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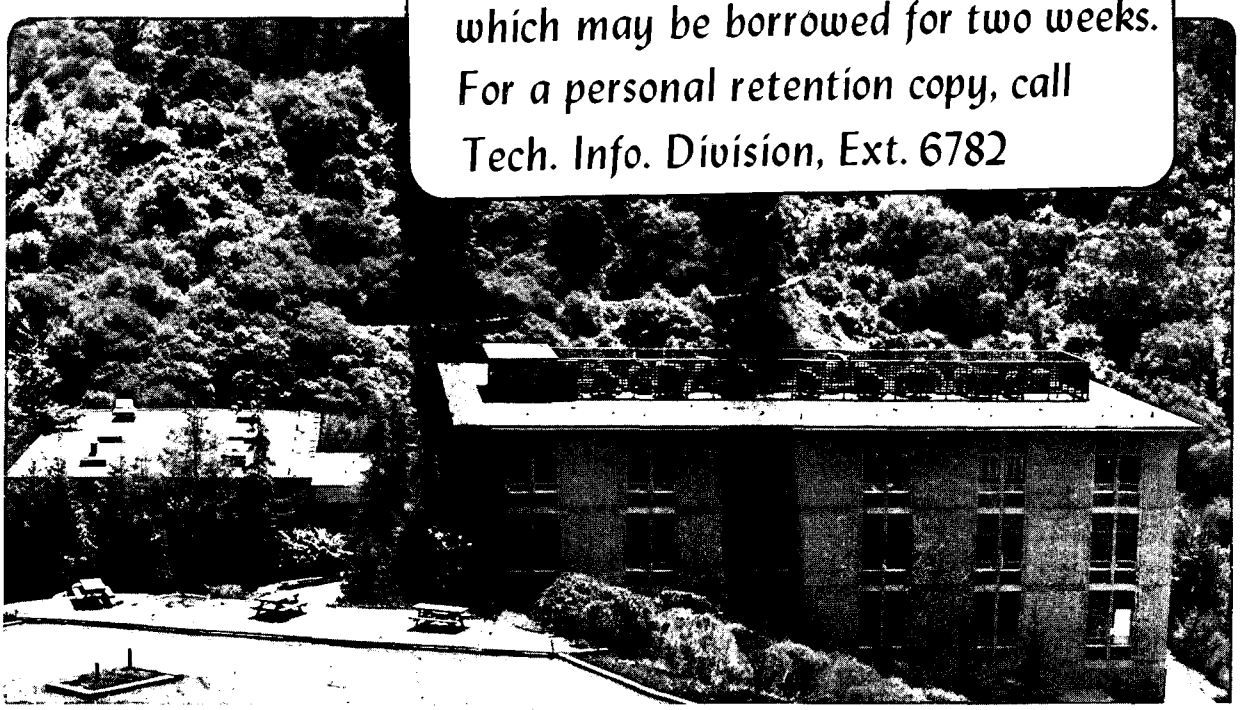

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MEDIUM CARBON STEEL ALLOY DESIGN FOR WEAR APPLICATIONS

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ABSTRACT

The fracture characteristics of steels are strongly influenced by martensite substructure, retained austenite stability, and morphology. Attractive strength-toughness properties have been attained with Fe/Cr/C/Mn alloys. These same alloys, when tested under sliding wear conditions, also exhibit good wear resistance which compares favorably to that of commercial wear-resistant alloys. The most significant finding is an apparently strong correlation between sliding wear resistance and retained austenite, which in turn appears to correlate with Charpy impact properties. Little correlation was observed between hardness and wear resistance for the experimental steels.

I. INTRODUCTION

Metal wear in mining and mineral processing equipment such as digger teeth, jaw crushers, conveyors, ball mills etc., constitutes a serious economic problem with an annual expense exceeding 15 billion dollars[1]. Conventionally, the selection criteria for maximum sliding or abrasive wear resistance has been the initial underformed hardness. Although hardness is an important parameter, it is not always true that the hardest material is the most wear resistant. Consequently, it is important to consider other metallurgical variables which influence wear resistance. Although strain-hardening behavior has been recognized[2] to be an important indicator of a capacity to resist wear, several investigators[3-6] have

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suggested that optimum abrasive or sliding wear resistance is obtained through design of a microstructure which combines high strength with high toughness. Even though this concept is not observed to be valid for wrought or cast low-alloy steel (which exhibits high impact toughness), in many other situations it has been suggested that increases in impact and/or fracture toughness while maintaining strength, serve to increase wear resistance[3-6]. Unfortunately, in most engineering materials high strength is obtained at the direct expense of toughness and vice-versa. However, micro-composite structures such as an austenite-martensite micro-duplex structure have shown promise for achieving high toughness-strength combinations[4-10].

It is generally recognized that most ferrous martensitic materials exhibit abrasive wear resistance superior to pearlitic, ferritic, or bainitic materials. Similarly, it is widely known that the martensitic transformation can be exploited to produce a variety of strength and toughness combinations in high-strength steels. While the cheapest method for increasing strength in martensitic steels is to increase carbon content, toughness deteriorates monotonically. Therefore, over the past decade, studies have been performed on ternary Fe/Cr/C and quaternary Fe/Cr/C/Mn alloys to research systematically the influence of alloying elements on medium carbon martensitic structures and resultant mechanical properties[7-14]. These structures have been shown to consist of dislocated lath martensite, with fine intralath carbides, surrounded by interlath films of retained austenite. Additions of Mn up to 2wt% in the Fe/4Cr/.3C alloy serve to increase both impact and fracture toughness without loss in strength[10-11]. Since previous investigations observed little change in the martensite substructure with addition of Mn, but observed lateral

thickening of austenite films, the increased toughness was attributed to the increase in the austenite content[11].

In summary, the results have been the development of both vacuum and air melted steels of strength and toughness exceeding that of presently available medium carbon wear resistant steels.

Since considerable background data is available on controlled experimental medium carbon steels[10], the wear resistance studies were initiated on these alloys[15]. For comparison, several commercial wear plate materials were selected. These commercial steels had similar compositions at similar strength levels to the experimental ones. The microstructures of all steels were characterized using light and electron microscopy prior to testing.

II. EXPERIMENTAL PROCEDURES

A. Materials Preparation

Experimental heats of Fe/4Cr/.3C with 0 to 2% Mn were vacuum induction melted and Fe/3Cr/.3C/2Mn/0.5Mo was air melted at Diado Steel Corporation in Japan. The compositions of these alloys are shown in Table 1. These ingots were cross forged and then homogenized at 1200°C (2192°F) for 24 hours. Heat treatments were performed (Fig. 1) (when necessary), on specimen blanks (Fig. 2) in a vertical tube furnace with an argon atmosphere.

The composition of the commerical low and medium alloy wear-resistant steels are given in Table 1. The steels were received from the respective manufacturers in the heat-treated condition. Specifically, Firmex was austenitized at 885°C, quenched and tempered at 470°C. Astralloy was conventionally normalized. Abrasalloy was austenitized at 840°C, quenched,

and tempered at 425°C. Vacuum melted AISI 4340 was also included in this study due to its wide-spread use. This material was given a single heat treatment as described in Figure 1.

B. Metallography

Light and transmission electron microscopy (TEM) were performed only on the commercial steels since detailed microscopy had previously been done on the experimental alloys[10-14]. Specimens for light microscopy were cut from heat treated materials, mounted, and polished. The microstructures were revealed by etching with 2% Nital solution. Thin foils for TEM were obtained by cutting a 500μm slice of material from the heat treatment bulk via a diamet saw. These slices were chemically thinned in HF + H_2O_2, cut into 3.0mm disks, and ground to a thickness of 50-100μm. Twin-jet electropolishing was subsequently performed in a chromic-acetic acid solution until a hole formed at the disk center. Thin foils were examined at 100kV in a Philips EM 301 and a JEM 7A electron microscope.

The average volume fraction of retained austenite present in the experimental and commercial steels was measured by Mössbauer spectrographic techniques. X-ray quantitative analysis on these steels was done previously[10,11]. The Mössbauer effect is well-known to be a nuclear γ-ray resonance phenomenon[16]. Quantitative determination of retained austenite is possible due to the intensities of the paramagnetic peaks generated by the austenite phase being proportional to the amount of austenite present. This technique facilitates determination of small volume fractions of retained austenite because of its insensitivity to texture effects. Although it would have been desirable to also perform Mössbauer analyses on the surface of the worn specimens, the worn areas were too small (approximately

1400μm in diameter) to obtain accurate analyses.

C. Wear Measurements

1. Specimen Preparation. The majority of the experimental steel wear specimen were machined from the undeformed regions of heat-treated compact tension specimens used in a previous study. The commercial materials were taken from heat treated stock. The typical specimen blank, shown in Figure 2, was cut from the bulk then turned on a lathe to form 1/4" diameter hemispherically-tipped cylindrical pins. Removal of 125 to 250μm from the surface of the hemisphere by light grinding, under flood cooling on a 400 grit diamond wheel, was done to attempt to remove microstructural damage induced by turning.

It was observed that scatter in the sliding wear data could be reduced by polishing the surfaces of the specimens after final grinding. Consequently, the hemispherical surfaces of sliding wear specimens were polished to remove grinding scratches using Buehler 600 grit abrasive paper followed by 1 micron diamond paste on microcloth, while the specimen was rotating in a lathe at 500 rpm. Care was also taken during polishing to apply light loads so as to minimize specimen heating.

All the specimens were cleaned in N-heptane to remove oil and dirt accumulated during preparation. Ultrasonic cleaning in acetone followed by alcohol was done to remove residue left by the other solvents. The specimens were then dried in vacuum.

The specimens were weighed prior to testing on a Mettler H54AR analytical balance to an accurancy of ±.01mg. Each specimen was weighed at least three times and the median reading recorded. After wear testing, the specimens were recleaned as described above, and then reweighed. The

measured weight loss of the pin was determined and was used to compute wear resistance as shown below:

$$\text{Wear Resistance} = \frac{1}{\text{Wear Rate}}$$

$$= \frac{\text{Sliding Distance}}{\text{Volume of Metal Removed}}$$

$$= \frac{\text{Material Density} \cdot \text{Sliding Distance}}{\text{Weight Loss}} \quad (\text{mm/mm3})$$

D. Sliding Wear Measurements

Wear testing was done on a pin-on disk wear machine fabricated at Lawrence Berkeley Laboratory in 1977. Since no ASTM standard has been set for sliding wear measurements, the test parameters used here were selected to produce a measureable amount of mild sliding wear in the "absence" of specimen heating. Consequently, the pins were worn for 4 hours each at 10 rpm disk speed under 1 kg deadweight load. A minimum of 3 specimens was used to establish each datum point for all the steels tested. The disk against which the specimens were worn was .95 cm thick, 12.7 cm in diameter, AISI 4340 quenched and tempered to $53R_C$. Each test was conducted on a fresh wear track at constant radius of 4.92 cm. Hence, only one wear test was performed on each side of the disk. The disk was then ground to remove 6 mils (150μm) from each side and subsequent tests were then performed. Only one wear disk was used for this study to insure reproducibility. Periodically, the hardness of the disk was checked and was found not to change. The surface of the wear track was also periodically examined and no metal transfer appeared to occur between the pins and the disk.

E. Abrasive Wear Measurements

Abrasive wear tests were performed on a pin-on disk tester constructed by G. Yang[17]. This machine was fashioned after that of Mishra[17] and was used to simulate high stress abrasive wear. Silicon carbide, 120 grit paper, was the abrasive medium, because it has been shown that the rate of wear is independent of particle size below 60 grit[19].

Following an initial run-in[19], the test encompass 1 kg dead-weight loading of the hemispherically tipped specimen which made one pass over fresh abrasive paper travelling a spiral path length of 2.2 meters. Worn specimens were then cleaned and weighed as previously mentioned.

III. RESULTS

A. Microstructure

The microstructures of the experimental Fe/Cr.C/Mn (and Ni) alloys have been shown to consist of dislocated lath martensite surrounded by continuous interlath films of retained austenite[9-14] (Figure 3). Widmanstatten cementite occurs on a fine scale (∿1μm) within the martensite laths after tempering at 200°C. This condition exhibits the highest toughness-strength ratio in both fine (∿30μm) and coarse grained alloys (∿280μm). However tempering above 300°C induces tempered martensite embrittlement as a consequence of retained austenite decomposing to interlath particles of ferrite and cementite which serve to reduce toughness significantly (∿25J) and to reduce strength slightly (∿100mPa)[7].

As previously mentioned, increasing the Mn content to 2% increased the volume fraction of retained austenite. As shown in Figure 9 this treatment was observed to reduce sliding wear resistance which occurred

by lateral film thickening. It has been suggested[10,11] that increased austenite content in these alloys is responsible for the observed increase in impact and fracture toughness. However, above 3% Mn twinned martensites were observed to form (20) which are known to de detrimental to toughness in these steels[9].

The microstructures of the commercial steels were considerably different from those of the experimental alloys. The mechanical properties of these materials are shown in Table III. Because of the fine microstructures, optical metallography yielded little information. However, inclusions elongated in the rolling direction were observed in Firmex. An SEM micrograph (Figure 4) with corresponding X-ray map showed these inclusions to be rich in sulphur indicating that they are probably MnS.

Transmission electron microscopic observation on Firmex suggests that the structure is a combination of non-uniformly distributed bainite and martensite (Fig. 5). Mössbauer spectroscopy showed 1 to 1-1/2% retained austenite to be present.

Transmission electron microscopy of the quenched and tempered Abrasalloy (Figure 6) showed interlath as well as intralath cementite. The intralath carbides were finely distributed throughout the ferritic regions. Mössbauer spectroscopy showed less than 0.3% of retained austenite. The absence of retained austenite, the presence of cementite, and the low hardness ($34.5R_C$) suggests this material is tempered martensite.

Astralloy, however, appears to have a more complex structure (Fig. 7). No interlath carbides could be resolved, so the structure is not upper bainitic. Mössbauer spectroscopy indicated that greater than 20% paramagnetic phase was present. A small volume fraction of microtwins was also observed.

Since a large amount of work has been performed[21-24] on martensitic AISI 4340, its structure is well-known to be dislocated lath martensite with interlath retained austenite. Although its structure and strength levels are similar to the experimental materials, its toughness is substantially less. Mössbauer spectroscopy showed 6% austenite is present in the 4340 tested here.

B. Wear Measurements

The results of sliding and abrasive wear tests are shown in Figures 8-13 and in Table 2 and 3 along with the respective mechanical properties. For several conditions of the experimental alloys, sliding wear resistance was independent of hardness (Figure 8). Increasing the Mn content above 1%, which increases impact and fracture toughness while hardness remains essentially constant, significantly increased sliding wear resistance (Table 11). In all cases austenite grain refinement increased sliding wear resistance 20 to 30%. Since both grain refinement and increased Mn contents are known[10,11,15] to increase retained austenite content in these alloys, it is seen that there is an increase of sliding wear resistance with increasing austenite content (Figure 9). Because retained austenite has been suggested[4,6,11,19] to affect toughness, a relation between wear resistance and classical measurements of toughness would thus be expected. A weak correlation was observed between plane strain fracture toughness and sliding wear resistance (Figure 10). However, there appears to be a noticeable trend that sliding wear resistance increase with impact energy for the 2% Mn experimental alloy in various heat treated conditions (Figure 11).

Contrasting the results from the experimental alloys with those of the commercial alloys, the grain refined Fe/4Cr/.3C/2Mn vacuum melted alloy

was observed to be the most sliding and abrasive wear resistant (Figs. 12 and 13). Equal to the best of the commerical alloys examined, Abrasalloy, was the air melted, coarse grained Fe/3Cr/.3C/2Mn/.5Mo experimental alloy. It is interesting to note that Abrasalloy was the "softest" of the commercial alloys yet the most wear resistant. Firmex, Astralloy, and AISI 4340 exhibited sliding wear resistance substantially less than that of Abrasalloy and most of the experimental alloys.

IV. DISCUSSION

A. Experimental Alloys

The results of the sliding wear measurements show several interesting trends. Hardness has traditionally been believed to be a primary factor affecting sliding or abrasive wear resistance. However, materials with similar tensile strengths but different microstructures will often have the same hardness but frequently have quite different wear resistances[3-5]. In the present study the wear resistances of the experimental alloys for several compositions in fine and coarse grained conditions were observed to be <u>independent</u> of hardness and, in most cases, to far exceed that of the commercial steels examined (Figure 8).

The results indicate that microstructure is the important metallurgical variable influencing sliding wear behavior. The predominantly superior behavior of the grain refined and tempered Fe/4Cr/.3C/2Mn over the commercial steels appear to be due to the presence of dislocated lath martensite with a fine intralath distribution of Widmanstatten cementite in association with interlath films of retained austenite. The retained austenite has been shown to benefit fracture toughness when it is stabilized, e.g. with Mn additions[10]. The present data in Figure 9 shows that there appears

to be a 25% increase in wear resistance corresponding to an increase of retained austenite from 1 to 3%. In the present study, Mössbauer spectroscopy repeated on the same material used before revealed the same trend as the X-ray data even though the magnitude of the austenite content was found to average from 1 to 6%.

Although grain refinement and alloying were observed to significantly affect retained austenite content and toughness values in the Fe/Cr/C Mn system, it is still not clear by what mechanism austenite apparently serves to increase wear resistance. It is acknowledged that the presence of retained austenite may have secondary effects on the surrounding martensite substructure such as affecting the amount of carbon in solution rather than acting to blunt or branch cracks through transformation to martensite. It is also acknowledged that the increased toughness and sliding wear resistance attributed to increased retained austenite, achieved through manganese addition, may in part be due to the intrinsic effects of manganese rather than to the presence of austenite. However, in any case, the presence of continuous interlath retained austenite appears to benefit the wear resistance of these materials.

To attempt to confirm the trend of increasing wear resistance with austenite content, a temper martensite embrittled specimen having a very low austenite content was tested. It was found to agree well with the established trend of sliding wear resistance increasing with austenite content (Figure 10). Consequently, there appears to be an association of continuous interlath films of retained austenite in martensitic steel with increased wear resistance.

Since it has been observed that wear resistance increases with

austenite content and that increased austenite content appears to be related to increased impact and toughness, a relationship would be expected between toughness and wear resistance. Attempts to relate sliding wear to plane strain fracture toughness did not yield a good correlation (Figure 10). However, this observation may be due to insufficent K_{IC} information, to establish a trend. Yet, an apparently significant trend to increasing sliding wear resistance with Charpy V-notch impact energy was observed for various conditions of the experimental 2% Mn steel (Figure 11). Although there are some exceptions to this trend, these results do suggest that design of microstructures for high strength and impact toughness may lead to improved sliding wear resistance. Futher study is needed to elucidate the mechanisms of wear in order to better understand the trend.

B. Commerical Alloys

Contrasting the wear behavior of the commercial alloy of that of the experimental steels reveal the general superiority of both vacuum and air melted experimental steels (Figure 12). Unlike the experimental steels, the commercial materials exhibited a trend to decreasing sliding wear resistance with increasing material hardness (Figure 8). This trend is difficult to explain because of the differences in alloy composition, heat treatment and microstructure. However, large carbides and inclusions, as observed in Astralloy and Firmex, could act as stress concentrators, thereby being sites for failure initiation during sliding wear. This explanation appears to be consistent with the behavior of Abrasalloy which, in the absence of any large inclusions or undissolved carbides, had the highest wear resistance of the commercial steels at the lowest hardness.

From these results it seems apparent that microstructure plays an important role in determining sliding wear resistance. Consistent with this study, previous investigators[2,4,6] have suggested that steel containing martensite or bainite (and we emphasize it would be lower bainite) are preferable to ferritic or pearlitic microstructures for resisting wear. This conclusion is further supported by two body abrasive wear tests for which the fine-grained 2% Mn experimental steel was observed to be the most wear resistant, followed by Abrasalloy (Figure 13). Firmex exhibited less wear resistance, which is also consistent with the present results.

V. CONCLUSIONS

1. Austenite-martensite microduplex structures appear to be desirable for improved sliding and abrasive wear resistance compared to bainite, bainite-martensite, or simply 100% martensite steels.
2. The results indicate that increasing Charpy toughness increases sliding wear resistance. This correlated well with the duplex microstructure.

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FIGURE CAPTIONS

Fig. 1. Illustration of heat treatments applied to the experimental alloys. Single heat treatment promoted an average prior austenite grain size of 280μm. Double heat treatment promoted an average grain size of 30μm.

Fig. 2. Sketch of wear specimen preparation from heat-treated blank.

Fig. 3. Transmission electron micrograph of as quenched Fe/4Cr/.3C/2Mn alloy: (a) bright field shows dislocated lath martensite; (b) dark field imaging continuous interlath films of retained martensite.

Fig. 4. Optical scanning electron micrographs of Firmex: (a) optical inclusions parallel to rolling direction (indicated by arrow); (b) and (c) SEM image and sulphur X-ray map show inclusions to be sulphur rich, most probably MnS.

Fig. 5. Transmission electron micrograph of Firmex: (a) bright field of several laths containing Widmanstatten cementite; (b) dark field showing extent of Widmanstatten precipitation.

Fig. 6. Transmission electron micrograph of Abrasalloy: (a) bright field, (b) dark field of cementite spot showing intra - and interlath cementite particles.

Fig. 7. Transmission electron micrograph of Astralloy: (a) bright field showing martensite; (b) dark field of martensite reflection.

Fig. 8. Sliding wear resistance as a function of hardness. Experimental alloys exhibit wear resistances essentially independent of hardness.

Fig. 9. Shows increasing sliding wear resistance with austenite content. Note that grain refinement of 2% Mn alloy increases wear resistance

as well as retained austenite content. Retained austenite data from Reference 9.

Fig. 10. Sliding wear resistance shows a poor correlation to plane strain fracture toughness values. Fraction toughness measured as per ASTM E399, 1972 standard.

Fig. 11. Sliding wear resistance appears to correlate with Charpy impact energy for various conditions of the Fe/4Cr/.3C/2Mn alloy.

Fig. 12. Histogram of relative sliding wear resistance of experimental versus commercial alloys.

Fig. 13. Histogram of relative two body abrasive wear resistance of experimental versus commercial alloys.

TABLE CAPTIONS

Table 1 - Alloy compositions for experimental and commercial steels.

Table 2 - Mechanical properties and wear data for experimental alloys.

Table 3 - Mechanical properties and wear data for commercial alloys.

TABLE 1

STEEL COMPOSITION

EXPERIMENTAL ALLOY	C	Cr	Mn	Ni	Mo	Co	Si	Ti	V	Fe
Fe/4Cr/.3C	0.29	4.00	----	----	----	----	----	----	----	Bal.
Fe/4Cr/.3C/1Mn	0.24	4.10	1.0	----	----	----	----	----	----	Bal.
Fe/4Cr/.3C/2Mn	0.25	4.00	1.93	----	----	----	0.07	----	----	Bal.
Fe/4Cr/.3C/5Ni	0.27	3.8	----	5.00	----	----	----	----	----	Bal.
Fe/3Cr/3C/2Mn/SMo	0.29	2.94	1.86	.03	.52	----	.01	----	----	Bal.
INDUSTRIAL ALLOYS										
Abrasalloy	0.35	0.45	0.87	0.58	0.14	----	0.20	----	----	Bal.
Astralloy	0.29	1.67	1.07	3.68	0.37	0.08	0.42	0.007	.01	Bal.
Firmex	0.26	0.30	1.94	0.73	0.24	----	0.57	0.06	----	Bal.
Aisi 4340	0.40	0.70	0.75	1.75	0.25	0.02	0.02	----	.01	Bal.

TABLE II

MECHANICAL PROPERTIES AND WEAR DATA

FOR EXPERIMENTAL ALLOYS

VACUUM MELTED	Tempering Temp.	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	% REDUCTION OF AREA	K_{IC} (MPa-$m^{\frac{1}{2}}$)	IMPACT ENERGY (J)	HARDNESS (Rc)	SLIDING WEAR RESISTANCE ($mm/mm^3 x10^6$)	ABRASIVE WEAR RESISTANCE ($mm/mm^3 x10^2$)	% RETAINED AUSTENITE**
Coarse Grained Alloys										
Fe/4Cr/.3C/2Mn	as quenched	1427	1827	33	64.8	4.6	53.1	6.92	-	3.0
	200°C	1345	1634	36	198*	54.2	47.8	6.84	1.13	3.0
	300°C	1220	1462	19	-	25.1	42.0	5.34	-	-
	500°C	1034	1207	24	-	5.4	37.0	5.24	-	-
Fe/4Cr/.3C/5Ni	200°C	1289	1613	-	135.2	59.0	45.8	5.47	-	-
Fine Grained Alloys										
Fe/4Cr/.3C	200°C	1289	1565	32	-	27.8	47.2	6.67	-	2.0
Fe/4Cr/.3C/.5Mn	200°C	1282	1531	49.1	91	44.1	46.1	6.50	-	-
Fe/4Cr/.3C/1Mn	200°C	1276	1538	50	120.9	54.2	45.6	6.46	-	4.5
Fe/4Cr/.3C/2Mn	as quenched	1303	1669	38.7	92.3	41.4	47.8	7.27	-	6.0
	200°C	1269	1586	50.8	198.0*	67.1	47.0	8.68	1.15	6.0
	300°C	1255	1482	58.5	-	40.0	45.3	5.70	-	1.5
Fe/4Cr/.3C/5Ni	200°C	1331	1669	57.5	112.1	56.5	47.8	7.71	-	-
AIR MELTED										
Coarse Grained										
Fe/3Cr/.3C/2Mn/.5Mo	200°C	1353	1641	26.5	129	54.0	48	7.91	-	

* Violated Plane Strain Conditions Calculated K_Q instead of K_{IC}

** As Determined by Mössbauer Spectroscopy

TABLE III

MECHANICAL PROPERTIES AND WEAR DATA FOR EXPERIMENTAL ALLOYS

ALLOY	YS (MPa)	UTS (MPa)	% REDUCTION AREA	K_{IC} MPa-m 1/2	IMPACT ENERGY (J)	HARDNESS (R_c)	SLIDING WEAR RESISTANCE($mm/mm^3 x 10^6$)	ABRASIVE WEAR RESISTANCE($mm/mm^3 x 10^2$)
Abrasalloy	1207	1241	45	*	*	34-38	7.89	0.96
Astralloy	1083	1662	39	*	42.3	45	4.09	-
Firmex	1269	1365	50	*	20.3	39.5	5.44	0.94
AISI 4340	1551	2000	13	49	17.6	52	3.70	-

*Information not available from manufacturer

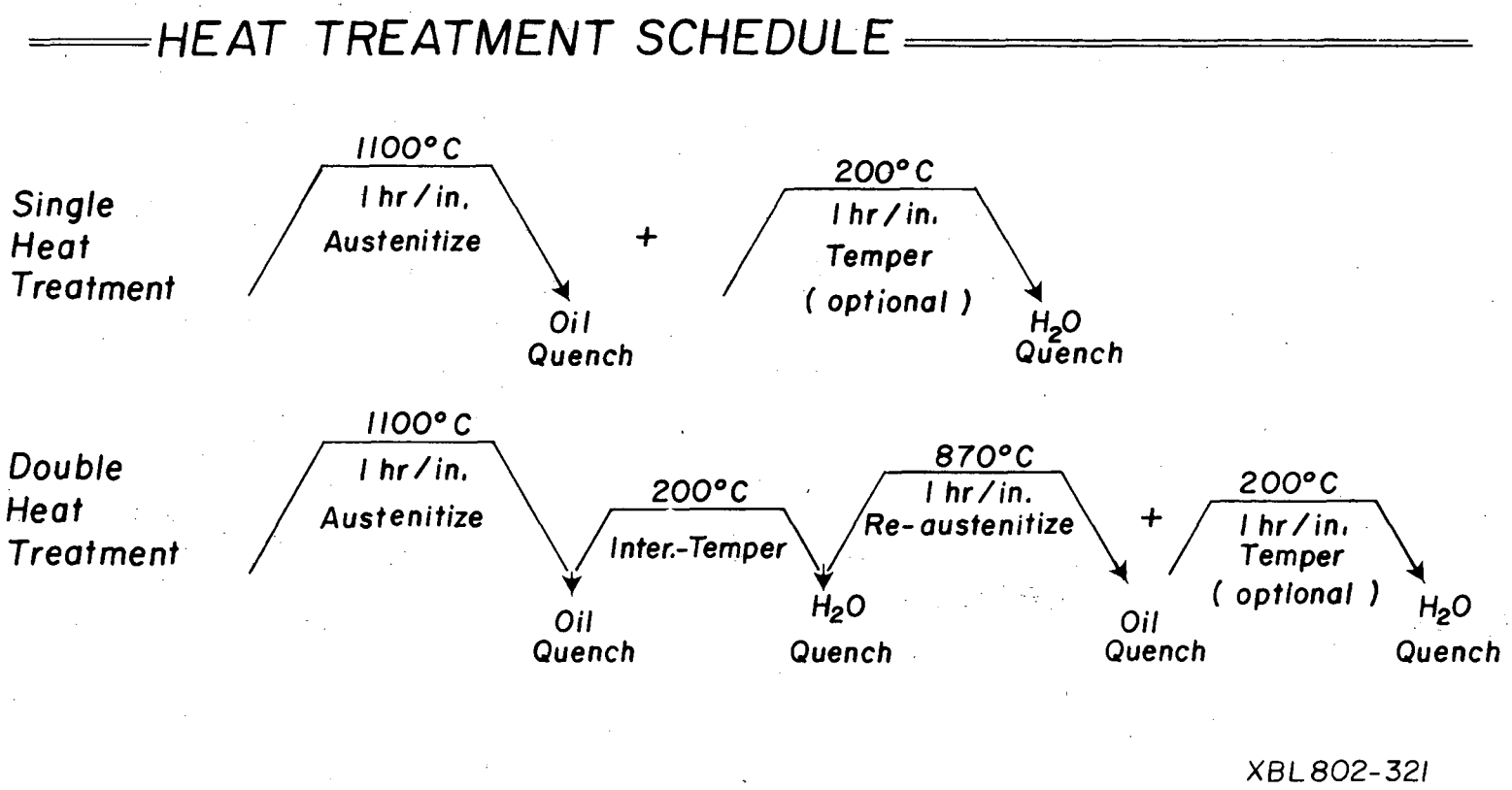

HEAT TREATMENT SCHEDULE
Single Heat Treatment
1100°C
1 hr/in.
Austenitize
Oil Quench
+
200°C
1 hr/in.
Temper
(optional)
H_2O Quench
Double Heat Treatment
1100°C
1 hr/in.
Austenitize
Oil Quench
200°C
Inter.-Temper
H_2O Quench
870°C
1 hr/in.
Re-austenitize
Oil Quench
+
200°C
1 hr/in.
Temper
(optional)
H_2O Quench
XBL 802-321

Fig. 1

WEAR SPECIMEN PREPARATION

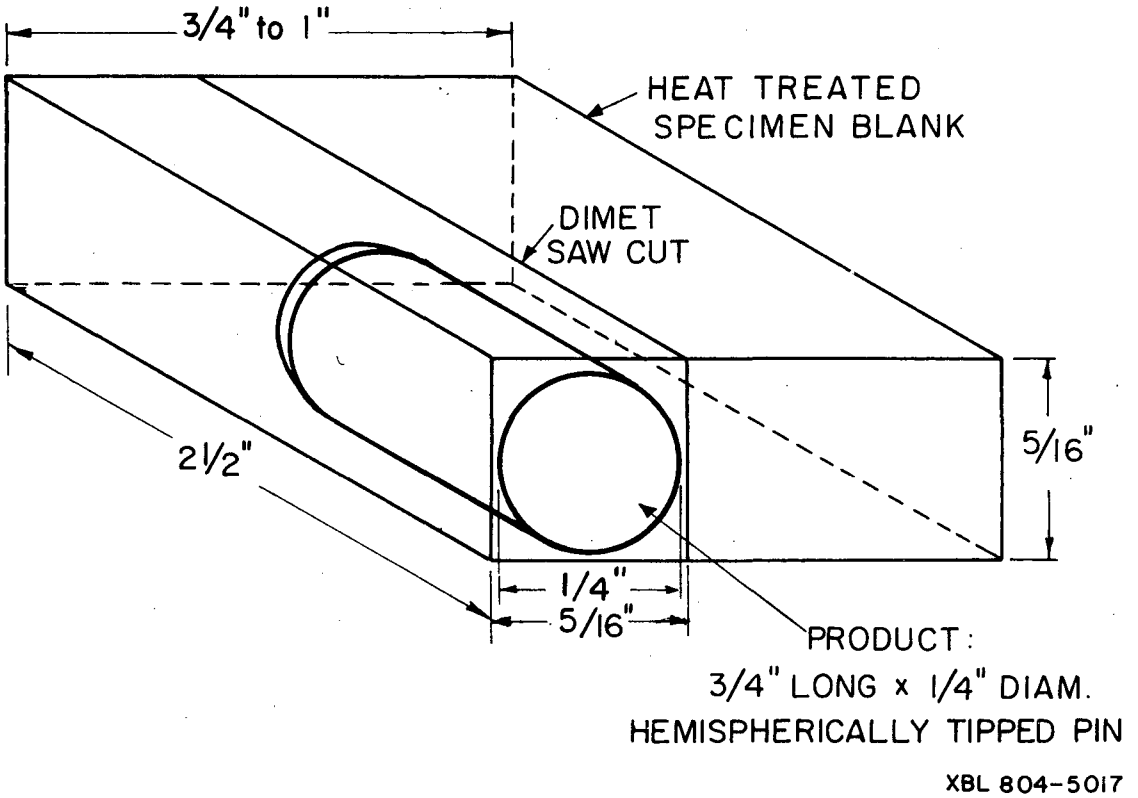
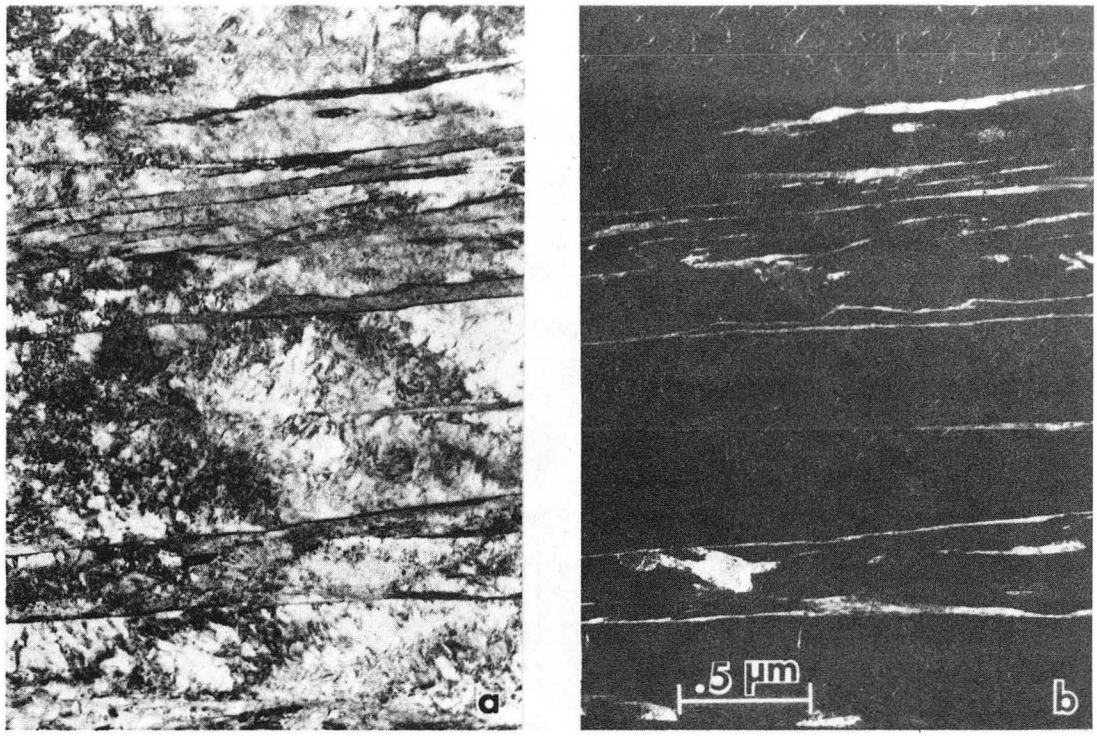
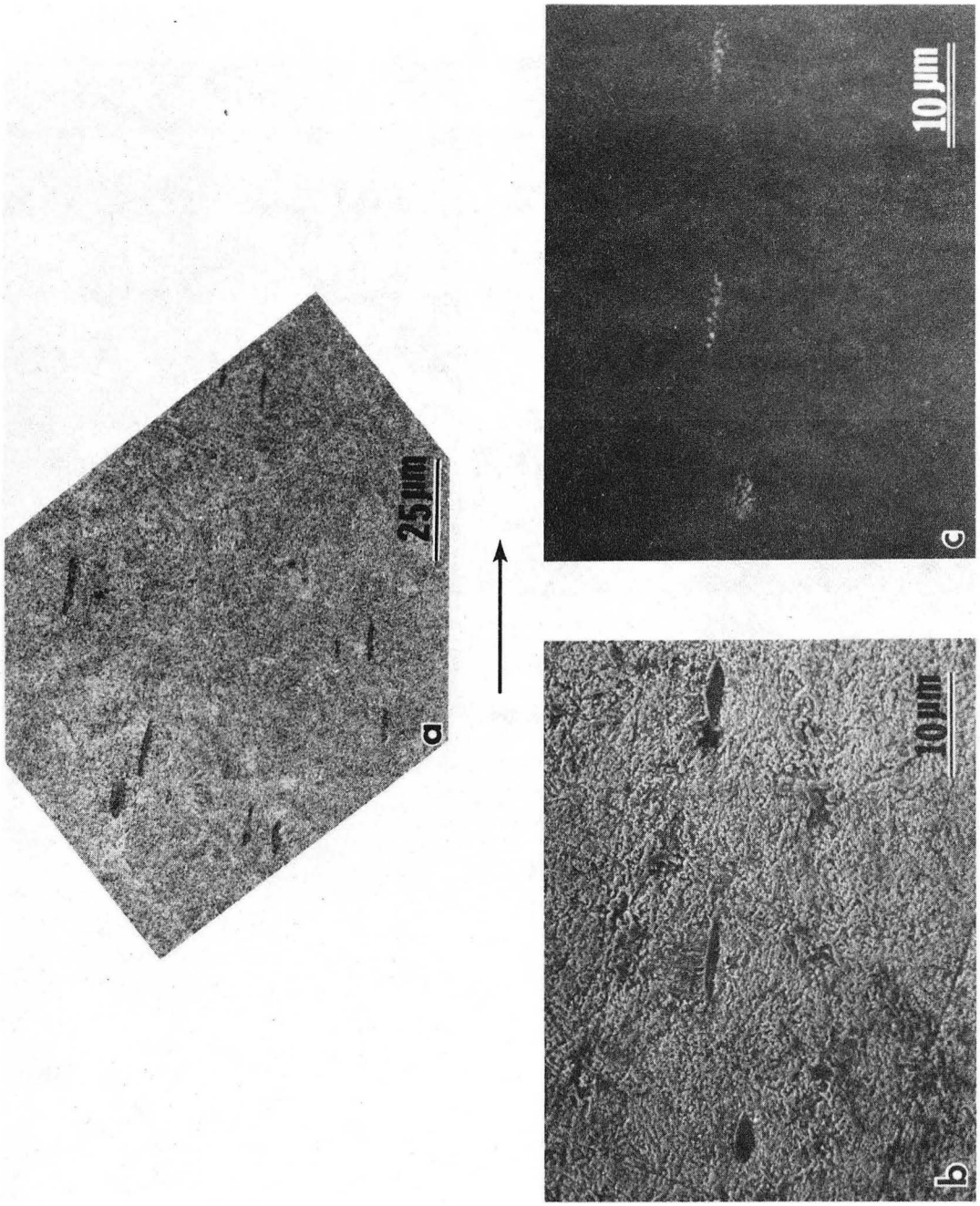


Fig. 2



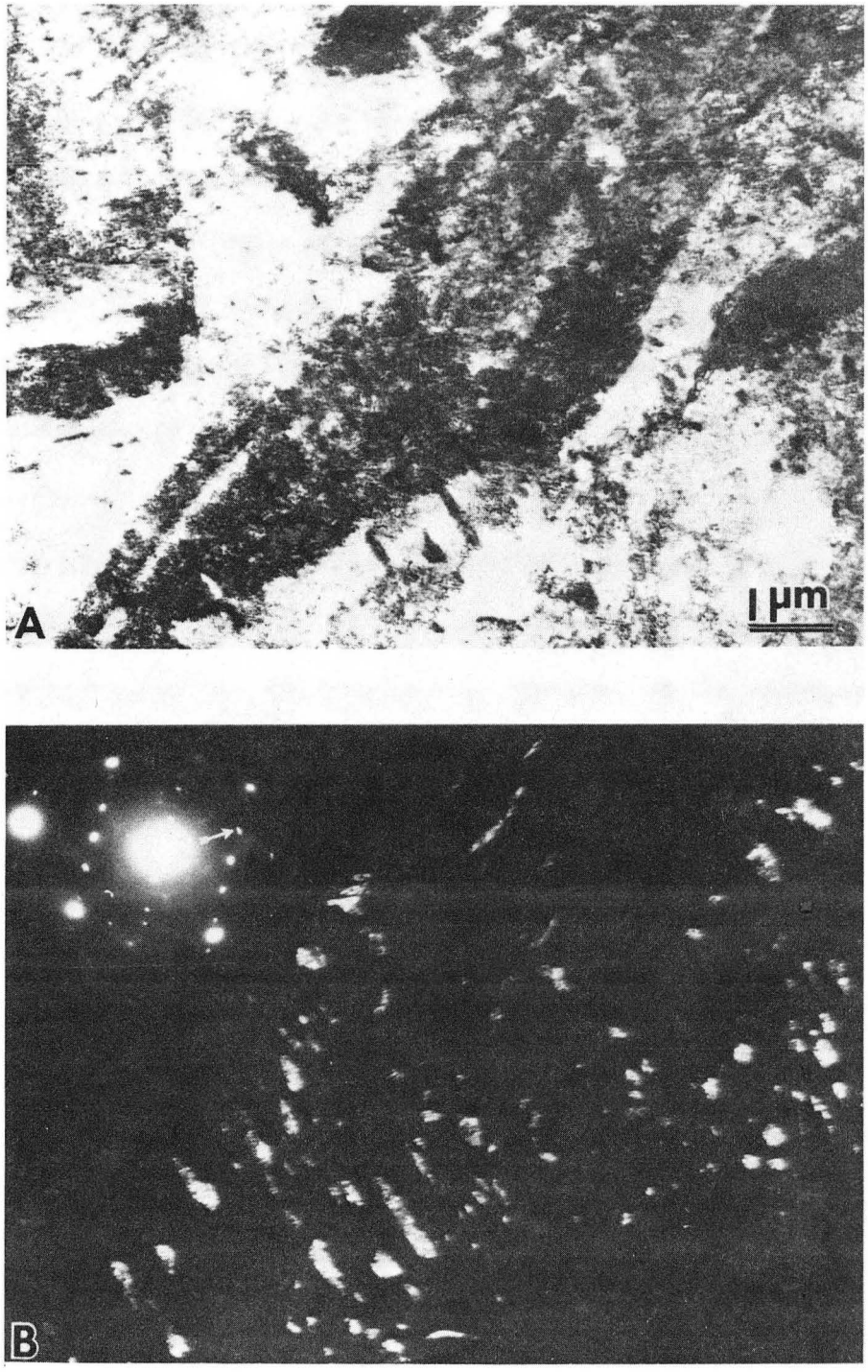
XBB 794-4551

Fig. 3



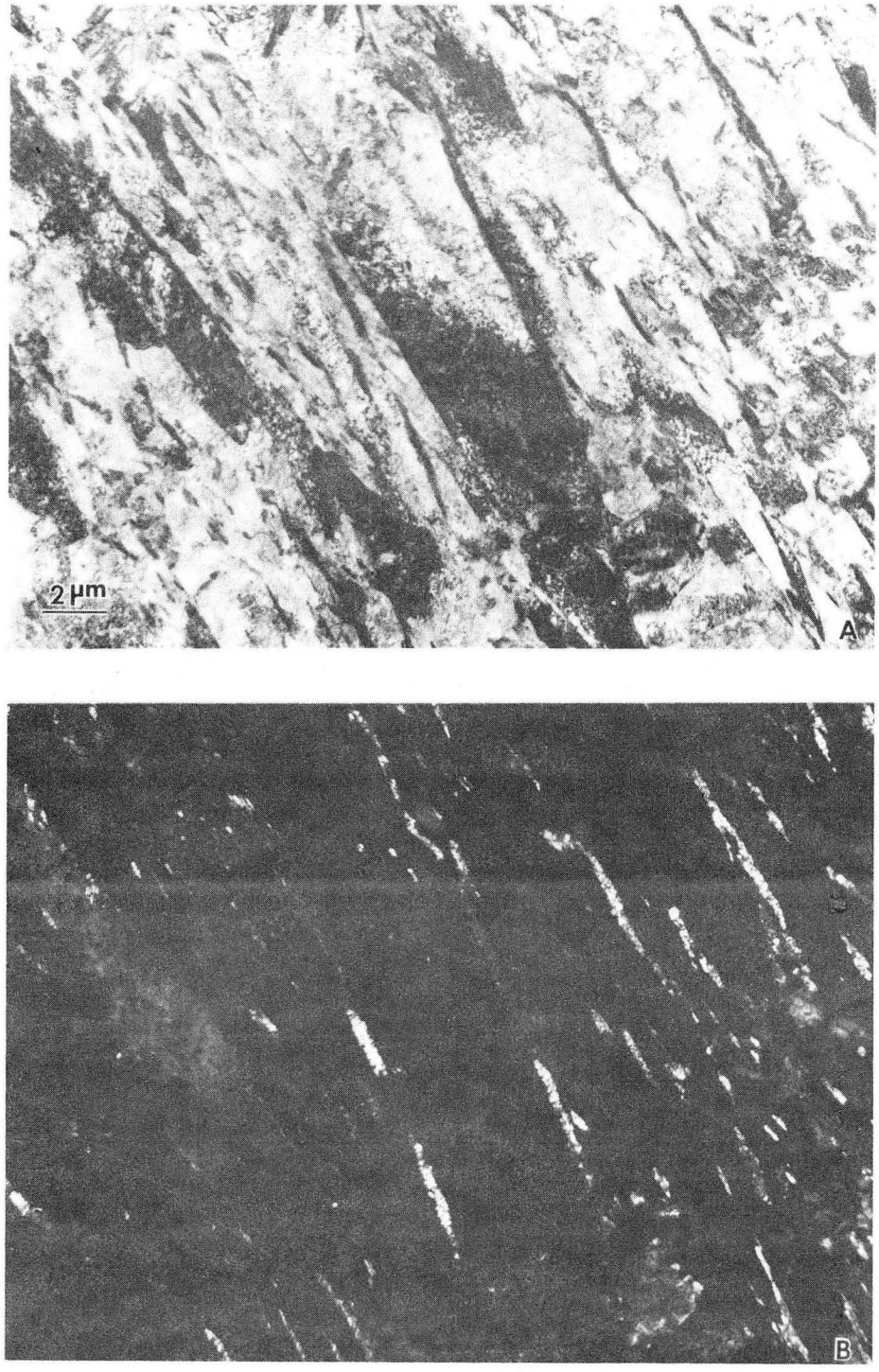
XBB 805-5765

Fig. 4



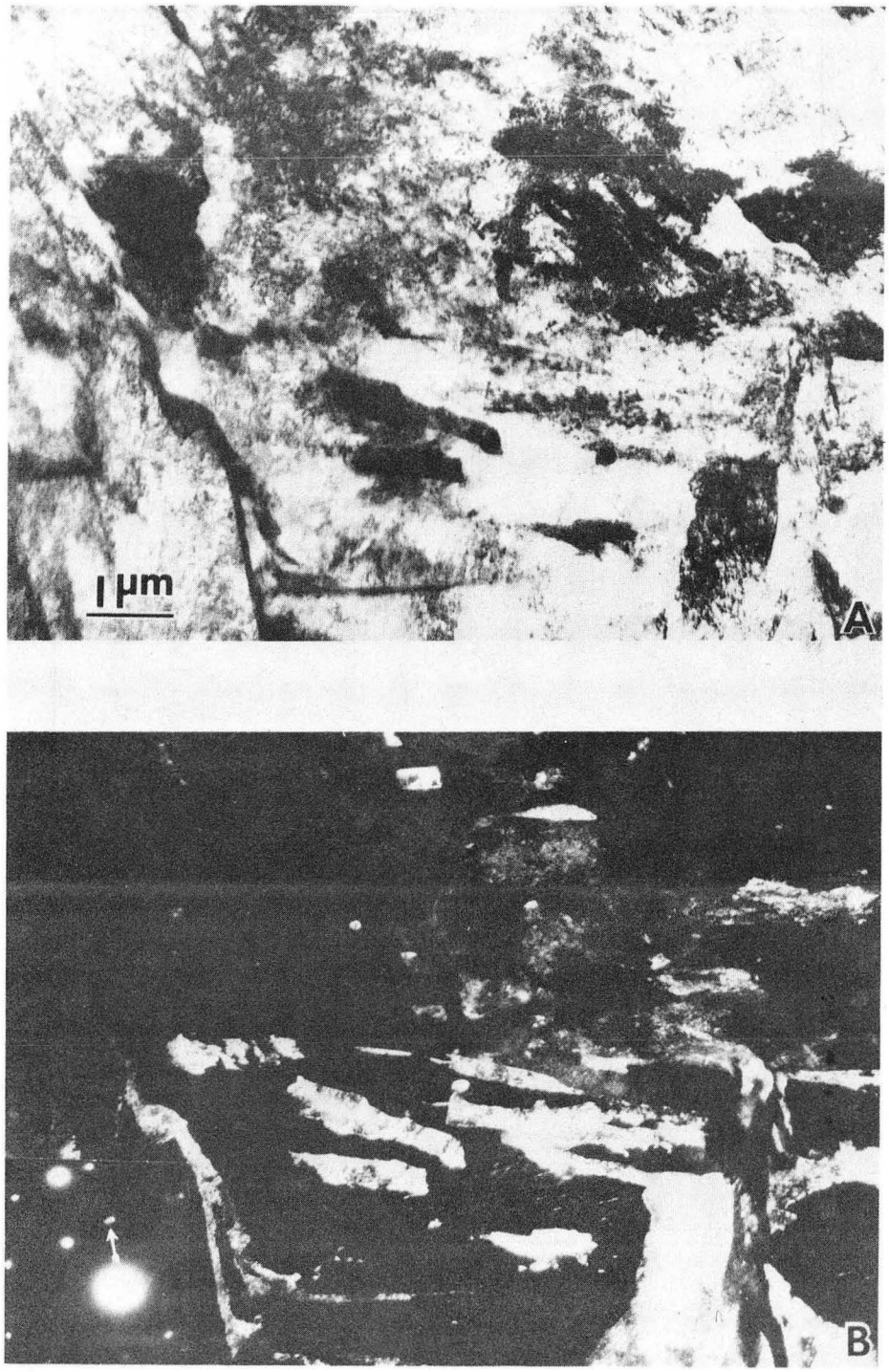
XBB 805-5768

Fig. 5



XBB 805-5771

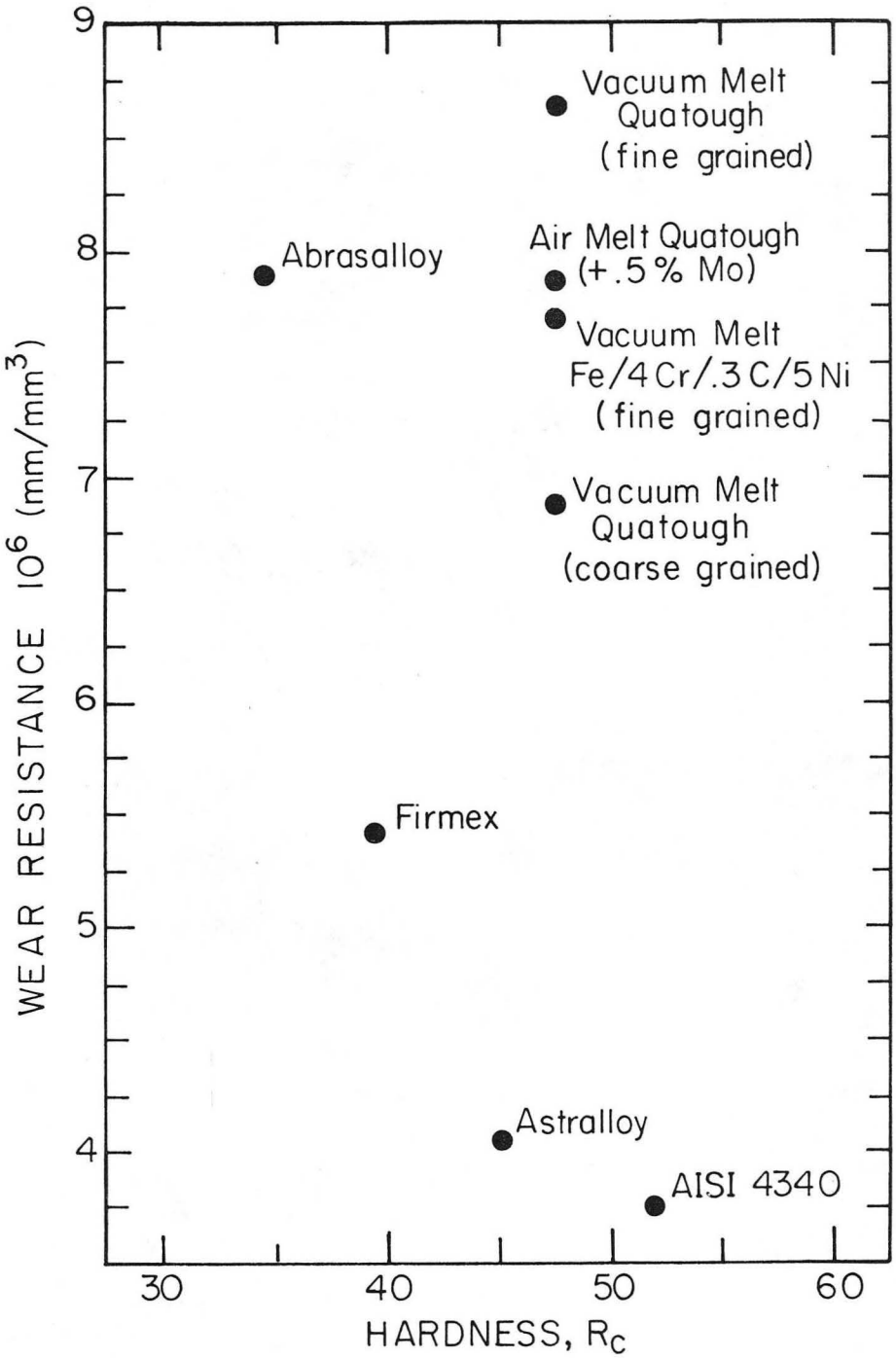
Fig. 6



XBB 805-5770

Fig. 7

EFFECT OF HARDNESS ON WEAR RESISTANCE



XBL 801-4564

Fig. 8

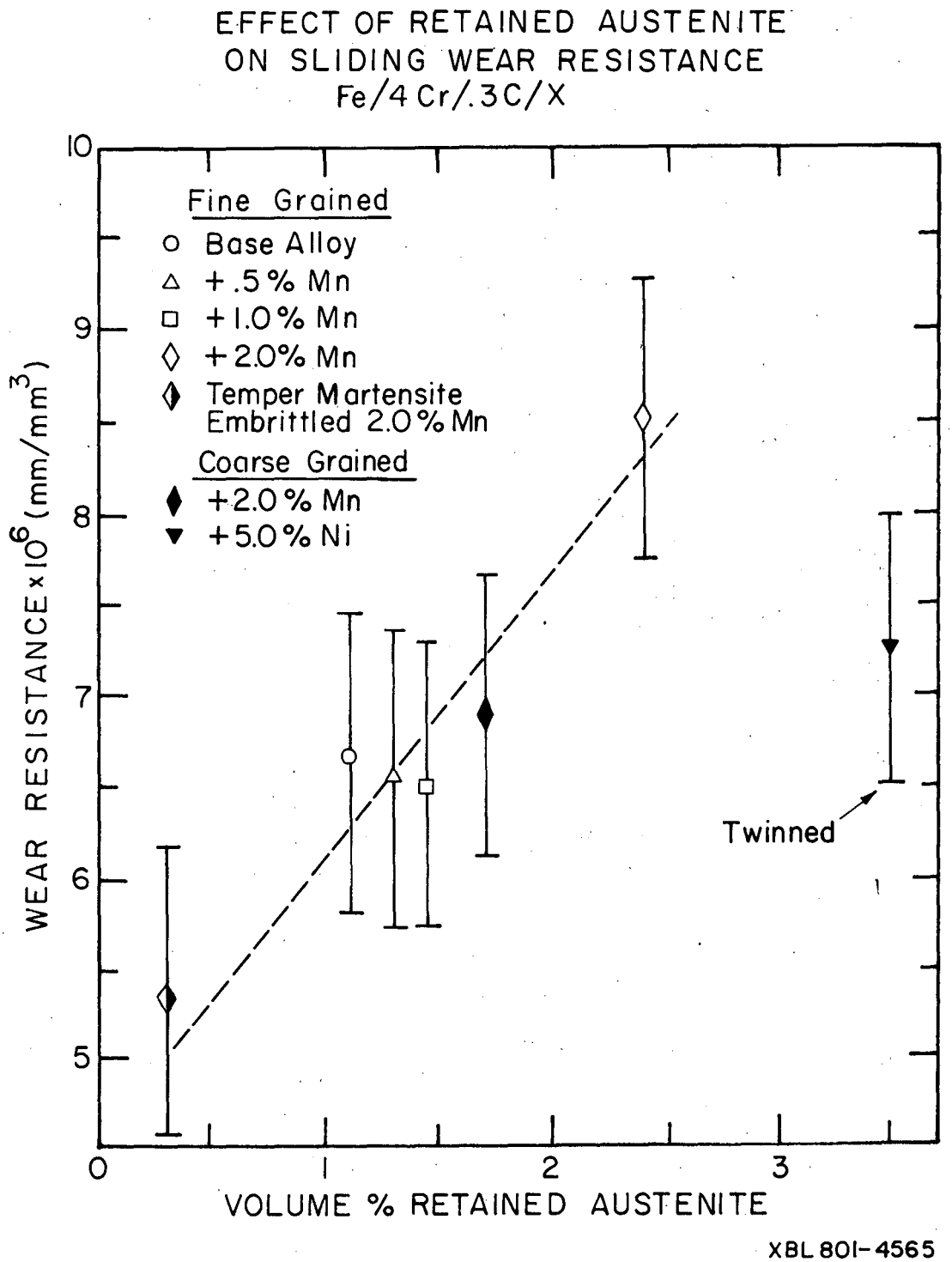
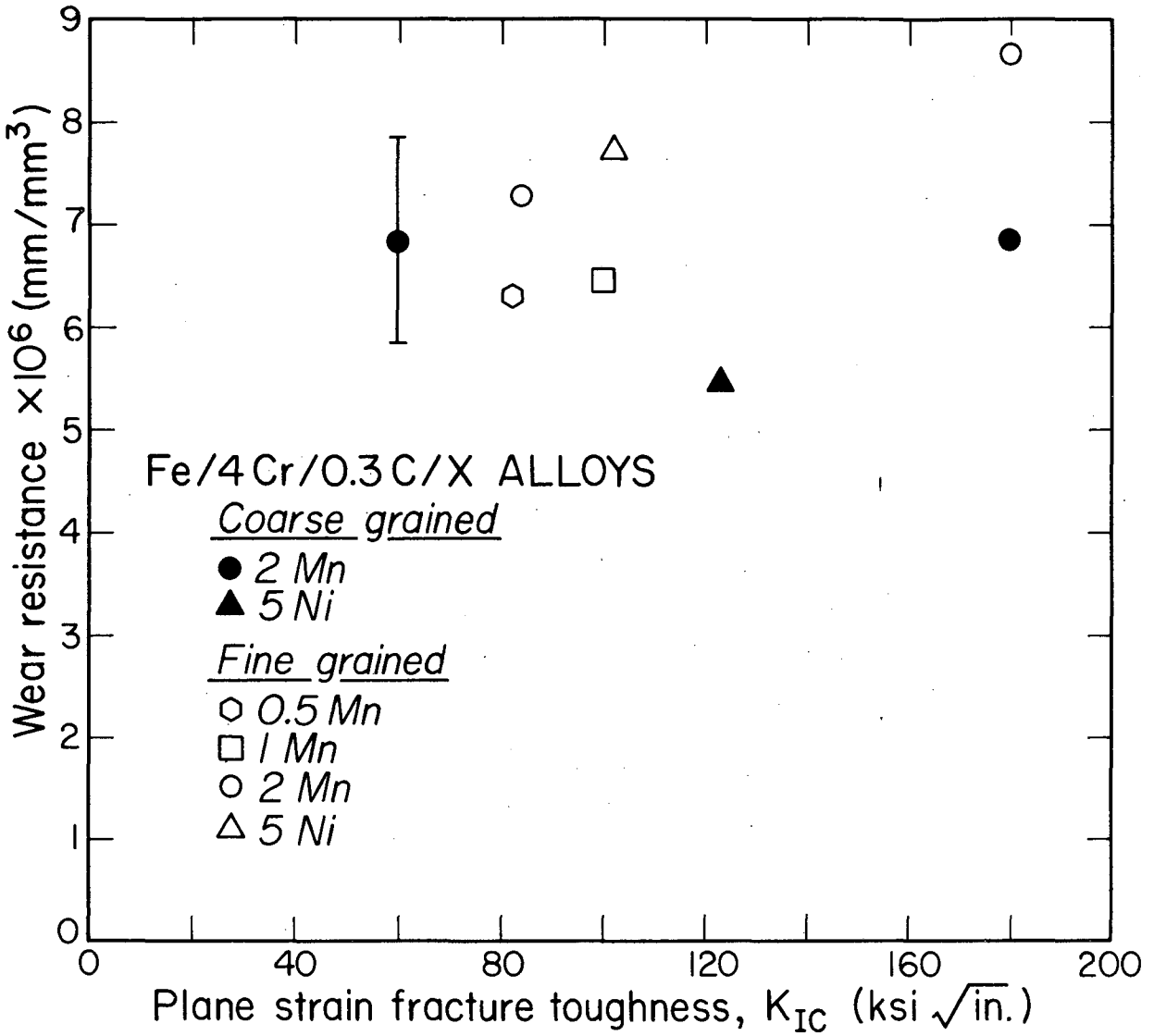
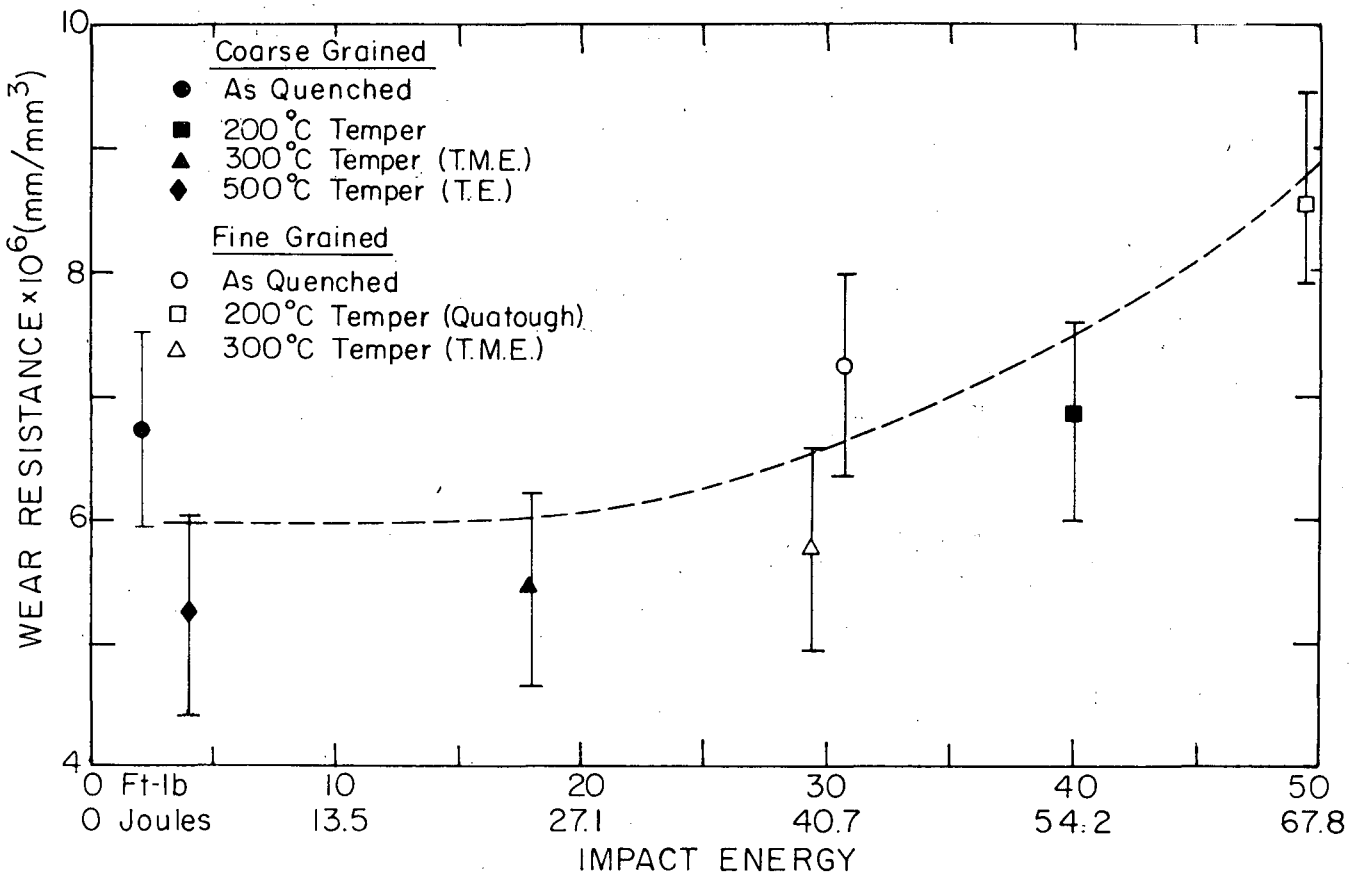

EFFECT OF RETAINED AUSTENITE
ON SLIDING WEAR RESISTANCE
Fe/4 Cr/.3C/X
Fine Grained
Base Alloy
+.5% Mn
+1.0% Mn
+2.0% Mn
Temper Martensite
Embrittled 2.0% Mn
Coarse Grained
+2.0% Mn
+5.0% Ni
Twinned
WEAR RESISTANCE x 10^6 (mm/mm^3)
VOLUME % RETAINED AUSTENITE
10
9
8
7
6
5
0
1
2
3
XBL 801-4565

Fig. 9



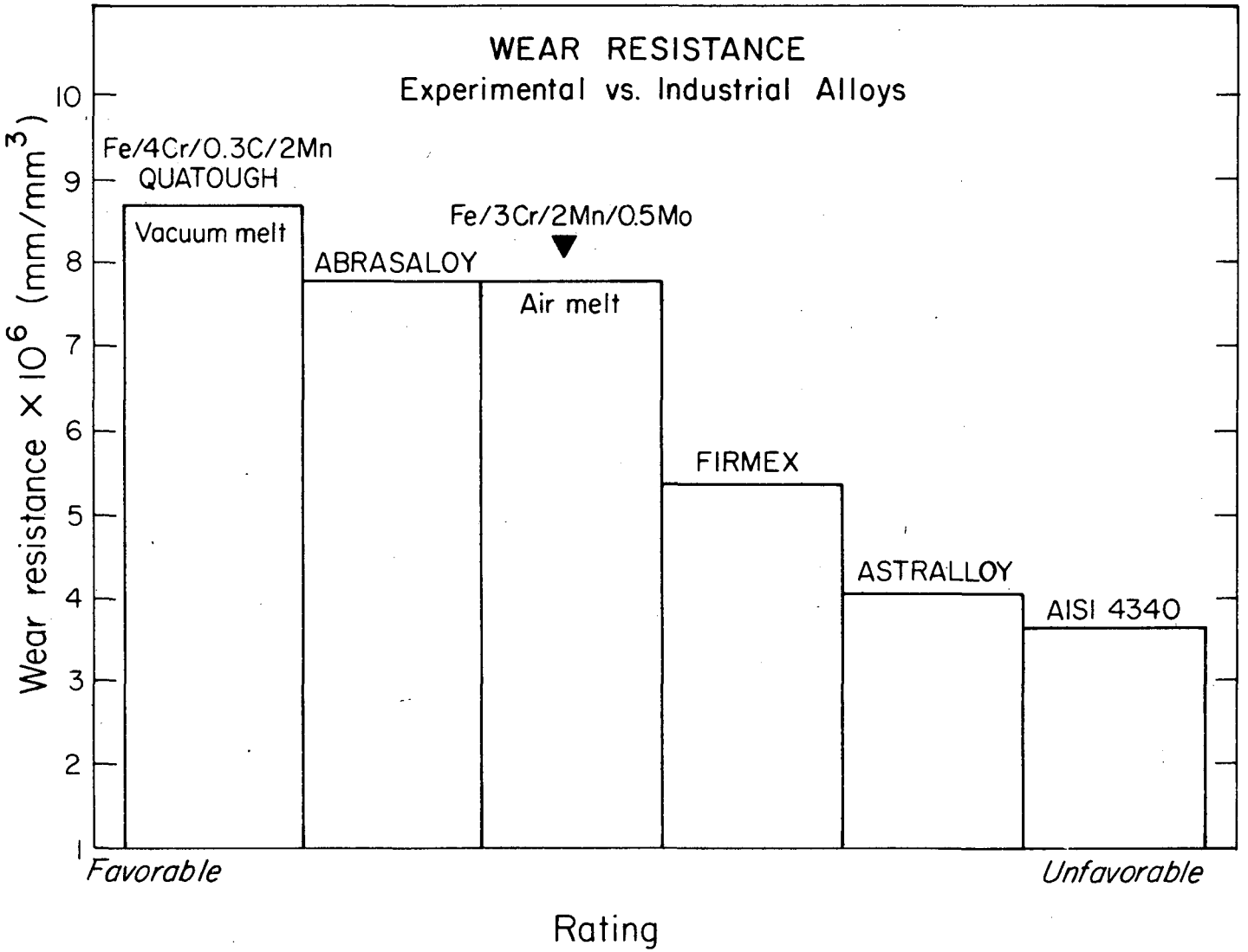
XBL 802-323

Fig. 10



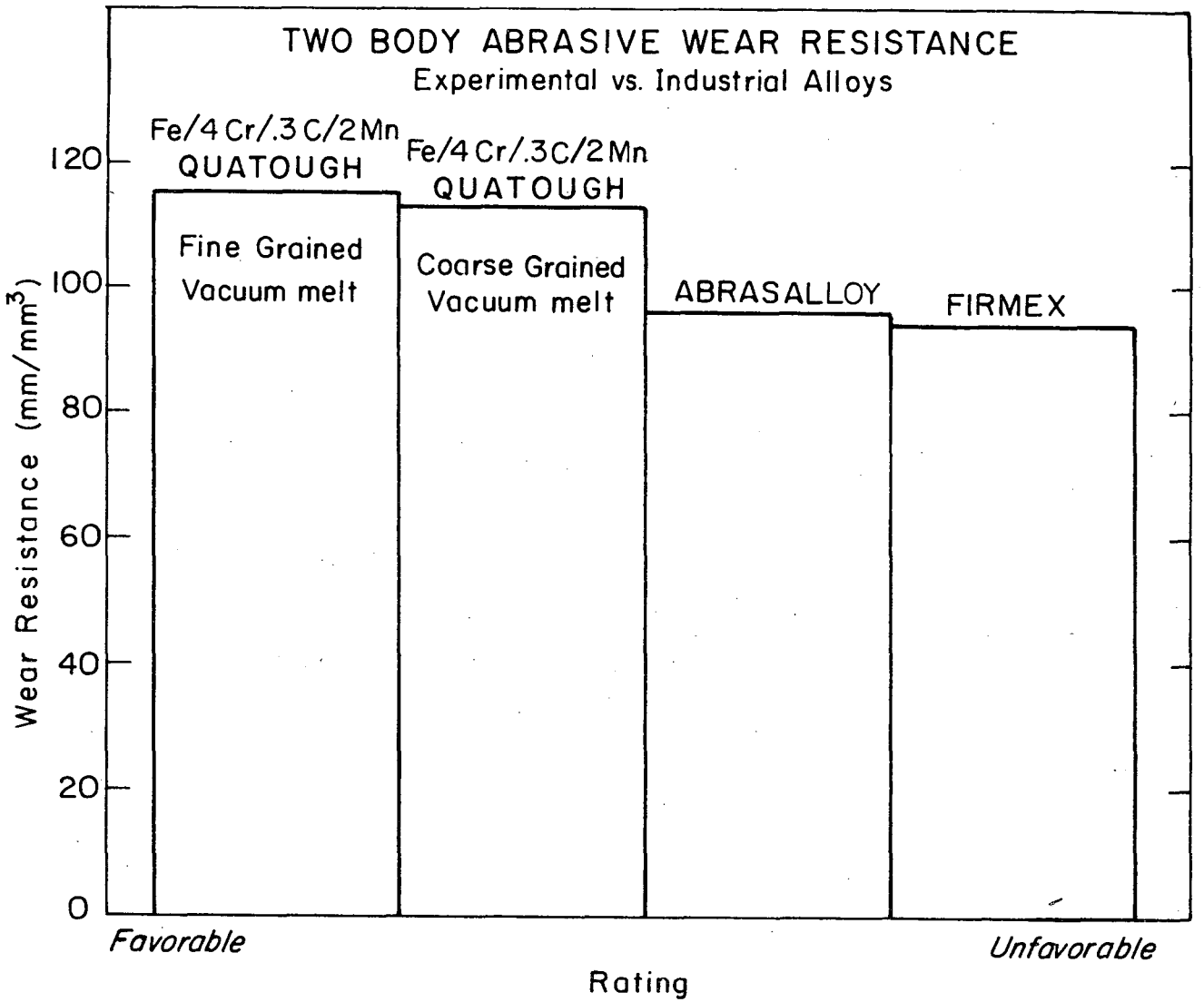
XBL 801-4563

Fig. 11



XBL7911-13211

Fig. 12



XBL 813-8719

Fig. 13

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