

The role of microstructural features in abrasive wear of a D-2 tool steel

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There are three major constituents, i.e. tempered martensite, retained austenite and primary carbides of Cr_7C_3 and Cr_{23}C_6 , in the microstructure of a D-2 tool steel. An abrasive wear test with SiC sand paper under two different loads was conducted on specimens having various contents of the above constituents in order to investigate their role in the wear characteristics. It is found that although the wear resistivity seems to vary with changing retained austenite content or hardness, the primary carbides, however, are more likely to be the dominating factor causing the weight loss, especially for wear under a relatively heavy load. From microstructural examination of the worn specimens, cracks and spallation initiated from the primary carbides were observed. Both of the primary carbides and retained austenite were massively removed from the worn surface layer. On the other hand, the role of retained austenite was significant only for the wear test under a light load.

1. Introduction

The role of microstructure on wear resistivity of metals has been studied intensively [1-6], and it is generally recognized that the wear resistivity can be improved with toughness as well as hardness of the tested material. The improvement has been related to the flow stress, and the work hardening in several simple systems, but for multiphase metals, simple correlations are less clear. Nevertheless, in previous works on alloy steels [7, 8], the role of retained austenite has been emphasized. It was found that the steels containing retained austenite exhibited superior wear resistivity to those with little or no retained austenite. This beneficial effect was attributed to the ductile nature of retained austenite. However, because changes of other constituents, such as martensite, carbides, etc., are generally accompanied by change in the retained austenite content in alloy steels, the simple correlation between wear resistivity and retained austenite becomes quite speculative [9].

In this work, the relationships between each constituent content and the abrasive wear resistivity of a high chromium and high carbon alloy steel, D-2 tool steel, were investigated.

2. Experimental details

The chemical composition of the D-2 tool steel used in this experiment is shown in Table I. Rod-shaped specimens of 1.2 cm diameter were prepared and subjected to different heat treatments to have either various contents of retained austenite with the same hardness (designated group N), or different hardness with the same retained austenite content (designated group S). The details of the heat treatments adopted are given in Table II.

The volume fractions of both retained austenite and

TABLE I Chemical analysis (wt %) of D-2 tool steel

Fe	C	Si	V	P	S	Cr	Mo
Bal.	1.42	0.30	0.24	0.02	0.004	12.0	0.83

tempered martensite in each specimen were evaluated with an X-ray diffraction technique from CuK_α radiation. The selected diffraction peaks for this evaluation were 3 1 1 A, 2 2 0 A and 2 1 1 M (letters "A" and "M" denote the austenite phase and martensite, respectively). The content of primary carbides was also analysed using optical microscopy. The microstructure, as well as the worn morphology of the specimens, were examined both optically and by electron probe microanalysis (EPMA).

The abrasive wear tests were performed on a pin-on-disc abrasion tester. A schematic diagram of the arrangement is shown in Fig. 1. Both the testing specimen and a reference specimen (taken as specimen N3) were simultaneously contacted on an 180 grit SiC abrasive paper which had been adhered to the rotating disc of the tester. During wear, a fixed constant

TABLE II Conditions of heat treatment

Specimen no.	Austenization		Super-cooling in liquid nitrogen	Tempering	
	Temp. (°C)	Time (min)		Temp. (°C)	Time (min)
N1	1000	10	No	258	60
N2	1000	20	No	258	60
N3	1050	10	No	258	60
N4	1050	20	No	258	60
S1	1000	10	Yes	258	60
S2	1000	20	Yes	271	60
S3	1050	10	Yes	400	60
S4	1050	20	Yes	400	60

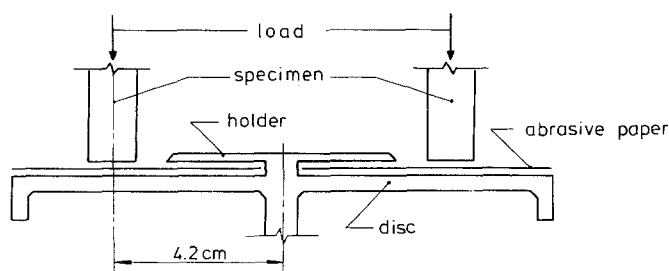


Figure 1 Schematic diagram of the abrasive wear arrangement.

TABLE III Hardness of testing specimens

	Specimen no.							
	N1	N2	N3	N4	S1	S2	S3	S4
Hardness (R_c)	58.8	59.4	59.1	59.4	59.2	59.6	60.9	61.2

load, either 0.5 or 1.0 kg (i.e. 0.043 and 0.086 MPa, respectively), was applied to both testing and reference specimens. The rotating speed of the disc was 1 cycle/sec, and the radius distance of contact point to disc centre was 4.2 cm. Each specimen was worn for 30 cycles before weight loss was measured. Then, the abrasive paper used was replaced by a new sheet to repeat the same test. Fifteen measurements were obtained from each specimen. A wear ratio, defined as

$$\text{wear ratio} = \frac{\text{Average weight loss of testing specimen}}{\text{Average weight loss of reference specimen}}$$

was then calculated to evaluate the relative wear resistivity of each specimen. The lower the value of wear ratio, the superior the wear resistivity.

3. Results

Table III shows the Rockwell C hardness of each specimen. All specimens of group N have a hardness around $R_c 59$, but the specimens of group S, which quenched into liquid nitrogen before tempering, have a hardness in a range $R_c 59$ to 61.

Fig. 2 shows the typical microstructure of specimens before heat treatment. Large primary carbides are imbedded in the matrix of ferrite and cementite. After heat treatment, the tempered martensite, as well as the primary carbides, can be observed in Fig. 3. It is clear to note that the primary carbides have shrunk. From

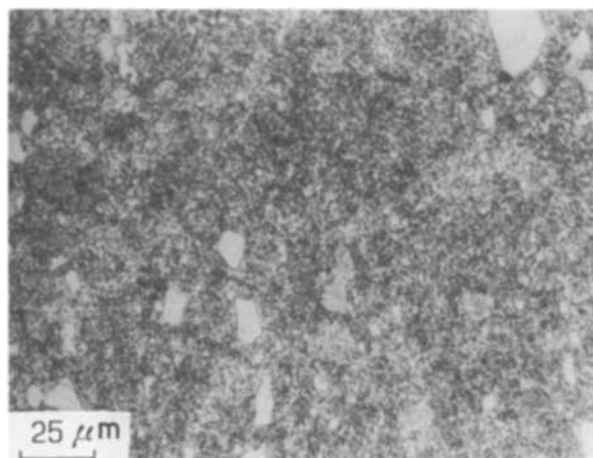


Figure 2 Optical microscopy of a D-2 specimen before heat treatment (etched by 2% Nital).

TABLE IV Calculated volume fraction of the three major constituents in the microstructure

	Specimen no.							
	N1	N2	N3	N4	S1	S2	S3	S4
Retained austenite (%)	7.7	9.6	18.2	21.6	6.4	6.2	7.2	8.0
Tempered martensite (%)	79.8	78.9	71.3	69.4	81.6	82.3	82.3	83.0
Primary carbides (%)	12.5	11.5	10.5	9.0	12.5	11.5	10.5	9.0

Fig. 4, it is found that these primary carbides are chromium-rich.

From X-ray diffraction, the presence of austenite, martensite and primary carbides (which have been identified as Cr_7C_3 and $Cr_{23}C_6$), are clearly observed. Fig. 5 displays the relative variation of diffraction intensity of each constituent in the four specimens of group N. The diffraction intensities of martensite and primary carbide decrease but that of retained austenite increases as austenization temperature and time increase (Specimens N1 to N4). Table IV shows the calculated volume fraction of retained austenite in each specimen. It is found that the specimens of group N have broadly varied contents of retained austenite, about 7 to 21%, but those of group S have a relatively low and restricted content of retained austenite, around 6 to 8%. The volume fractions of primary carbides and tempered martensite in each specimen are also included.

Table V shows the wear ratio results of abrasion tests. From the plot of wear ratio against retained austenite content, as shown in Fig. 6, it is found that among the specimens of group N (which have

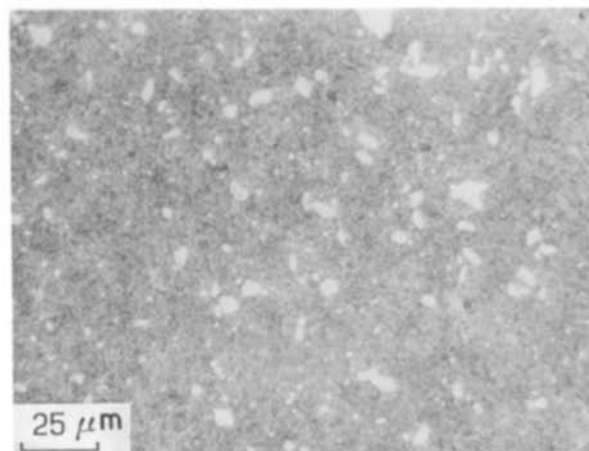


Figure 3 Optical microscopy of a quenched and tempered specimen (etched by 5% Nital).

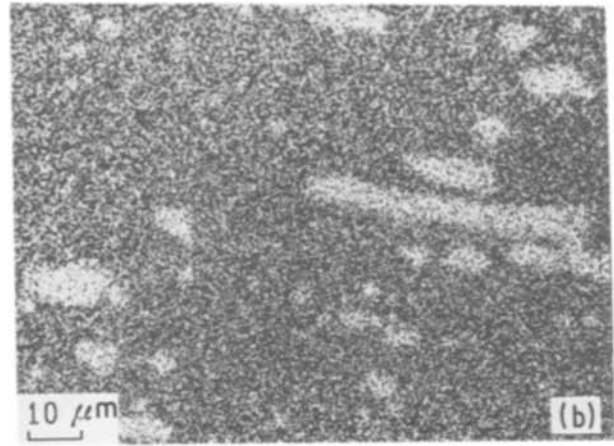
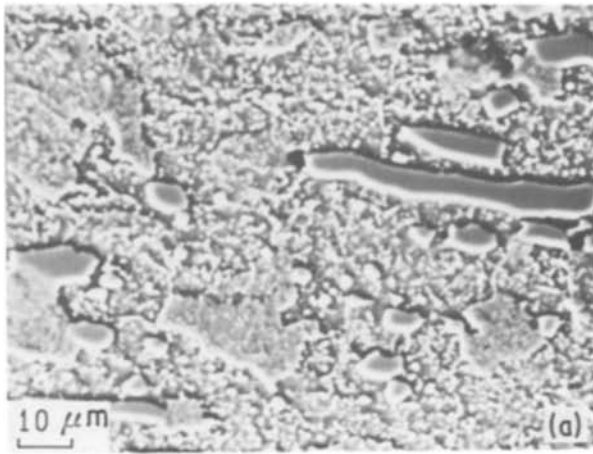


Figure 4 The microstructure of a quenched and tempered specimen observed by EPMA: (a) secondary electron image, (b) X-ray mapping of CrK_α radiation.

TABLE V Results of wear tests as wear ratios

Load (kg)	Specimen no.							
	N1	N2	N3	N4	S1	S2	S3	S4
0.5	1.11	1.10	1.00	0.97	1.23	1.19	1.06	1.04
1.0	1.16	1.14	1.00	0.98	1.19	1.15	1.02	1.00

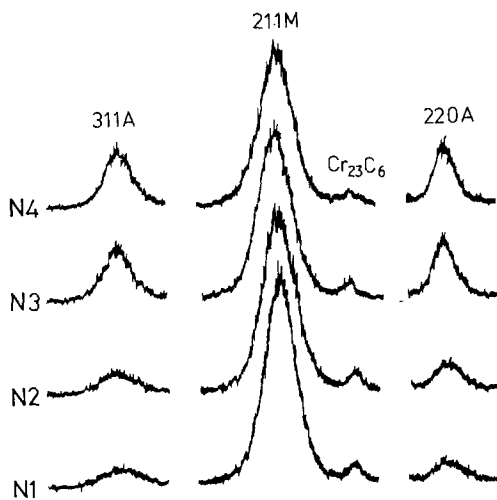


Figure 5 Relative variation of X-ray diffraction peaks of specimens N1, N2, N3 and N4, respectively.

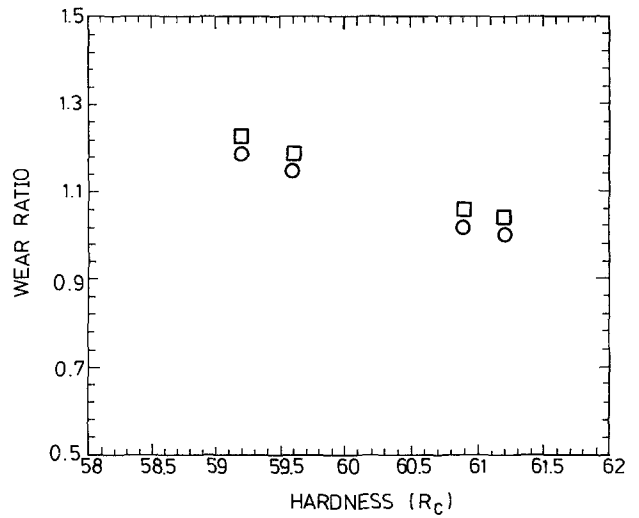


Figure 7 Plot of wear ratio against hardness for specimens of group S. (○) 1.0 kg load, (□) 0.5 kg load.

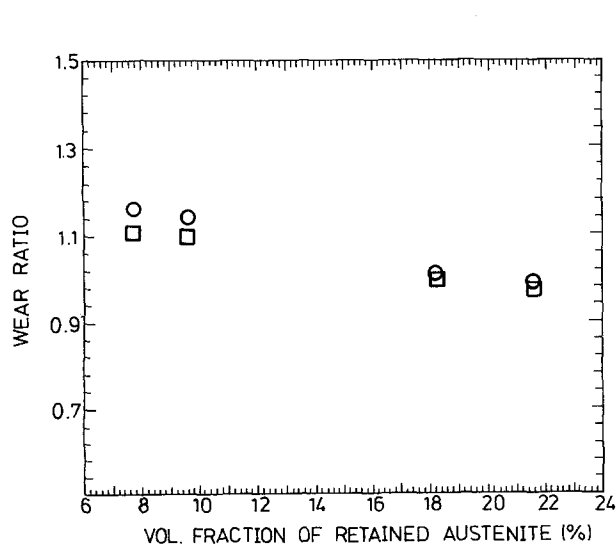


Figure 6 Plot of wear ratio against volume fraction of retained austenite for specimens of group N. (□) 0.5 kg load, (○) 1.0 kg load.

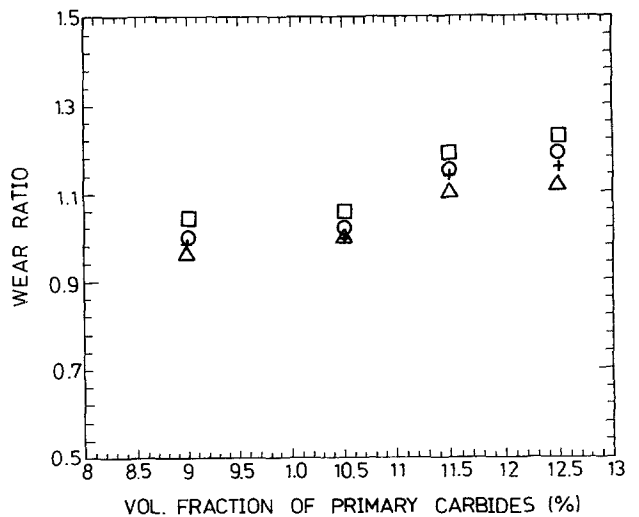


Figure 8 Plot of wear ratio against volume fraction of primary carbides for specimens of both groups. Group S: (□) 0.5 kg load, (○) 1.0 kg load. Group N: (Δ) 0.5 kg load, (+) 1.0 kg load.

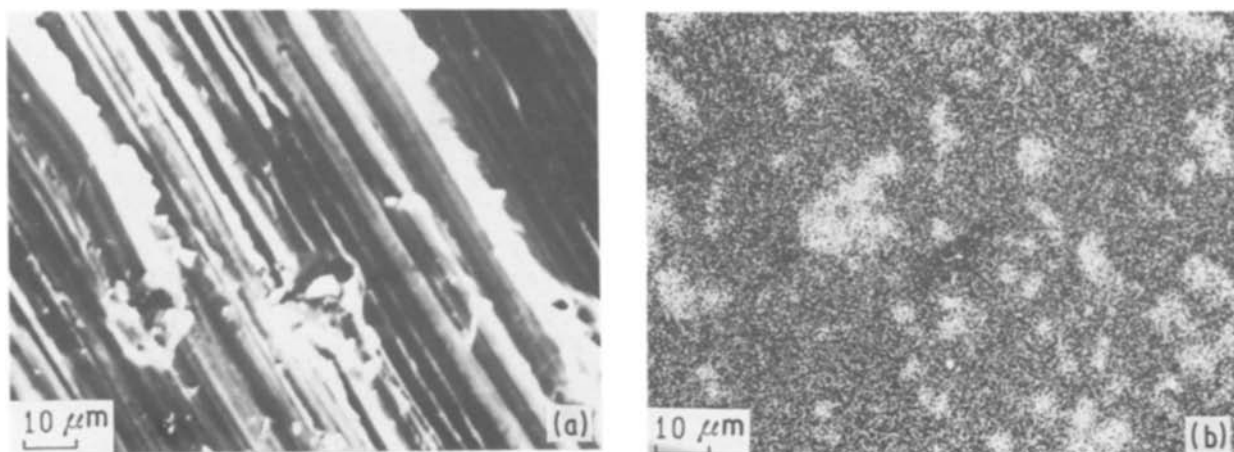


Figure 9 Surface morphology of a worn specimen observed by EPMA: (a) secondary electron image, (b) X-ray mapping of CrK_{α} radiation.

nearly the same hardness), the higher the content of retained austenite, the better the wear resistivity. Similar testing results were obtained for both 0.5 and 1.0 kg loads. On the other hand, from Fig. 7, the wear resistivity of group S specimens (which have nearly the same content of retained austenite) is significantly increased as hardness increases. However, controversially, the wear resistivity is also substantially affected by the content of primary carbides, as shown in Fig. 8.

The morphology of worn surface has been examined with EPMA. Fig. 9a shows a typical result of the worn morphology. Spalling and cracking are observed around the wear grooves. Fig. 9b shows the corresponding chromium X-ray mapping. The bright areas in the image indicate the locations of primary carbides. It is clear that the primary carbides are not obstructive to the grooving by SiC particles. On the contrary, cracks are observed around the primary carbides. It can be more easily observed from Fig. 10 that the cracks and spallations initiate from these carbides. Figs 11a and b demonstrate the results of X-ray diffraction from the surface of a specimen before and after the wear test, respectively. The diffraction peaks of both retained austenite and primary carbides are very much reduced after wear. However, the peaks of martensite are virtually unaffected. The result indicates that during the test, a large amount of both retained

austenite and primary carbides is scratched off from the worn layer.

4. Discussion and conclusion

From Fig. 9a, it is suggested that there are two major mechanisms causing the weight loss in the wear test, i.e. the direct plowing by the hard SiC particles, and the spallation by cracking. In order to reduce the weight loss in wear, it is generally accepted that a high value of hardness helps to resist plowing and a good toughness is required to inhibit cracking and spallation. The results of Figs 6 and 7 seem consistent with the above arguments. However, controversial results are noticed for the specimens of group S when tested under different loads. It is seen from Table V that for the test under a 0.5 kg load, the measured wear ratios of group S specimens are clearly higher than those of group N specimens, but for the wear test under 1.0 kg,

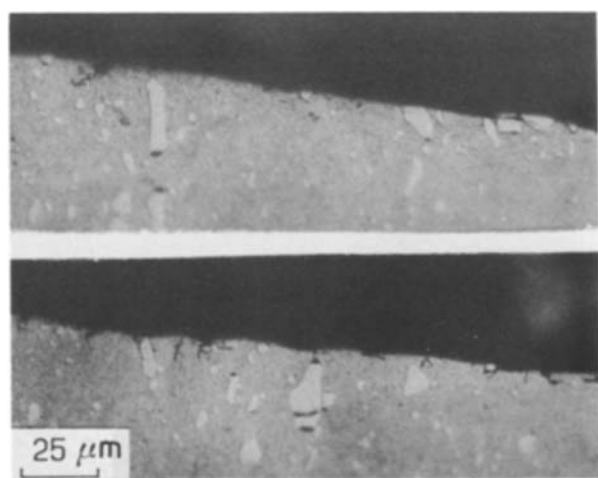


Figure 10 Cross-sectional optical microscopy of a worn specimen. Bright areas indicate the primary carbides.

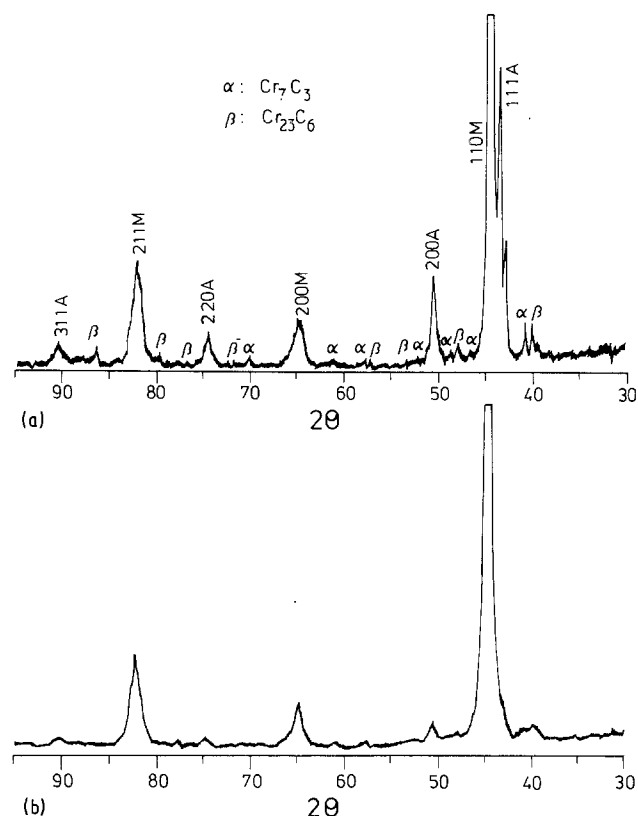


Figure 11 X-ray diffraction patterns of a specimen surface (a) before and (b) after wear.

the measured wear ratios of group S specimens are only slightly higher than those of group N specimens. The above results indicate that either the retained austenite or hardness may not be the major factor affecting the wear resistivity of the material studied in this experiment.

As the content of primary carbides is also one of the major constituents in the specimens, it must be taken into consideration. From Figs 9 and 10, it is clearly observed that the cracks and spallation initiate enormously from the primary carbides in the worn specimen. These carbides are obviously detrimental to wear resistivity. Also, from Fig. 11, both retained austenite and primary carbides are largely removed from the worn layer, which indicates a large part of the weight loss is caused by the loss of these two phases during wear. It is thus clear that the primary carbides must be one of the dominating factors affecting the wear resistivity of the material. Such a conclusion is consistent with Fig. 8. The improvement of wear resistivity motivated by the reduction of primary carbides has been found in both groups of specimens. Furthermore, it is noted from Fig. 8 that there is a difference in the results for different loads. For 1.0 kg load, the measured wear ratios of any two specimens having the same content of primary carbides but different contents of retained austenite, are only slightly different from each other. This indicates that the primary carbides are the most important factor in controlling the wear resistivity under a heavy load. For a light load, i.e. 0.5 kg, the specimens of group S display a significantly worse wear resistivity than

those of group N. By examining the microstructural differences in the specimens, it is suggested that the large carbides are relatively difficult to crack under a light load, and therefore, the retained austenite becomes significant in improving the wear resistivity.

In conclusion, the abrasive wear resistivity of a D-2 alloy steel is significantly affected by the content of primary carbides. These large carbides can be easily cracked during wear, which causes the weight loss by spallation. The deterioration induced by these primary carbides has a dominant effect on the wear resistivity for wear under a heavy load. On the other hand, the role of retained austenite is significant only for wear under a light load.

References

1. P. L. HURRICKS, *Wear* **26** (1973) 285.
2. E. HORNBOKEN, *ibid.* **33** (1975) 251.
3. N. P. SUH, N. SAKA and S. JAHANMIR, *ibid.* **44** (1977) 127.
4. P. J. MUTTON and J. D. WATSON, *ibid.* **48** (1979) 385.
5. N. PRASAD and S. D. KULKARNI, *ibid.* **63** (1980) 329.
6. D. A. RIGNEY (ed.), in "Fundamentals of Friction and Wear of Metals" (ASM, Metals Park, Ohio, 1980) p. 1.
7. W. J. SALESKY and G. THOMAS, in "Wear of Material 1981" (ASME, New York, 1981) p. 298.
8. N. J. KAR, *ibid.* p. 415.
9. T. B. WU and R. J. YOUNG, in Proceedings of the 7th International Conference on Strength of Metals and Alloys, Montreal, Canada, August 1985, edited by H. J. McQueen, J. P. Bailon, J. I. Dickson, J. J. Jonas and M. G. Akben (Pergamon, New York, 1985) p. 1551.

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