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MICROALLOYED STEEL PREFORMS

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Microalloyed Steel	Heat Treatment
Niobium	Forging Reduction
Vanadium	Quench Medium
Test Matrix	Tempering Temperature
Bar Diameter	Mechanical Properties

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analysis was conducted on two types of microalloyed steel to study their metallurgical, mechanical, and processing characteristics, and also to evaluate the suitability of utilizing these alloys as forgings for small gun tube components. The primary benefit associated with these steels is that optimum properties can be attained by direct quenching from the forging temperature. Presently, typical hot forgings must be thermally treated after forging to obtain desired properties.

(CONT'D ON REVERSE)

20. ABSTRACT (CONT'D)

A test matrix was constructed to facilitate examination of the previously stated characteristics. The criteria included alloy type, heat-treatment temperature, forging reduction, tempering temperature, and bar diameter. Test results were compiled in a mechanical property data base that included hardness, tensile and yield strength, impact toughness, and ductile-to-brittle transition temperature. Further evaluation of these data enabled the determination of a desired processing route to achieve optimum properties.

Based on the limited drawing specification requirements of only hardness, it was determined that several different processing combinations could yield acceptable results. However, for optimum properties (hardness), it was found that section thicknesses should be limited to one inch or less. In addition, for optimum processing conditions, it was determined that hot working and tempering operations did not significantly affect material properties.

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INTRODUCTION

The objective of this analysis was to study the metallurgical characteristics, mechanical properties, and processing techniques of microalloyed steel to determine its optimum suitability for forging of small gun tube components. At the time of our investigation, very little data were available on the thermochemical processing techniques or the mechanical properties pertaining to the forging of these alloys. The only existing data pertained to the processing of flat rolled products, and this technology was not applicable to hot forgings. Therefore, it became crucial to properly assess the potential use of microalloyed steel in small forgings.

A comprehensive test matrix (Table I) was established to investigate the critical areas. The various conditions examined included alloy type, heat-treatment temperature, forging reduction, tempering temperature, and bar diameter.

Results obtained from these different test conditions were used to construct a data base of mechanical properties such as hardness, tensile and yield strength, impact toughness, and ductile-to-brittle transition temperature. Subsequently, this information was available for comparison with materials and processes currently employed in production of the small forgings in question.

Overall, the microalloyed steel was evaluated for use in small forgings for which the only criteria required per the drawing specifications were maximum/minimum hardness and adherence to FED-STD-66.

Evaluation of incoming results took place at frequent intervals during the analysis such that in the event substandard material properties were exhibited in comparison to previous test results, the remainder of that test segment was then eliminated from the matrix.

Presently, typical hot forgings must be processed according to the following procedure to attain desired properties: heat treatment, hot working, quenching, and tempering. Although microalloyed steels are somewhat more expensive than the traditionally used alloy steels such as 4140 and 4340, their economic benefits are predicted to be realized in the reduction of processing costs. The main premise behind these reductions is the claim that optimum properties in these microalloyed forgings can be achieved by direct quenching from the forging temperature with no additional processing required, which would be an enormous benefit to Watervliet Arsenal.

BACKGROUND

Microalloying is the process by which small quantities of rare earth elements (less than 5 lb/ton), such as niobium and vanadium, are added to very low carbon, alloy steels. These small additions act to increase the strength and toughness in High Strength Low Alloy (HSLA) rolled steel without increasing the carbon or manganese contents which would induce detrimental mechanical property effects (ref 1). Originally, these steels were developed and employed in the building of the Alaskan pipeline in the late 1960's (ref 2).

Since then, several generations of HSLA microalloyed steels have evolved with applications in new areas, such as hot forgings. Third generation microalloyed steels, which possess properties similar to commercially quenched and tempered steels without additional tempering operations, have found great success in the Japanese and European automotive industries. The similarity between microalloyed and commercially quenched and tempered steels is due to a combination of factors, including nickel additions; composition control; a cold, fast water quench; and a high Mf temperature (38 to 43 Rockwell hardness (HRC)). In general, the forgings are direct quenched from the forging temperature and do not require any special forging practices, with the exception of a water cooling system. This process should yield a product with a microstructure of lath martensite and tempered carbides, possessing a hardness of 38 to 43 HRC with excellent strength and toughness features (ref 2).

EXPERIMENTAL PROCEDURE

The evaluation was performed on niobium-based Chapparal steel, Microtuff 10, and vanadium-based British steel, Vanard, of bar diameters ranging from 1 to 2.5 inches. Three heat-treatment (soak) temperatures of 1652° F (900° C), 1832° F (1000° C), and 2192° F (1200° C) were used. Forging reductions of either zero or 84 percent were used. The quench medium in all instances was water. The tempering temperature was either none or 350° F (177° C).

Material evaluation procedures consisted of the following:

1. Mechanical property testing
    * Rockwell hardness (HRC) testing
    * Tensile testing (0.160)
    * Charpy impact toughness testing
2. Chemical analysis

3. Microstructural evaluation

4. Scanning electron microscopy (SEM)/Energy Dispersive Spectroscopy (EDS)

RESULTS

Mechanical Property Testing

* Rockwell Hardness Testing - Results of the HRC testing are compiled in Table II. As shown by these data, many of the test specimens did attain the required hardness to meet the drawing specifications of the candidate forgings listed in Table III.

The primary problem revealed through this analysis, however, was the inability to maintain uniform hardness in bars of large section size. Data in Table II show that for bars of 1.5 to 2.5 inches, the variations between the hardness at the inner diameter (I.D.) and outer diameter (O.D.) averaged 10 to 15 points on the Rockwell C scale. In one extreme instance the variation was as much as 30 points. It was determined that uniformity of hardness is limited to small section sizes of less than 1.5 inches. Results of testing specimens of this size revealed I.D. and O.D. variations on average of 2 to 4 points on the Rockwell C scale. These results were acceptable and of much greater consistency than the readings from the specimens of larger section thicknesses. In processing these specimens, it was determined that uniformity of hardness increased with increased agitation during the quenching operation. Overall, based on the data from this portion of the analysis, the critical design consideration appeared to be the bar size.

Based on hardness testing results, the preferential processing sequence which will yield results to satisfy the requirements of the drawing specifications would be based on the hardness values obtained. For example, to comply with the 35 to 40 HRC requirement, the optimum hardnesses were those of specimens "K" and "Q." These samples both underwent the 2192° F heat treatment and had a section thickness of 1-inch diameter. Specimen "K" was tempered and specimen "Q" was untempered. Samples that satisfied the 30 to 35 HRC drawing requirements were "G," "H," and "P." All of these test specimens were also heat treated at 2192° F, and were less than 1.5 inches in diameter. All samples were untempered.

As previously stated, elimination in the test matrix took place after certain intervals in the testing procedure. At this point the hardness of the Microtuff 10 ("F") was compared to that of the Vanard ("A"). The hardness of the Microtuff 10 exceeded that of the Vanard by approximately 15 Rockwell C points. Based on the Vanard data, this material would only be applicable to forgings with lower hardness requirements in the range of 25 to 30 HRC. Although there are three candidate forgings in this range, the Microtuff 10 can be processed in such a way as to comply with these requirements. Since hardness is the primary evaluation criterion in this analysis, the Vanard material was subsequently eliminated from the test matrix. Also at this point in the analysis, the effect of forging was evaluated. Based on examination of the hardness data from specimens "G" and "H," which were in the forged and unforged conditions, respectively, it was determined that hot working did not significantly affect properties of the microalloyed steel and thus was also eliminated from the test matrix.

* Tensile Testing - Results of the tensile testing are displayed in Table IV. Although only two of the drawing specifications listed yield strength requirements, we believed it was equally important to establish yield and tensile strength and ductility as part of the data base properties in order to fully characterize the mechanical properties of this material. Overall, many of the specimens did show adequate to good strength levels.

Many parallels existed between these results and those of the hardness testing with respect to the different test conditions. Generally, the larger the section size, the lower the yield and tensile strength levels. In the smaller section-size samples, for the same treatment conditions, the strength levels exceeded those of the larger diameter bars by approximately 30 to 40 Ksi. Like the hardness results, these are also related to the rate of cooling in the bars. Of the specimens tested for strength, the optimum results appeared in samples "G," "H," and "K." All were 1-inch diameter bars and heat treated at 2192° F. The properties of sample "G" were slightly less desirable than sample "H," which was untempered. Sample "K," which was untempered, possessed the highest strength level. In addition, these are the only three samples which met the yield strength requirements of the drawing specifications of the candidate forgings.

* Charpy Impact Toughness Testing - Results of the Charpy impact testing are contained in Table V. Again, although only two of the drawing specifications of the candidate forgings contain toughness requirements, we believe these additional data would enhance our understanding of the properties and characteristics of microalloy steel. Generally, most of the impact values obtained were adequate. Again, many parallels existed between the results obtained from this test and the previous strength and hardness data. As previously discovered, the larger the section size, the lower the impact toughness values. In the bars of smaller section size, the impact toughnesses exceeded those of the larger diameter bars by approximately 3 to 5 ft-lb. Of all the specimens tested for toughness, the sample with the best results, and therefore the optimum processing procedure was specimen "P." Specimen "P" was a 1.5-inch diameter bar, heat treated at 2192° F, and untempered. It was also the only specimen which could satisfy any of the two required toughnesses of the drawing specifications of the candidate forgings.

In addition to the above Charpy impact testing, a ductile-to-brittle transition temperature test was conducted to determine the ductile-to-brittle transition temperature of the Microtuff 10 material.

A 1-inch diameter bar was selected, heat treated at 2192° F, and water quenched. This satisfied the requirements of the drawing specifications and required the least amount of processing. The results are displayed in Figures 1 and 2, which show the ductile-to-brittle transition temperature as approximately 11° F. This is fairly high and may implement a minimum temperature restriction for service conditions of the proposed components.

Chemical Analysis

The results of the chemical analysis are contained in Table VI. As shown, all results are within the limits of the vendor's specifications with the exception of sulfur, which was beyond the limits of experimental deviation. An excess quantity of sulfur was present, consistent with the large proportion and magnitude of manganese-sulfide inclusions present in the microstructure.

Microstructural Evaluation

Figures 3 through 5 illustrate the results of the microstructural examination in the as-polished condition. These photomicrographs clearly reveal the large size and quantity of silicate, oxide, and sulfide inclusions present in the Microtuff 10 material. The quantity of dirt in this material may present a problem with the mechanical performance of components constructed from this material. Specifically, if the inclusion content and magnitude reach critical proportions, mechanical properties may subsequently become eroded as excess dirt is known to reduce the fatigue life, fracture toughness, and ductility of a material.

Several different heat treatments were performed on bar stock of varying section size as listed in Table I. Microstructural results from several select specimens in the etched condition (2 percent nital) are illustrated in Figures 6 through 8. As shown, the microstructures attained at the centers of the bars were dependent on the heat treatments (cooling rate and quench severity) performed and the section size of the bar stock used. The microstructures are characteristic of low alloy steels and contain a combination of martensite and bainite. The coarseness of the grains was determined to vary depending on the test condition (ref 3).

Scanning Electron Microscopy/Energy Dispersive Spectroscopy

Figures 9 through 11 illustrate SEM results of the Charpy impact specimen fracture surfaces. As revealed through these fractographs, the specimens displayed a very flat fracture surface and the characteristic "river patterns" or "tongues" normally associated with cleavage and quasi-cleavage fractures. Features on this order are indicative of low energy, brittle-type failures which are consistent with the relatively low toughness values obtained via the Charpy impact tests.

Figure 12 is an example of one type of included material discovered on the fracture surfaces of the Charpy specimens. Qualitative chemical analysis utilizing EDS determined these inclusions dispersed over the fracture surface to be calcium-aluminum-silicate and manganese-sulfide as shown in Figures 13 and 14.

CONCLUSIONS

Based on the findings of the material evaluation portion of this analysis, there are several combinations of processing conditions which will yield properties sufficient to satisfy the hardness requirements of the candidate forgings. Depending on the requirements of the specific forging, these are (1) 2192° F heat treatment and water quenching in the tempered or untempered condition for 1-inch diameter bar stock, or (2) 2192° F heat treatment and water quenching in the untempered condition for 1 to 1.5-inch diameter bar stock.

Mechanical property data showed that there was little response by the Microtuff 10 to either the forging or tempering operations. When the 84 percent reduction was performed, enhancement of material properties was minimal. In addition, on suggestion from the vendor, the 350° F tempering operation was performed in an effort to increase toughness. However, this also had little effect on the material properties from the untempered condition. Therefore, since these operations either failed to produce significant improvements in material properties or acted to increase manufacturing costs, they were excluded from the optimum processing route.

In retrospect, based on the limited requirements of the drawing specifications of the candidate forgings, which primarily rely on hardness requirements as the basis of selection, many of the test specimens did attain the required hardnesses. However, the limitation to obtaining uniformity of hardness is a section thickness of less than 1.5 inches, with very strong agitation during the quenching operation. Because of these restraining factors, the microalloyed steel should be limited to applications smaller than this section size. Also on the basis of HRC testing, the Vanard material was determined to be inferior to the Microtuff 10 material. In addition, very few of the test specimens were able to conform to the strength and toughness requirements of the two candidate forgings which specified these properties. Many of the specimens did show adequate strength and toughness levels despite a rather high ductile-to-brittle transition temperature.

Additional concern surfaced over the results of the chemical and microstructural portions of the analysis. Sulfur did not meet vendor specifications and was beyond the limits of experimental deviation, thereby causing concern as to the possible detrimental effects on the mechanical performance of the Microtuff 10 material. Also, the inclusion content of the material as revealed by the microstructural evaluation was questionable. The vast quantity of inclusions and also their large size may result in reduced mechanical performance of the material, particularly in the areas of fatigue life and fracture toughness.

Results of the SEM and EDS analyses reinforced the findings of other portions of this evaluation. The fracture surfaces of the Charpy specimens exhibited characteristics of brittle fracture which included cleavage and quasi-cleavage. EDS also confirmed the presence of calcium-aluminum-silicate and manganese-sulfide inclusions found on the fracture surfaces.

RECOMMENDATIONS

Based on the results of our analysis, it is recommended that the Microtuff 10, niobium-based, microalloyed steel be used only for specific applications in which the section size is sufficiently small so that a uniform hardness and microstructure can be attained. It is also recommended that the steel be cleaner and that the chemistry match the vendor designations.

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2. Wright, Peter H., "Microalloyed Forging Steels: A New Generation," Advanced Materials and Processes, Vol. 134, No. 6, December 1988, pp. 23-31, 34.

3. Kou, Sindo, Welding Metallurgy, John Wiley & Sons, New York, 1987, pp. 188-193.

TABLE I. TEST MATRIX

SAMPLE	MATERIAL	HEAT TREATMENT TEMPERATURE (°F)	QUENCH MEDIUM	TEMPER TEMPERATURE (°F)	BAR DIAMETER (IN.)	FORGING REDUCTION (%)
A	Vanard	1652	Water	None	2.0	0
B	Microtuff10	1652	Water	None	2.5	0
C	Microtuff10	1832	Water	None	2.5	0
D	Microtuff10	1832	Water	350	2.5	0
F	Microtuff10	1652	Water	None	2.0	0
G	Microtuff10	2192	Water	None	1.0	84
H	Microtuff10	2192	Water	None	1.0	0
J	Microtuff10	2192	Water	350	1.0	84
K	Microtuff10	2192	Water	350	1.0	0
P	Microtuff10	2192	Water	None	1.5	0
Q	Microtuff10	2192	Water	None	1.0	0
R	Microtuff10	2192	Water	None	2.5	0
S	Microtuff10	2192	Water	None	2.0	0

TABLE II. ROCKWELL HARDNESS VALUES

SAMPLE	AVERAGE HRC	RANGE (I. D. - O. D.)
A	27.0	19.4 - 35.0
B	30.4	24.5 - 35.7
C	30.3	27.7 - 34.5
D	31.1	28.2 - 36.4
F	42.2	31.6 - 61.2
G	36.5	33.4 - 38.0
H	37.0	36.1 - 38.2
J	21.4	20.2 - 22.3
K	37.8	36.8 - 40.9
P	36.1	32.5 - 42.1
Q	39.5	38.2 - 40.1
R	32.3	25.1 - 38.5
S	36.7	31.9 - 41.1

TABLE III. CANDIDATE FORGINGS

DRAWING #	TITLE	YIELD STRENGTH (KSI)	ROCKWELL HARDNESS	IMPACT TOUGHNESS (-40°F)	WEAPON SYSTEM
11579671	Shaft (Forging)		35/41 HRC		155-mm M185
11579779	Plug (Forging)		30/37 HRC		81-mm M29A1
12529651	Extractor Forging, Right		35/40 HRC		120-mm M256
12529657	Extractor Forging, Left		35/40 HRC		120-mm M256
7144210 DF	Guide, Expanding Pin		35/41 HRC		4.2 Mortar Mount M24A1
8765657 DF	Lever		25/32 HRC		105-mm M68
8765808 DF •	Body - Extractor		27 MAX HRC		105-mm M68
8765811 DF	Crank	140 - 170	35/40 HRC	15 ft-lb	105-mm M68
8767087 DF	Bar		27 MAX HRC		How 155-mm MN126
8768866 DF	Bearing		80/100 HRB		4.2 Mortar Mount M24A1
8769203 DF	Hub		30/36 HRC		165-mm M135
1157805 DF	Adjustor		30/36 HRC		155-mm M126E1
11578240 DF	Barrel Ring		35/41 HRC		81-mm M29A1
11578902 DF	Head		25/31 HRC		155-mm M199
11578376	Collar		35/41 HRC		155-mm M185
11577221	Cap, Tube	125 - 150		35 MIN ft-lb	4.2 Mortar

TABLE IV. TENSILE TEST VALUES

SAMPLE	AVERAGE YIELD STRENGTH (0.2% OFFSET) (KSI)	YIELD STRENGTH RANGE (0.2% OFFSET) (KSI)	AVERAGE ULTIMATE TENSILE STRENGTH (KSI)	ULTIMATE TENSILE STRENGTH RANGE (KSI)	AVERAGE % REDUCTION IN AREA	RANGE % REDUCTION IN AREA
A	91.1	88.9 - 94.9	141.8	136.8 - 148.4	55.0	51.8 - 56.6
B	92.2	84.2 - 100.5	132.1	125.1 - 132.1	N/A	N/A
C	104.7	89.5 - 117.2	148.1	133.3 - 161.0	N/A	N/A
D	104.8	93.8 - 115.8	142.0	128.4 - 157.0	N/A	N/A
F	N/A	N/A	N/A	N/A	N/A	N/A
G	133.2	130.3 - 137.2	187.1	185.6 - 187.7	55.14	48.6 - 59.2
H	137.5	135.7 - 139.3	181.5	179.2 - 183.9	55.2	53.6 - 56.8
J	76.1	74.8 - 77.5	125.1	122.3 - 127.6	52.4	49.0 - 54.3
K	140.9	140.0 - 141.8	180.9	180.8 - 180.9	58.2	58.2

TABLE V. CHARPY IMPACT TOUGHNESS VALUES

SAMPLE	AVERAGE IMPACT TOUGHNESS (FT-LB)	RANGE (FT-LB)
A	8.8	6.5 - 12.0
B	10.0	9.0 - 12.0
C	9.7	9.0 - 11.0
D	13.3	10.0 - 14.0
F	3.3	2.0 - 4.0
G	13.6	12.0 - 16.0
H	11.5	11.5
J	4.9	4.5 - 5.0
K	12.5	12.0 - 13.0
P	15.6	14.5 - 16.5
R	8.7	6.5 - 11.5
S	11.5	9.0 - 12.5

TABLE VI. CHEMICAL ANALYSIS (WT%)

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Nb
VENDOR* - HEAT ANALYSIS	0.13	1.74	0.017	0.030	0.59	0.35	0.15	0.12	0.21	0.10
VENDOR* - SPECIFICATION	0.10/0.15	1.65/2.00	0.03 max	0.03 max	0.50/0.70	0.35 max	0.20 max	0.20 max	0.15/0.20	N/A
BENET LABORATORIES	0.11	1.74	0.015	0.043	0.60	0.32	0.10	0.12	0.20	0.10

*CHAPPARAL STEEL

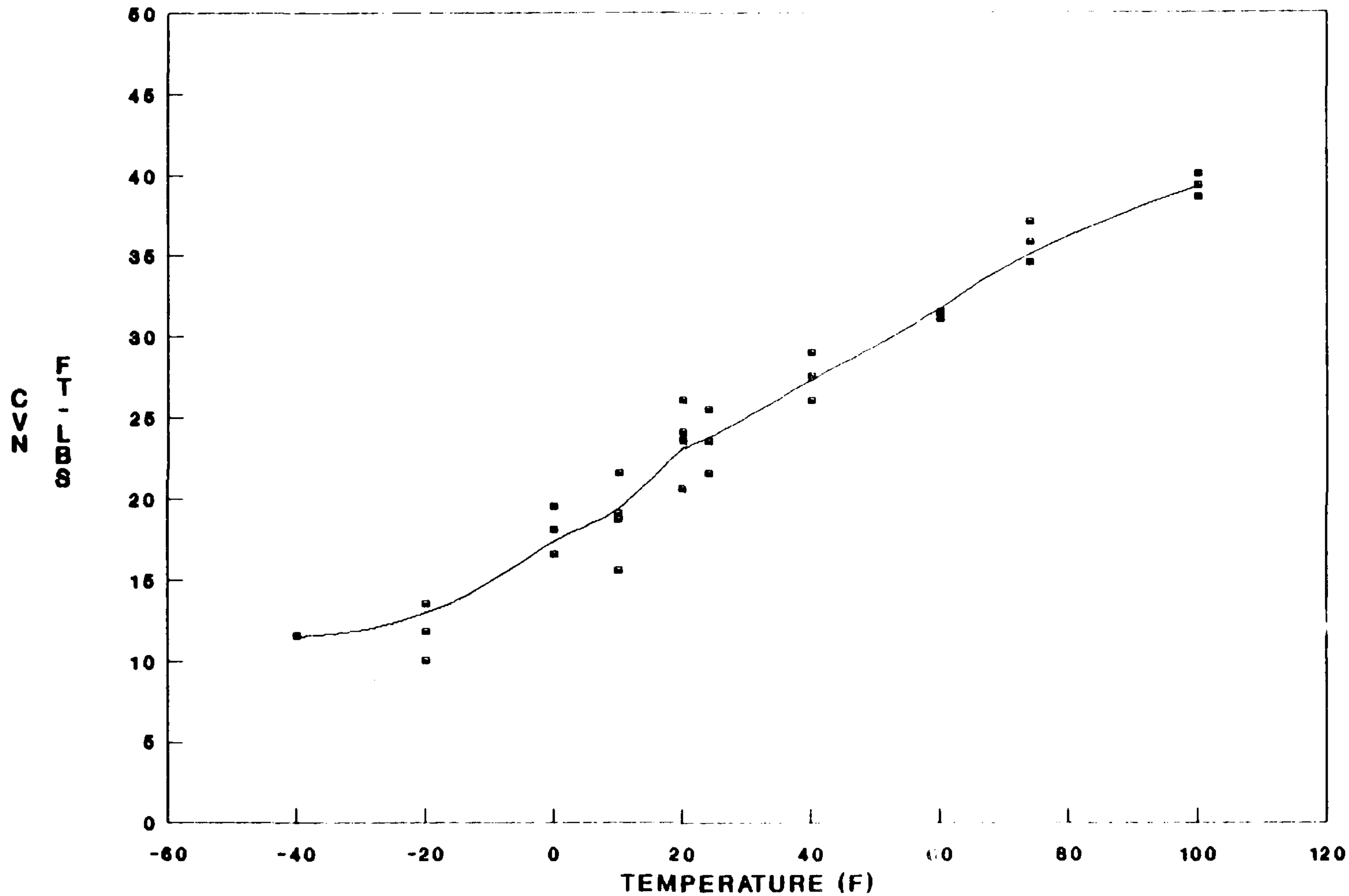


Figure 1. Ductile-to-brittle transition temperature curve for Microtuff 10 material

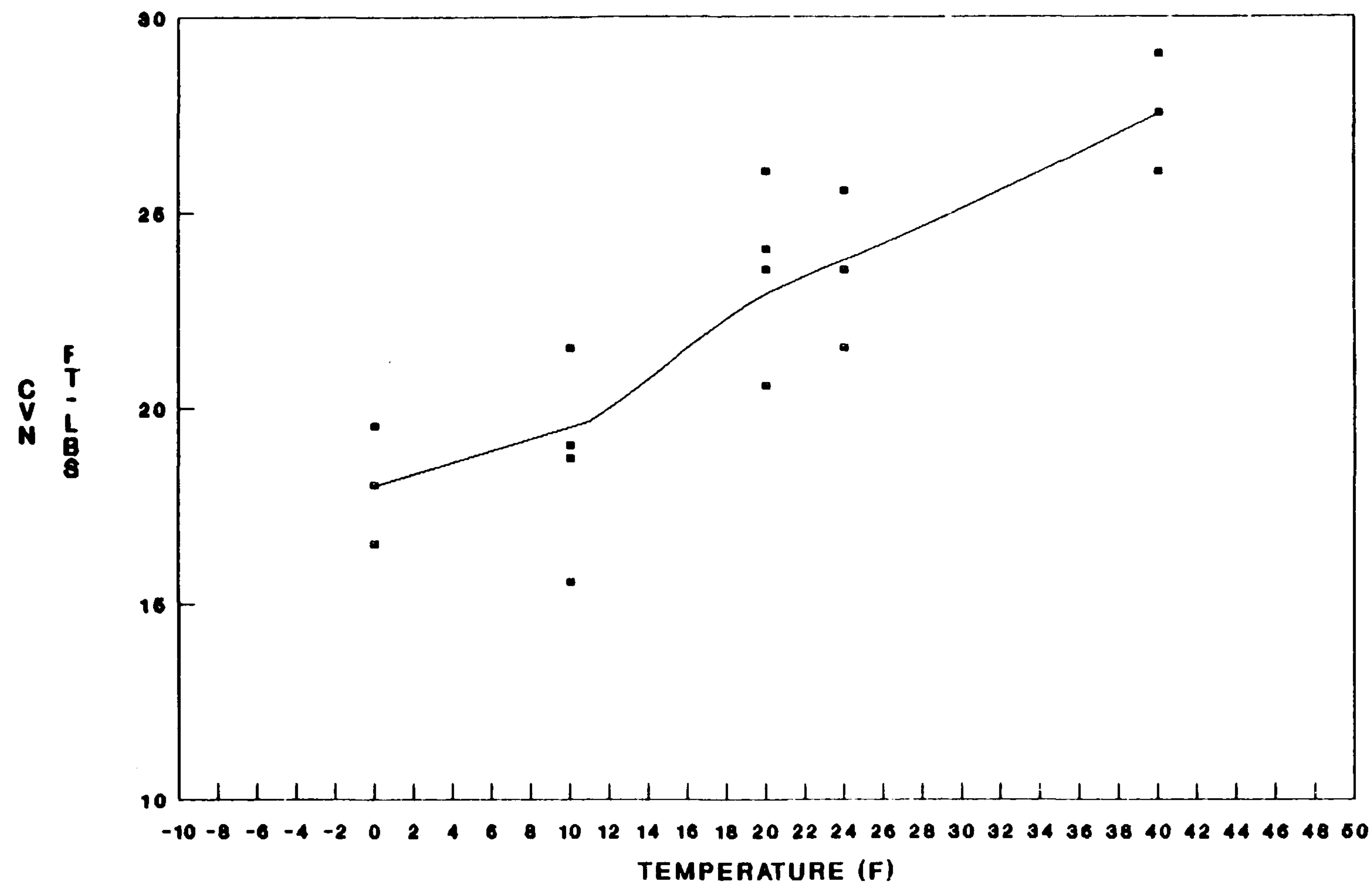


Figure 2. Expanded transition temperature range.

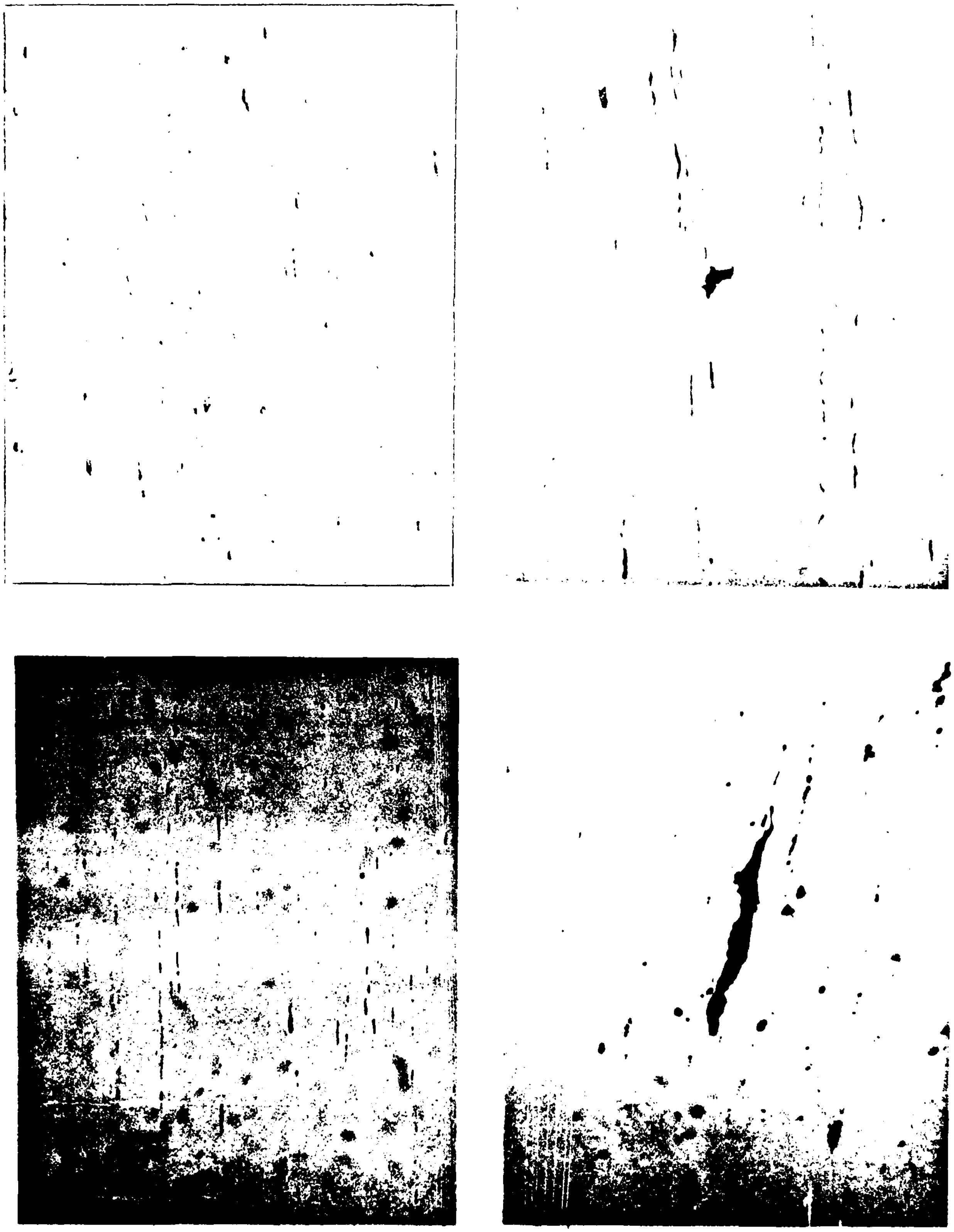


Figure 3. Photomicrographs illustrating inclusions in Microtuff 10 material, as-polished (100X).

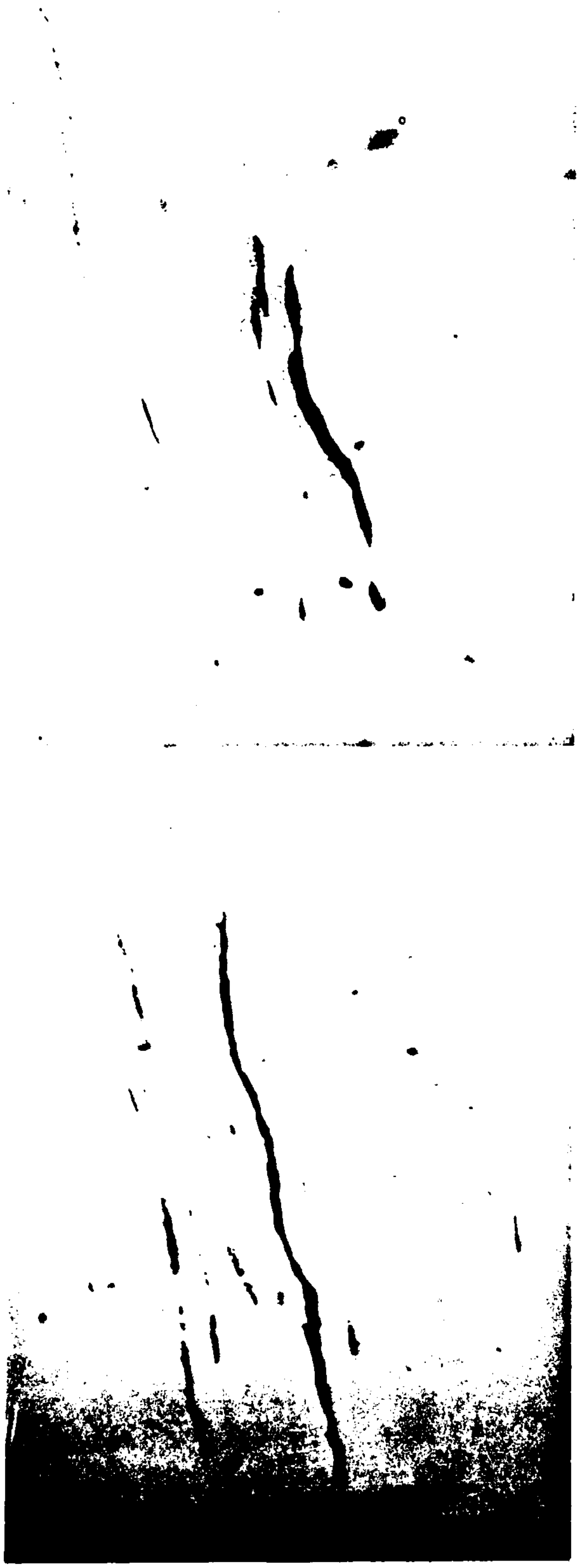


Figure 4. Manganese-sulfide stringers, as-polished (400X).

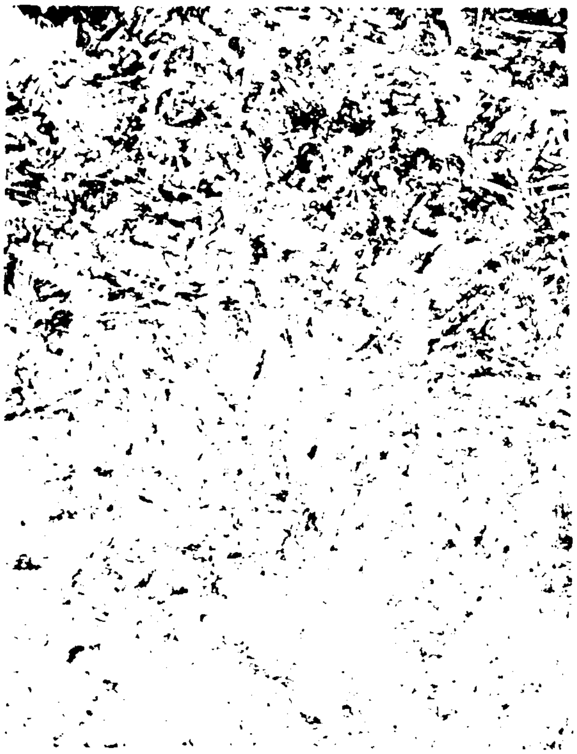
Figure 5. Oxide inclusions, as-polished (400X).

(a) Sample "C"

(b) Sample "G"

(c) Sample "K"

Figure 6. Photomicrographs illustrating microstructures of samples "C," "G," and "K" respectively (100X, 2% nital).



(a) Sample "C"

(b) Sample "G"

(c) Sample "K"

Figure 7. Photomicrographs illustrating microstructures of samples "C," "G," and "K" respectively (400X, 2% nital).

(a) Sample "C"

(b) Sample "G"

(c) Sample "K"

Figure 8. Photomicrographs illustrating microstructures of samples "C," "G," and "K" respectively (1000X, 2% nital).

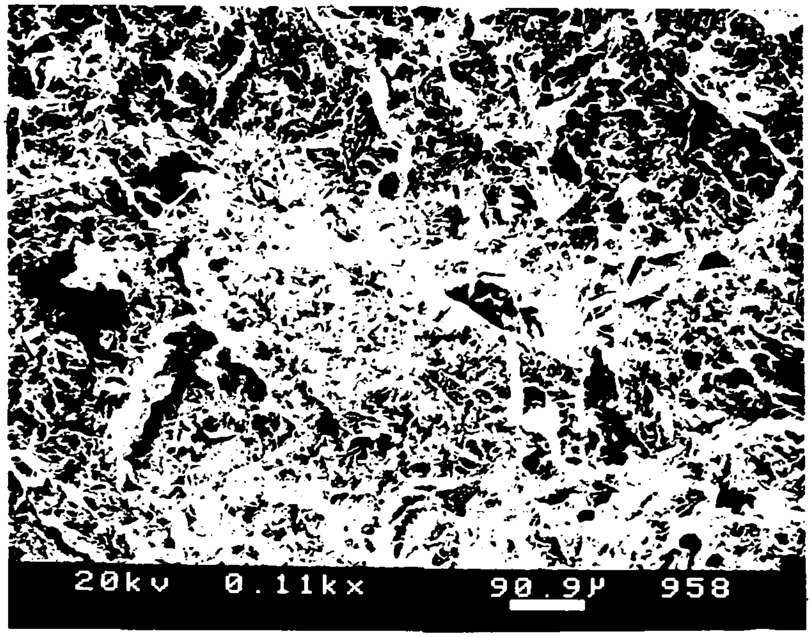


Figure 9. Fractograph of Charpy V-notch specimen revealing characteristic cleavage and quasi-cleavage features of brittle failure (110X).

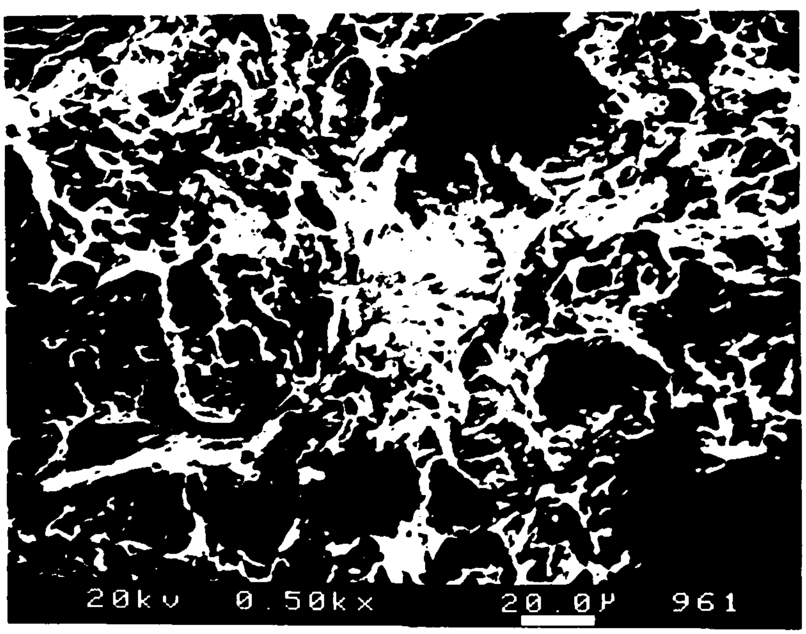


Figure 10. Fractograph of Charpy V-notch specimen revealing characteristic cleavage and quasi-cleavage features of brittle failure (500X).

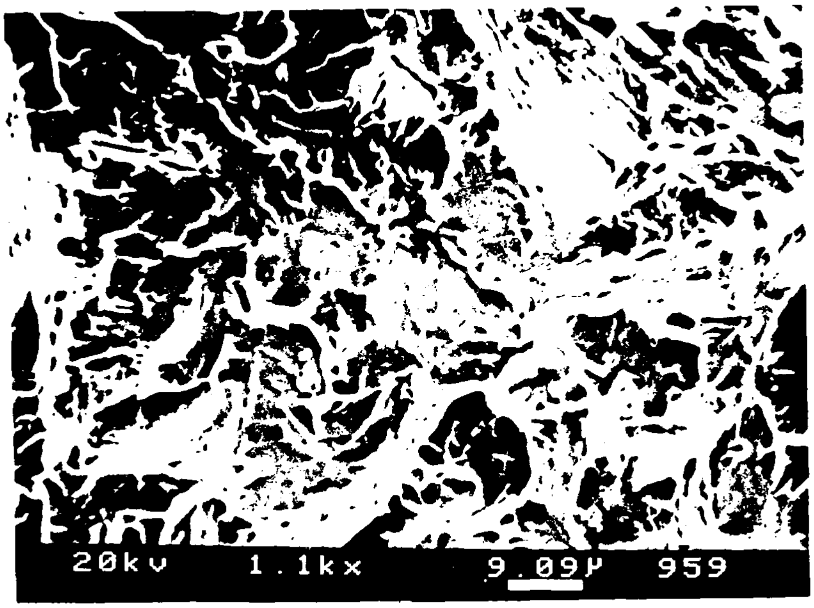


Figure 11. Fractograph revealing cleavage and quasi-cleavage features (200X).

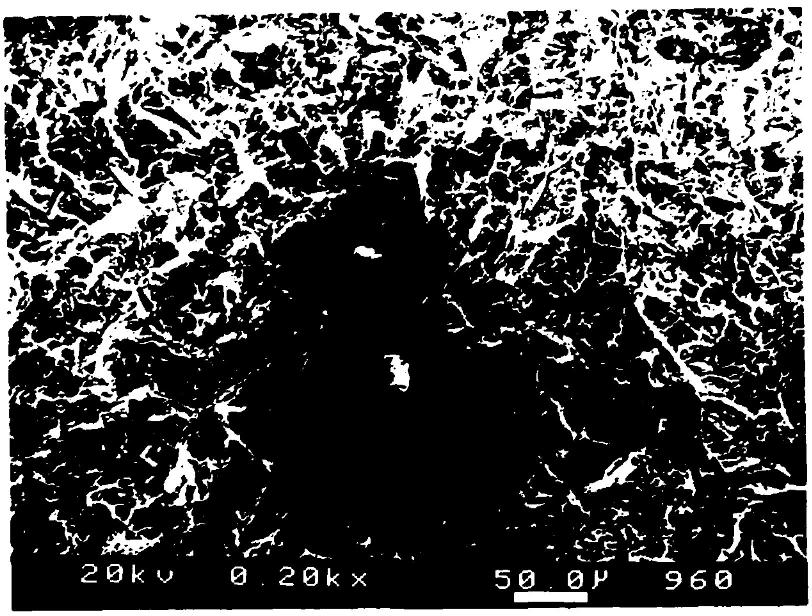


Figure 12. Included material discovered on fracture surface (200X).

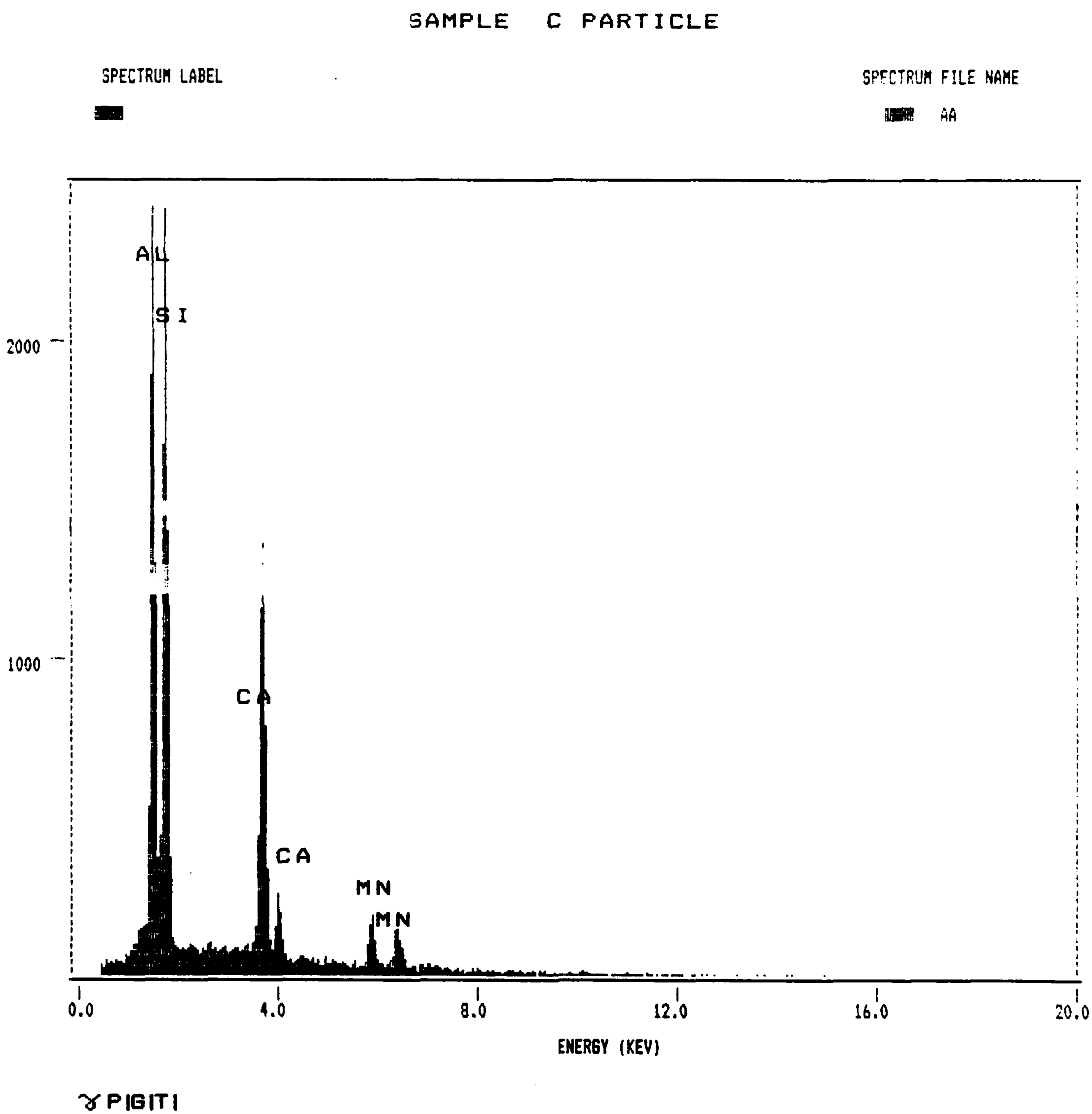


Figure 13. EDS analysis of sample "C" included material.

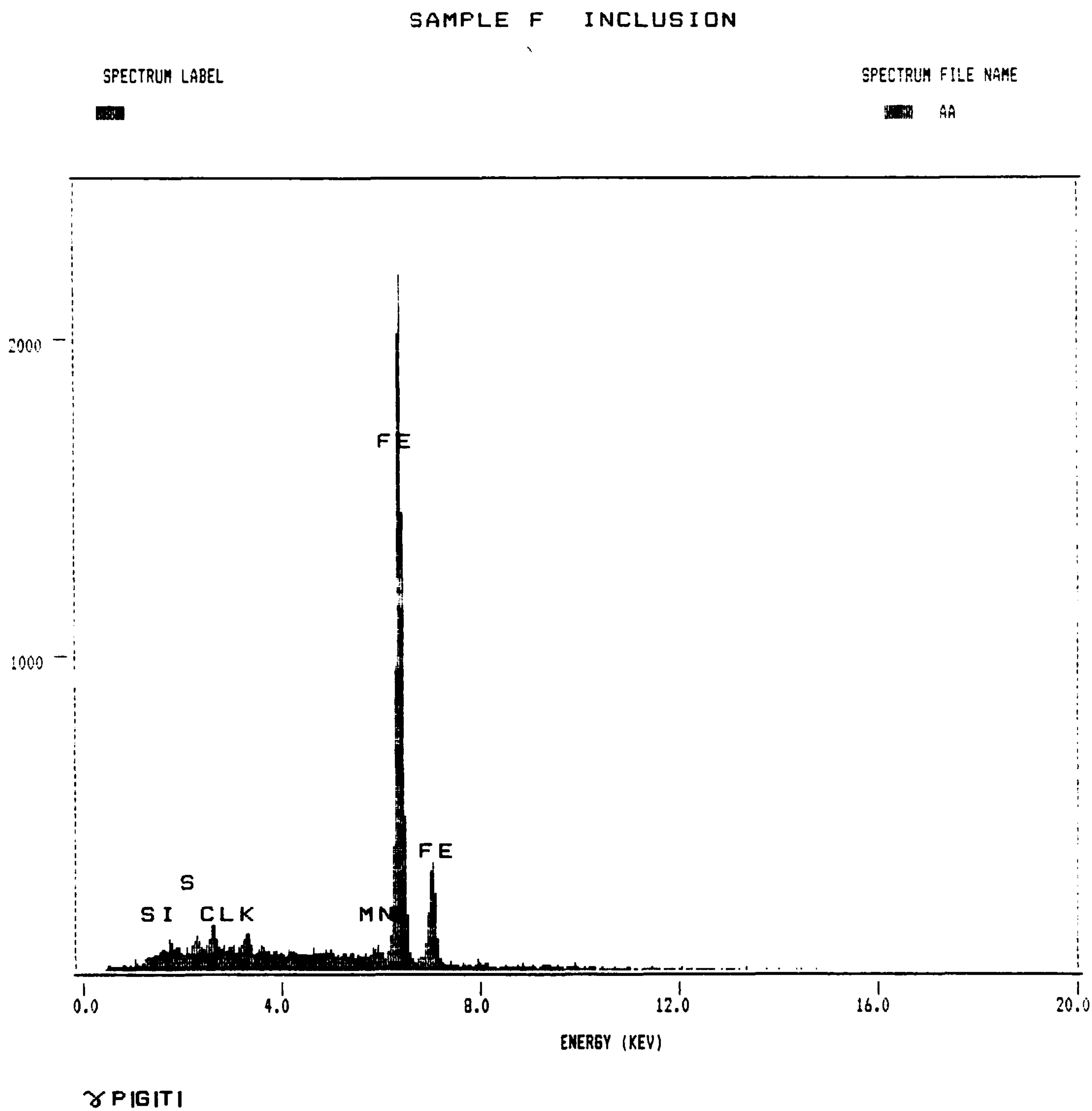


Figure 14. EDS analysis of sample "F" included material.

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