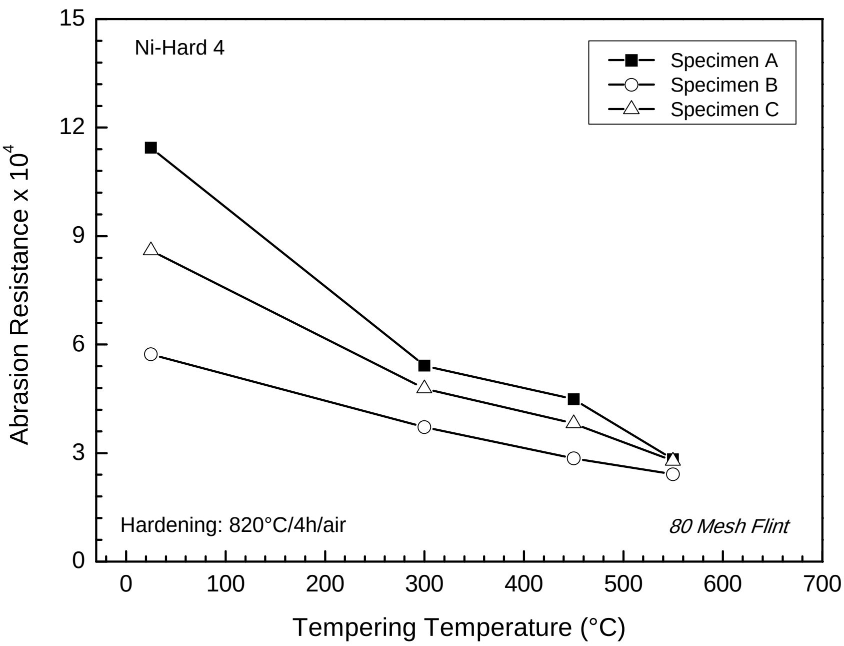


**Figure 7**: Abrasion resistance of Ni-Hard 4 specimens worn on 80 mesh flint abrasive as a function of tempering temperature.

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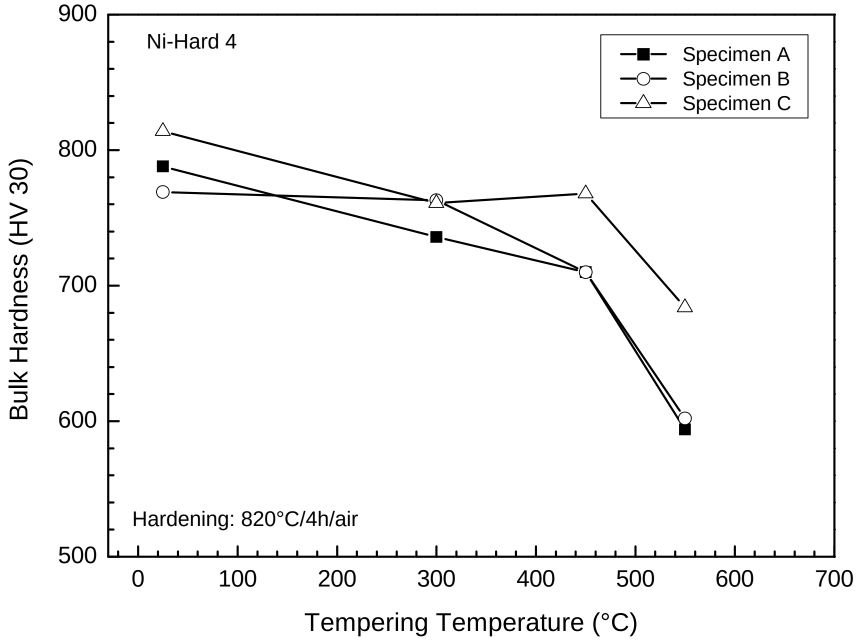


**Figure 8**: Bulk hardness of Ni-hard 4 specimens as a function of tempering temperature.

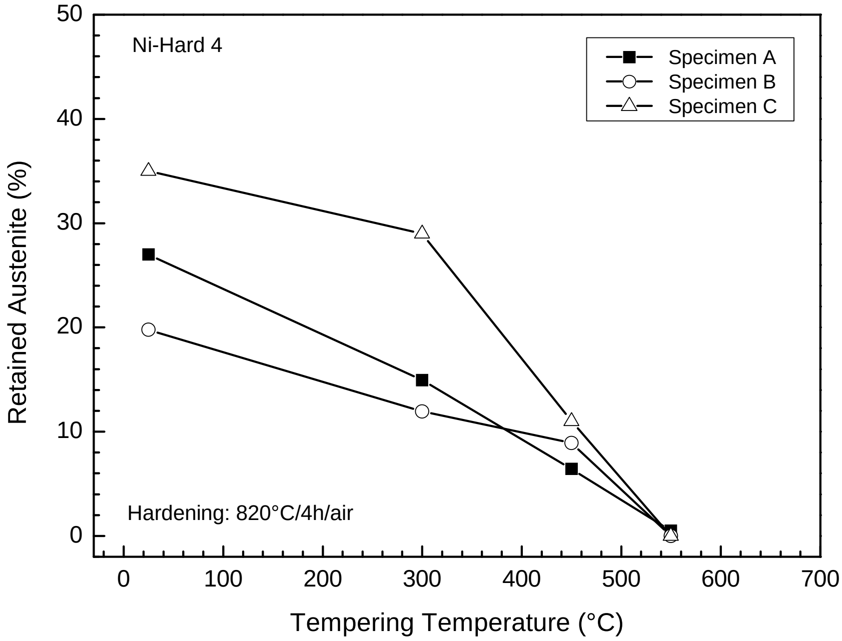


**Figure 9**: Retained austenite content in the matrix of Ni-Hard 4 specimens as a function of tempering temperature.

From hardness measurements made on the worn matrices, it was found that the microhardness of all matrices increased with different levels associated with retained austenite content and tempering temperatures. Figure 10 shows that the increase in matrix hardness due to abrasion increases with retained austenite. The matrix hardness increase was calculated as the difference between the hardness of the strained matrix (measured on the abraded matrix after the wear test) and the initial matrix hardness (measured on the polished surface before the wear test). The greatest values of hardness increase were found in as-hardened specimens, whereas the lowest ones in as-tempered microstructures at 550°C.

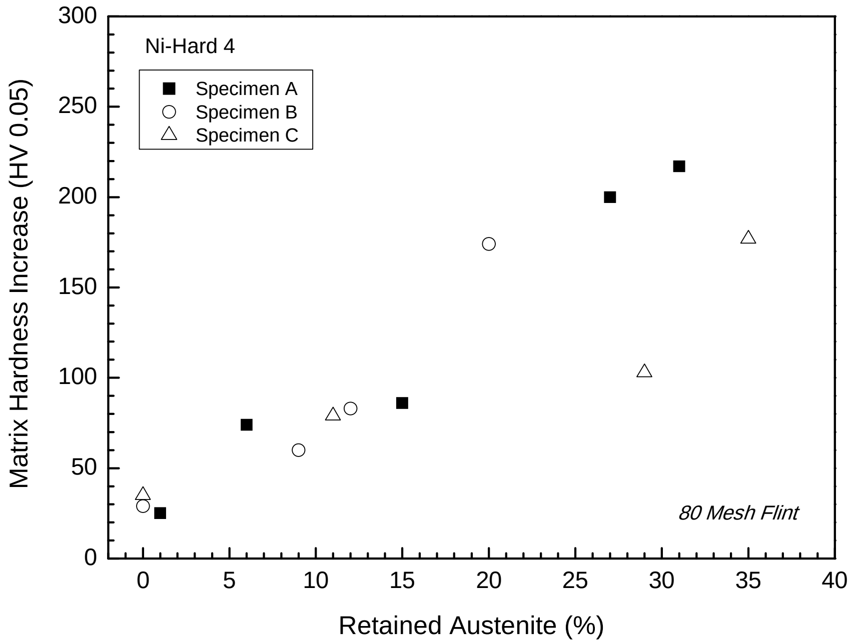


**Figure 10**: Increase in hardness of worn matrices (80 mesh flint) as a function of retained austenite.

### 3.3 Abrasion Resistance and Bulk Hardness

The wear resistance of Ni-Hard 4 alloys abraded on 80 mesh flint abrasive in relation to their bulk hardness values is presented in Figure 11. It suggests that the abrasion resistance generally increases with bulk hardness. However, a large spread in abrasion resistance data was found.

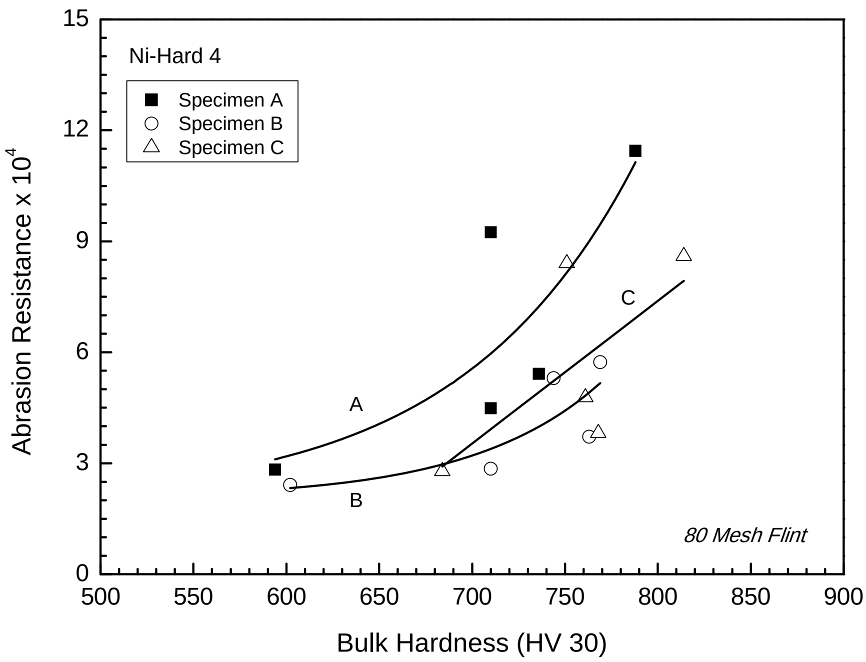


**Figure 11**: Abrasion resistance of Ni-Hard 4 specimens worn on 80 mesh flint abrasive as a function of bulk hardness.

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For a given bulk hardness of 710 HV 30, specimen A showed the highest abrasion resistance, whereas the lowest one was measured with specimen B. This behaviour indicates the importance of microstructure analysis in describing the wear resistance. The volume fraction of eutectic carbide and its microhardness are nearly the same for both specimens A and B. But when Figs. 2 and 3 are compared, it can be seen that the eutectic carbides of specimen B are smaller than those of specimen A. The fine eutectic carbide structure induced by a high solidification rate therefore decreases the abrasion resistance of specimen B, indicating that carbide morphology, as well as the carbide volume fraction, plays an important role in wear resistance.
Figure 11 shows that bulk hardness cannot be safely used as an indicator of wear resistance. However, microstructural parameters such as matrix type and composition, retained austenite in the matrix, and the nature of carbides (type, form, hardness, morphology and distribution, carbide spacing to abrasive grain size) have to be considered.(13,14) Besides, plastic deformation induced by the wear process may have a great influence on the abrasion resistance.(19-21)

### 3.4 Abrasion Resistance and Equivalent Hardness

As seen in Figure 11, bulk hardness alone can not describe satisfactorily the abrasion resistance of Ni-hard 4 alloys. Besides, microstructural parameters in isolation can not be safely used to indicate the wear resistance. Therefore, it is necessary to find a general model with which the wear behaviour can be better characterised. The model **"Equivalent Hardness"** was developed to describe the abrasion behaviour,(22) in which the influence of the work hardening resulted from the abrasion was considered. The equivalent hardness *($H_{eq}$)* is calculated as follows:

$$H_{eq} = f_m \times H_m + f_{hp} \times H_{hp} \qquad (2)$$

$f_m$: Matrix volume fraction
$f_{hp}$: Hard phase volume fraction
$H_m$: Matrix hardness measured after the wear test
$H_{hp}$: Hard phase hardness

Figure 12 shows the abrasion resistance increases with the equivalent hardness in a non-linear fashion. When Figures 11 and 12 are compared, a strong correlation can be seen between the abrasion resistance and equivalent hardness; whereas, a poor correlation was found between the abrasion resistance and bulk hardness. The strong correlation can be attributed to the matrix work hardening and the carbide volume fraction. The difference in the carbide hardness of the specimens (1237-1573 HV 0.05), worn on flint (900 HV 0.05), minimally influences the overall abrasion resistance; i.e., the wear damage in the carbide occurred in the low-wear region.

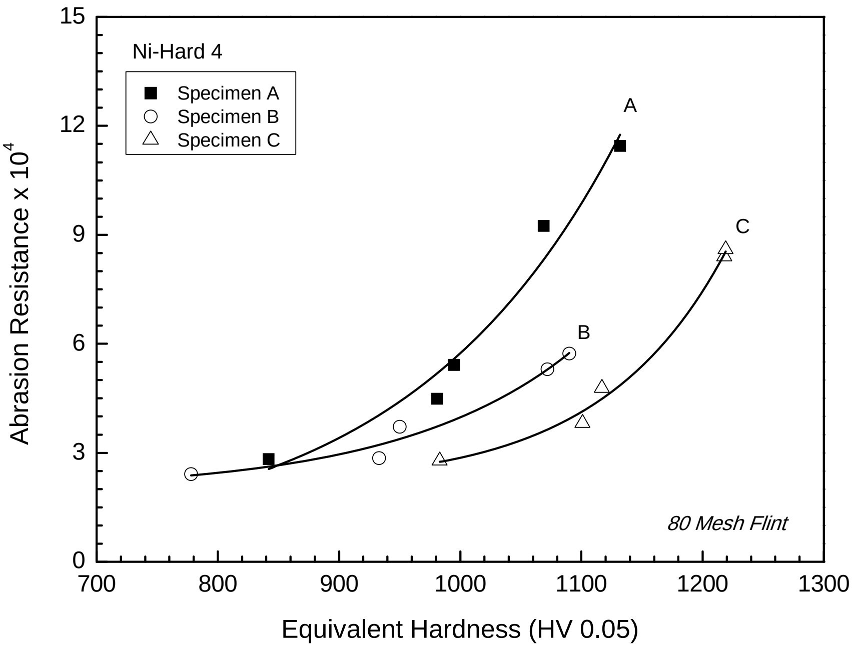


**Figure 12**: Abrasion resistance of Ni-Hard 4 specimens worn on 80 mesh flint abrasive as a function of equivalent hardness.

The non-linearity of the abrasion resistance with the equivalent hardness can be attributed to different wear mechanisms occurred in the matrix and the carbide [20]. Since flint abrasive is harder than the matrix; then, wear damage in the matrix can be caused by microploughing and microcutting. This is true even after strain hardening of the matrix. Due to higher carbide hardness (lower fracture toughness), compared with that of the flint abrasive, its wear damage can be caused by microcracking if the carbide is larger than the wear grooves done by the abrasion. Since the material removal occurs by a series process; i.e., the matrix is first removed before the carbide can be damaged, a non-linear behaviour can be expected. The same results were obtained by Gahr,(13) as well as Axén and Jacobson.(23)

## 4 CONCLUSIONS

The following conclusions can be drawn from this study:

- The greatest abrasion resistance of Ni-Hard 4 specimens was measured in as-hardened condition, whereas, the worst in as-tempered condition at 550°C.
- When Ni-Hard 4 specimens were worn on SiC and $Al_2O_3$, small differences in their abrasion resistance were recorded. However, significant differences in abrasion resistance of these specimens were found when worn on flint.
- Since most industrial applications for white cast irons involve abrasion with minerals no harder than 1200 HV, it may be concluded that pin abrasion tests of these alloys worn on flint should provide useful correlation with their service performance.
- Retained austenite in the matrix until 35% improved the abrasion resistance of Ni-Hard 4 due to work hardening induced by the wear process that led to increase the matrix hardness.

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- Since the bulk hardness of Ni-Hard 4 alloys cannot be safely used as an indicator of abrasion resistance, a general model "Equivalent Hardness" was developed to describe better the abrasion resistance.

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