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HIGH IMPACT STRENGTH STEELS
FOR LOW TEMPERATURE SERVICE

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HIGH IMPACT STRENGTH STEELS FOR LOW TEMPERATURE SERVICE

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Among the military characteristics specified for all ordnance equipment is satisfactory serviceability at ambient temperatures down to -65°F . It is thus demanded that artillery, tanks, other military vehicles, and all their components be capable of performing their service missions at subzero temperatures without failure of their metal parts. It is obvious that many parts of ordnance materiel are more or less repeatedly subjected to severe shock loads during their normal functioning; cannon tubes and breech rings during firing, armor plate when impacted by projectiles or high explosive shell, tank tracks and suspensions when hurdling obstacles, etc. Furthermore, the stress levels at which many ordnance components operate are so high, at least in localized regions such as the bores of gun tubes, armor in the vicinity of impacts, etc., that yielding and plastic flow in such areas is a usual occurrence. Finally, the evergrowing demand for lightweight military equipment to ease the logistical burden imposed by global mechanized warfare has resulted in the use of higher strength steels of lighter cross-section for gun tubes, structural components of artillery carriages and vehicles, etc.

To meet these varied demands successfully, ordnance steels must possess high strength, the ability to withstand shock loading at reduced temperatures, and the ability to undergo some plastic deformation without initiation or propagation of brittle fracture. The latter characteristics may be lumped together under the general term toughness. It has been long recognized, as summarized in a paper by Hollomon¹ et. al., that steels having tempered martensitic microstructures have mechanical properties superior to those of steels having other microstructures. At a given tensile strength level, steels heat treated to a tempered martensitic structure possess the highest yield-tensile strength ratio, excellent ductility, highest fatigue resistance, and the maximum toughness under conditions involving shock loading and low temperatures. Effort has therefore been directed to the production of critical items of ordnance equipment from steels possessing these essential characteristics.

In order to insure that critically stressed components of military equipment will perform satisfactorily under the extremes of service conditions, the Ordnance Corps has developed materials specifications based upon

1. "The Effects of Microstructure on the Mechanical Properties of Steel", J. H. Hollomon, L. D. Jaffe, D. E. McCarthy and M. R. Norton, Transactions American Society for Metals, Vol. 38, 1947, pages 807-844.

mechanical property requirements significant to the proper functioning of the items. Such specifications, in addition to the more usual requirements, include a toughness requirement involving the V-notched Charpy impact test to be conducted at subzero temperatures; the minimum energy value being adjusted to the yield strength or the hardness of the steel. The mechanical property requirements of most of these specifications were established from correlated data assembled during and since World War II, including data derived from post-mortem examination of serviceable and deliberately and accidentally failed components. The following specifications are examples:

- Spec MIL-S-10458A(ORD), Steel Forgings for Cannon Tubes and Barrel Components
 - Spec MIL-S-10026(ORD), Steel Castings (Centrifugal) for Gun Tubes
 - Spec MIL-S-12253(ORD), Steel Castings for Muzzle Brakes
 - Spec MIL-S-13326(ORD), Steel, Constructional, High Strength, Heat Treated (for Welded Structures)
 - Spec MIL-S-10185(ORD), Steel Forgings for Breech Rings
 - Spec MIL-S-10029(2)(ORD), Steel Castings for Breech Rings
 - Spec MIL-S-11415A(ORD), Steel Parts; Ordnance
- Also, specifications for Cast Steel Armor and Wrought Steel Armor

When the notched bar impact test was first introduced into Ordnance specifications in the mid-1940's, considerable opposition was encountered from various engineers and facilities who contended that the test, although useful from the laboratory and research viewpoints, was not suitable for production inspection and acceptance purposes because of its wide variability and sensitivity to minor changes in metallurgical structure and dimensions of test specimen. The Watertown Arsenal Laboratories found it necessary to embark upon an extensive testing and educational program to demonstrate the practical significance of the V-notched Charpy impact test and to prove that it can be performed accurately and reproducibly.

In accomplishing the above, jigs and fixtures have been developed and made available to industrial facilities for the economical quantity production and inspection of notched bar impact test specimens. In addition, manuals have been prepared and widely distributed covering the maintenance and calibration of impact test machines, procedures and equipment for testing specimens at subzero temperatures, and descriptions of machining procedures for making test specimens.

With the establishment of proper controls and testing techniques, it is found possible to reproduce the V-notched Charpy impact test within the range of $\pm 5\%$ in terms of breaking energy over the range of 10 through 100 ft.lbs. This degree of reliability puts the impact test in the same class with respect to accuracy and reproducibility as almost all other mechanical property tests which have been employed for many years in the acceptance testing of metals.

The philosophy which has been adopted by the Ordnance Corps towards ordnance materials specifications is illustrated by the development of the armor specifications. Initially, i.e. prior to World War II, armor specifications concerned themselves only with the ballistic protection attributes of the material. It was agreed that there were three important ballistic characteristics that must be controlled; these were:

- a. Resistance to penetration by armor-piercing projectiles
- b. Resistance to cracking or shattering when impacted by heavy or explosive ammunition
- c. Resistance to back-spalling or ejection of pieces of the armor from behind the plate upon impact by projectiles

Accordingly, ballistic tests capable of evaluating each of these characteristics were developed and incorporated into the armor acceptance specifications.

Metallurgical research during the early years of the war showed that each of the above ballistic quality characteristics was directly related to specific metallurgical or mechanical property attributes of the armor as follows:

Resistance to penetration - this quality is a function of the strength or hardness of the armor. Under many significant conditions of ballistic attack, the resistance of armor to penetration increases with increasing armor hardness up to the onset of excessive brittleness, at which point further increases in hardness result in progressive decreases in ballistic performance.

Resistance to cracking or shattering - this quality is directly related to the toughness of the armor, and is a function of the microstructure of the steel as influenced by chemical composition, hardenability, and heat treatment. The Charpy V-notched impact test, when conducted at subzero testing temperatures, yields results directly comparable to ballistic shock tests involving firing large caliber deforming projectiles or explosive shell at the armor.

Resistance to back-spalling - this quality is a function of the soundness of the steel. Laminations of non-metallic inclusions, piping, or any other segregations cause planes of weakness in rolled armor which results in back-spalls being ejected upon ballistic impact. These detrimental laminations are also revealed on fractured surfaces by simply breaking and examining sections cut from the armor.

Based upon the above, non-ballistic tests have been developed and now form the basis of the armor specification requirements. It is now recognized and accepted that the ballistic effectiveness of armor can be controlled by specifying the hardness range, minimum notched-bar impact resistance, and soundness of the steel. Tests to evaluate these quality characteristics are much easier and cheaper to perform than are ballistic tests, can be performed in the manufacturers' plants, and are more

meaningful to the steel producers in that they can be readily related to the manufacturing processes. Thus, defects in the finished material can be immediately traced to their specific causes and corrective measures quickly applied.

The above discussion has been detailed to a considerable extent in order to indicate the approach taken in Ordnance Corps materials specifications to relate end use performance to the pertinent metallurgical and mechanical property characteristics that must be present for satisfactory functioning of end items. The same procedures followed in the armor specifications have also been applied to the other materials specifications which have been previously outlined.

More recently, however, members of the staff of the Watertown Arsenal Laboratories² have proposed a quantitative method for the use of the V-notched Charpy impact test for the selection of steels having adequate toughness for the intended applications. This method is based upon the equivalence in effect of strain rate and test temperature upon the tendency of steel towards ductile or brittle fracture. A method was developed for the selection of the temperature at which to break the Charpy impact specimen to reproduce the fracture behavior of the actual steel part at its lowest anticipated service temperature and highest rate of loading. A safety factor is provided by selecting a test temperature for use in the specification which is 20°F below the calculated test temperature. The level of impact energy specified is taken at the midpoint of the impact transition curve (half-way between energies absorbed in fully ductile and fully brittle fractures) and is a function of the yield strength level.

The above method was employed to establish the impact test requirements of the specifications for both forged and cast breech rings. No failures in service resulting from brittle fracture have occurred in any breech rings procured to these specifications. The impact test requirements for the other specifications were largely based upon experience gained from correlated mechanical properties and service performance; tempered by the capability of the steel industry to produce and process the tonnage quantities of steel required for an all-out production program.

An important point is that none of the referenced end use specifications stipulate or limit, except as noted below, the chemical compositions of the steels selected for ordnance components. The carbon content of some steels, notably armor, is limited to approximately 0.32% maximum in order to insure weldability by commercially practicable means. The sulfur and phosphorus contents of most ordnance steels are limited to 0.040% maximum

2. "Impact Tests Help Engineers Specify Steel", SAE Journal, Vol. 59, March 1951.

because of the adverse effect of these elements upon the ductility and toughness of steel. This latter requirement is not particularly significant since most critically stressed ordnance steels must have sulfur and phosphorus contents generally below 0.025% in order to meet the notched-bar impact test requirements.

The manufacturer of ordnance steels may therefore, with virtually complete freedom, select any composition of steel provided it possesses sufficient hardenability to transform to an essentially martensitic microstructure during the prescribed heat treatment. Whatever lack of freedom which exists is imposed by the unavailability, strategic nature, or competitive costs of the various alloying elements employed in steel. The notable exception (it is a truism that all generalizations are plagued by significant exceptions) is that molybdenum is an essential alloying element in all critically stressed ordnance steels because of its specific effect in eliminating or alleviating the tendency towards temper embrittlement; the amount of molybdenum employed in these steels is generally in the range of 0.30 to 0.60%.

During World War II, the production of heat treated alloy steels for severely stressed ordnance equipment reached major tonnage proportions. During the height of the war, the production of such steels was at a rate exceeding 2,000,000 tons per year; the bulk of it going into the tank armor and artillery programs. The need for conservation of critical and strategic alloys early became vital; beginning in the spring of 1942, the War Production Board established upper limits for the use of nickel, chromium, vanadium, and molybdenum in ordnance steels. It became necessary to develop a new series of low alloy steels to replace the older, higher alloy steels of the Ni-Cr-Mo, Ni-Mo, Cr-Mo, Cr-Mo-V, etc. types which had Ni and Cr contents as high as 4 to 5%. This led to the development of the lean, "triple alloy" steel compositions, to the more widespread use of manganese up to about 1.75% as a hardenability promoting alloy in place of nickel and chromium, and to the use of boron treated steel, particularly in rolled and cast armor.

An especially important advance was the general adoption of water quenching for the hardening of alloy steels. Prior to and in the very early stages of World War II, most ordnance steels used in armor, guns, and projectiles were oil quenched, and the relatively slow cooling rates necessitated high alloy contents to provide the requisite hardenability. The changeover to drastic water quenching practices was a significant stride on the road to conservation of strategic alloys.

Work done during the early years of World War II did much to clarify our understanding of temper brittleness and other embrittlement phenomena in steel. Practicable methods for combatting embrittlement were developed and applied, such as grain size refinement and control, water quenching of alloy steels from the tempering temperature, modification of alloy content

noted that the greatest increase in impact resistance occurs at the lowest hardness level (240 Brinell), but the increase is significant at hardness up to at least 350 Brinell.

After adoption of the rare-earth addition practice by the American Steel Foundries, that company employed the following compositions for the production of tank armor castings:

	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Rare Earths</u>
For light castings up to approx. 2 1/2" thickness	.25	1.40	.40	.50	.50	.50	2 lbs/ton
For heavy castings up to approx. 8" thickness	.25	1.30	.40	1.00	1.00	.60	2 lbs/ton

During 1952, further experiments were conducted by the same facility with the aim of further reducing the alloy content of heavy armor castings by employing boron in conjunction with rare-earth metals. The results shown in Figure 3 demonstrate the success obtained in cast armor sections 1" to 8" in thickness. The composition that was finally standardized for use by the American Steel Foundries for all thicknesses of cast armor was the following:

<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>B</u>	<u>Rare Earths</u>
.25	1.40	.40	.25	.50	.50	.0015	2 lbs/ton

The boron was added in the form of a boron-ferro-silicon alloy and the rare-earth metals in the form of misch metal. This last composition is exceptionally low in strategic alloy content, particularly when it is considered that it is successfully employed for heavy sections (up to 8" thick) heat treated to meet specifications incorporating low temperature notched-bar impact test requirements.

Following the successful use of rare earth metals by the American Steel Foundries to improve the low temperature toughness of medium alloy heat treated steels, other industrial facilities as well as the Ordnance Corps instituted research and development projects to further investigate rare-earth metal additions to steel and to determine the mechanisms whereby the mechanical properties of steel are enhanced by such additions. A research program conducted by the Steel Founders' Society of America under a contract to the Watertown Arsenal demonstrated that the increase in the toughness of cast heat treated alloy steels was due in part to the desulfurization resulting from rare-earth metal additions in basic lined furnaces, and to a change in the shape and occurrence of inclusions. These effects were not, however, able to account for the entire improvement in ductility and

toughness in rare-earth treated steels. The strong affinity of rare-earth metals for oxygen, nitrogen and hydrogen must result in an effective degasification of steel, which may account for some of the improvement in its mechanical properties.

Although it was soon established that rare-earth metals did not increase the hardenability of steels, nevertheless, the mechanical properties of heat treated under-alloyed steels were considerably improved by the addition of rare-earth metals. The precise reason for this is not known and indicates the need for further research.

Table I provides additional data on the effect of rare-earth additions upon the low temperature toughness of steel. Rare earths in the amount of 2 lbs/ton were added to one of two successive ingots poured from the same heat of Mn-Mo, boron treated steel. The ingots were subsequently cross-rolled down to 1/2" thick plates which were heat treated to 160,000 psi yield strength (360 Brinell). The V-notch Charpy impact energy at -40°F in the direction transverse to the major direction of hot working was approximately 20 ft. lbs. in the untreated steel, and approximately 30 ft. lbs. in the rare-earth metal treated steel; an increase of 10 ft. lbs. or approximately 50% in impact resistance. Neither the yield strengths, tensile strengths, nor ductility were affected in this case by the rare-earth additions.

It is opportune at this time to emphasize the need for the determination of the mechanical properties of high strength ordnance steels in the direction transverse to the major direction of heat working. It is well known that the longitudinal ductility and notched bar impact resistance of bar stock and straight-away rolled plate is generally very high, and that the same properties, when measured in the transverse direction, may be very low. A ratio of longitudinal to transverse impact resistance as high as 10 to 1 has been observed in straight-away rolled plate, even when the steel was heat treated to a fully martensitic condition and tempered. When such material is subjected to shock loading, longitudinal fractures may be expected. Similarly, a pressure vessel or gun tube will readily fail if it is deficient in transverse ductility and toughness. All the Ordnance Corps materials specifications which were cited previously require that tensile and impact test specimens be taken from the transverse directions.

Unfortunately, much of the published data on the strength, ductility, and toughness of high strength steels represent longitudinal tests. The engineer must be cautioned against using these data for the selection of steels which may be subjected to shock loading or other stress application, where stresses in the transverse direction will be high. Furthermore, researchers should be encouraged to do the bulk of testing on transverse specimens, since most failures will propagate in the direction of minimum ductility, strength, and toughness.

the impact test requirements at the muzzle end (8" O.D.) but met them at the heavy breech end (16" O.D.). It is noteworthy that the same steel, but without the rare-earth metal addition, was deficient in impact resistance, having impact energies at -40°F from 8 to 9 ft. lbs. below that of the rare-earth treated steel. These results show promise for the development, if the need arises, of very low alloy nickel free steels for moderately large gun tubes.

The data presented in this paper were selected to show the progress which has been made to date in the development of low alloy non-strategic steels having high toughness at subzero temperatures when heat treated to yield strengths in the range of 100,000 to approximately 160,000 psi. Most of the steels employed for armor, gun tubes, recoilless rifles and various steel parts of ordnance equipment fall within this range of strengths and are considered high strength steels by ordnance standards. These strengths do not, however, approach those of the ultra-high strength steels (200,000 - 240,000 psi yield strength) which are becoming of increasing importance in aircraft applications.

It is felt, nevertheless, that the application of the same procedures which were used to conserve alloys and raise the toughness of steels in the 100,000 to 160,000 psi yield strength class will also produce corresponding benefits in the ultra-high strength steels. Work done at Armory Research Foundation³ has already demonstrated that the addition of rare-earth metals to SAE 4330 greatly increases the transverse notched bar impact properties at test temperatures down to -300°F and improves the ratio of longitudinal to transverse mechanical properties.

Despite the considerable progress which has already been made, much yet remains to be done. The effects of rare-earth metal additions to steel are incompletely understood. Also, it is uncertain which, if any, of the rare-earth metals is most beneficial and whether it is better to employ only one of these metals rather than the misch-metal. More needs to be learned about the specific effects of the various alloys upon the tempering of martensite and upon the mechanical properties of steels tempered at low to moderate tempering temperatures as well as the various embrittlement phenomena encountered in this range of tempering temperatures. Finally, the details of melting and deoxidation practice, and effects of gaseous impurities in steel should be correlated with the mechanical properties of high strength steels in order to determine the best steel making practices for high strength, high toughness steels.

3. "Rare Earths Improve Impact Properties of 4330", H. Schwartzbart, J. P. Sheehan, Iron Age, Vol. 175, No. 21, 26 May 1955.

TABLE I

EFFECT OF RARE EARTH METALS ON MECHANICAL PROPERTIES OF PLATE*

Ingot A - 2 lbs/ton of rare earth metals added.

Ingot B - no rare earth metals added.

		<u>Chemical Composition</u>								
<u>Ingot No.</u>	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Mo</u>	<u>B</u>			
A	.32	1.95	.020	.013	.22	.47	.002			
B	.32	1.96	.017	.017	.21	.48	.002			

		<u>Mechanical Properties</u>						
<u>Ingot No.</u>	<u>0.1% Yield Strength, PSI</u>		<u>Tensile Strength, PSI</u>		<u>% Elong.</u>		<u>BHN</u>	<u>Transverse</u>
	<u>Longitudinal</u>	<u>Transverse</u>	<u>Longitudinal</u>	<u>Transverse</u>	<u>Longitudinal</u>	<u>Transverse</u>		<u>V-Notch Charpy</u>
								<u>Impact at -40°F</u>
								<u>Ft. Lbs.</u>
A	159,400	160,100	170,300	171,500	17.6	17.3	363	28, 29, 32
B	159,200	160,800	169,100	169,500	18.0	16.3	363	19, 22, 21

*Data from Jones & Laughlin Steel Corporation.

Successive ingots cast from same heat of steel, one ingot treated with rare earth metals added to ingot mold. Ingot cross-rolled down to 1/2" plate; heat treatment 1625°F, water quench, tempered at 900°F.

TABLE II

EFFECT OF RARE EARTH METALS ON TRANSVERSE DUCTILITY OF CROSS-ROLLED STEEL PLATE*

Ingot C - no rare earth metals added.

Ingot D - 2-1/2 lbs/ton rare earth metals added to ingot.

Slabs from ingots cross-rolled to 1/2" plate.

Chemical Composition

<u>Ingot No.</u>	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>
C	.26	1.16	.017	.027	.23	.87	.65	.36
D	.27	1.16	.016	.015	.22	.80	.64	.35

Tensile Properties

<u>Ingot No.</u>	<u>Test Direction</u>	<u>Yield Strength PSI</u>	<u>Tensile Strength PSI</u>	<u>Elong. %</u>	<u>R.A. %</u>
C	Longitudinal	157,800	170,400	17.7	60.4
C	Longitudinal	153,400	171,700	16.5	58.9
C	Transverse	153,900	169,900	11.4	37.2
C	Transverse	156,200	170,700	12.0	41.2
D	Longitudinal	155,800	169,250	16.5	60.4
D	Longitudinal	156,800	169,850	15.3	58.6
D	Transverse	154,200	167,500	14.2	47.4
D	Transverse	156,800	170,700	14.2	48.3

*Data from United States Steel Corporation

TABLE III

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF LOW ALLOY
120MM GUN TUBE FORGINGS¹

<u>Forging No.</u>	<u>Chemical Composition</u>									
	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>P</u>	<u>S</u>	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>	<u>Boron</u>	<u>Rare-Earths</u>
K1	.36	.88	.33	.008	.012	1.33	1.91	.53	.0036	1#/ton
K7	.30	.63	.39	.017	.011	1.48	2.33	.58	.0037	None
K8	.30	.63	.39	.017	.011	1.48	2.33	.58	.0037	1#/ton
GS1	.25	1.62	.48	.019	.016	.55	—	.54	.0028	1-1/2#/ton
GS3	.29	1.52	.37	.017	.019	.59	—	.54	not reported	None

Transverse Mechanical Properties (Average of four tests)

<u>Forging No.</u>	<u>Breech End (16" OD, 3-1/2" ID)</u>					<u>Muzzle End (8" OD, 3-1/2" ID)</u>				
	<u>0.1% Yield Strength PSI</u>	<u>Tensile Strength PSI</u>	<u>Elong. %</u>	<u>R.A. %</u>	<u>V-Notch Charpy -40°F Ft.Lbs.</u>	<u>0.1% Yield Strength PSI</u>	<u>Tensile Strength PSI</u>	<u>Elong. %</u>	<u>R.A. %</u>	<u>V-Notch Charpy -40°F Ft.Lbs.</u>
K1	117,400	138,700	14.1	32.0	25	116,200	135,700	13.3	31.1	22
K7	104,100	126,100	15.4	36.2	30	112,600	130,800	13.5	33.5	22*
K8	103,600	125,600	17.7	47.2	42	110,800	128,300	16.3	43.9	32
GS1	115,800	134,800	13.3	31.1	22	114,700	130,200	11.3	25.3	22**
GS3	119,800	138,300	11.1	24.0	13*	111,600	127,300	10.9	24.5	14*

1. Data from National Supply Company, Ordnance Contract No. DA-04-495-ORD-490.

* Failed to meet requirements of Specification No. MIL-S-10458A(ORD).

** Failed to meet muzzle end impact requirements by 2 ft.lbs.

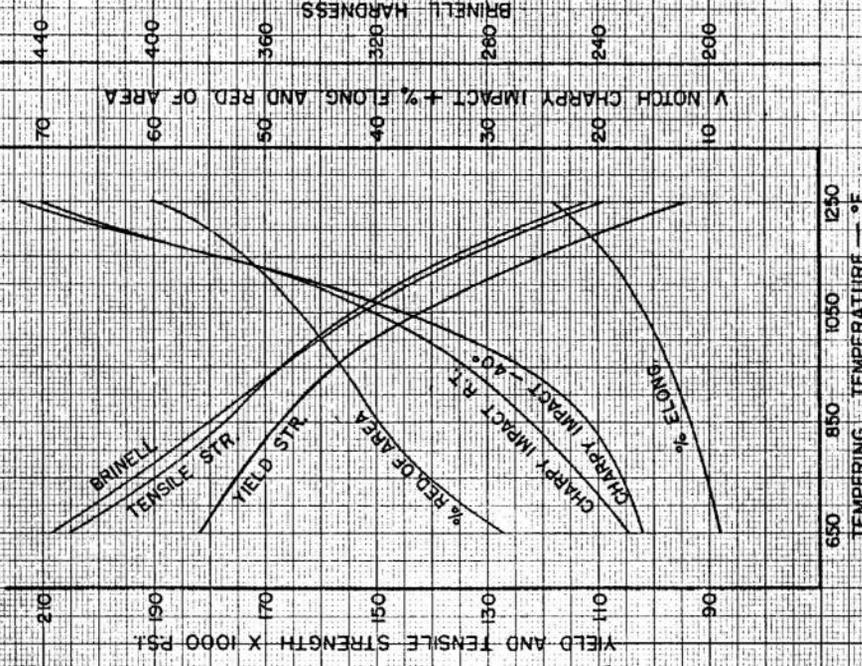
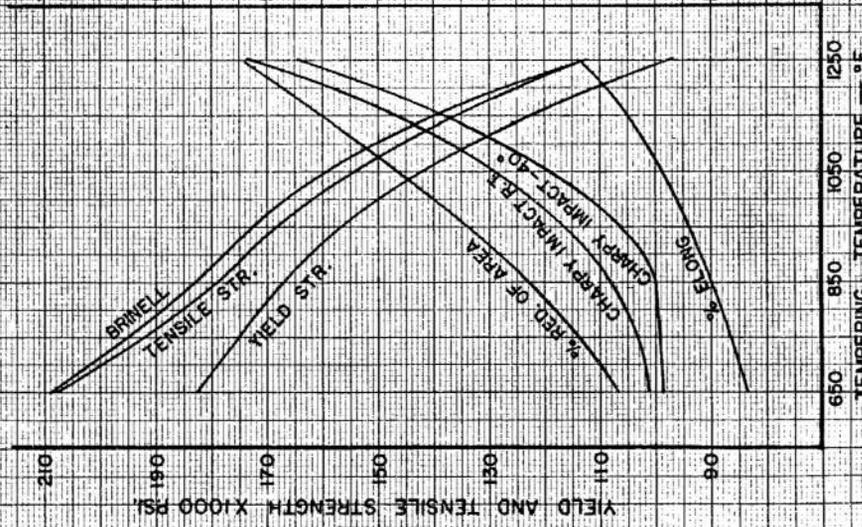
EFFECT OF 2 LBS/TON OF RARE EARTH METALS ON MECHANICAL PROPERTIES OF CAST STEEL*

NO RARE EARTH METALS ADDED

	C	Mn	Si	S	P	Cr	Ni	Mo
	.25	1.34	.37	.015	.015	.51	.46	.49

2 LBS/TON OF RARE EARTH METALS ADDED

	C	Mn	Si	S	P	Cr	Ni	Mo
	.25	1.33	.37	.015	.025	.51	.46	.49



* DATA FROM AMERICAN STEEL FOUNDRIES

FIGURE 1

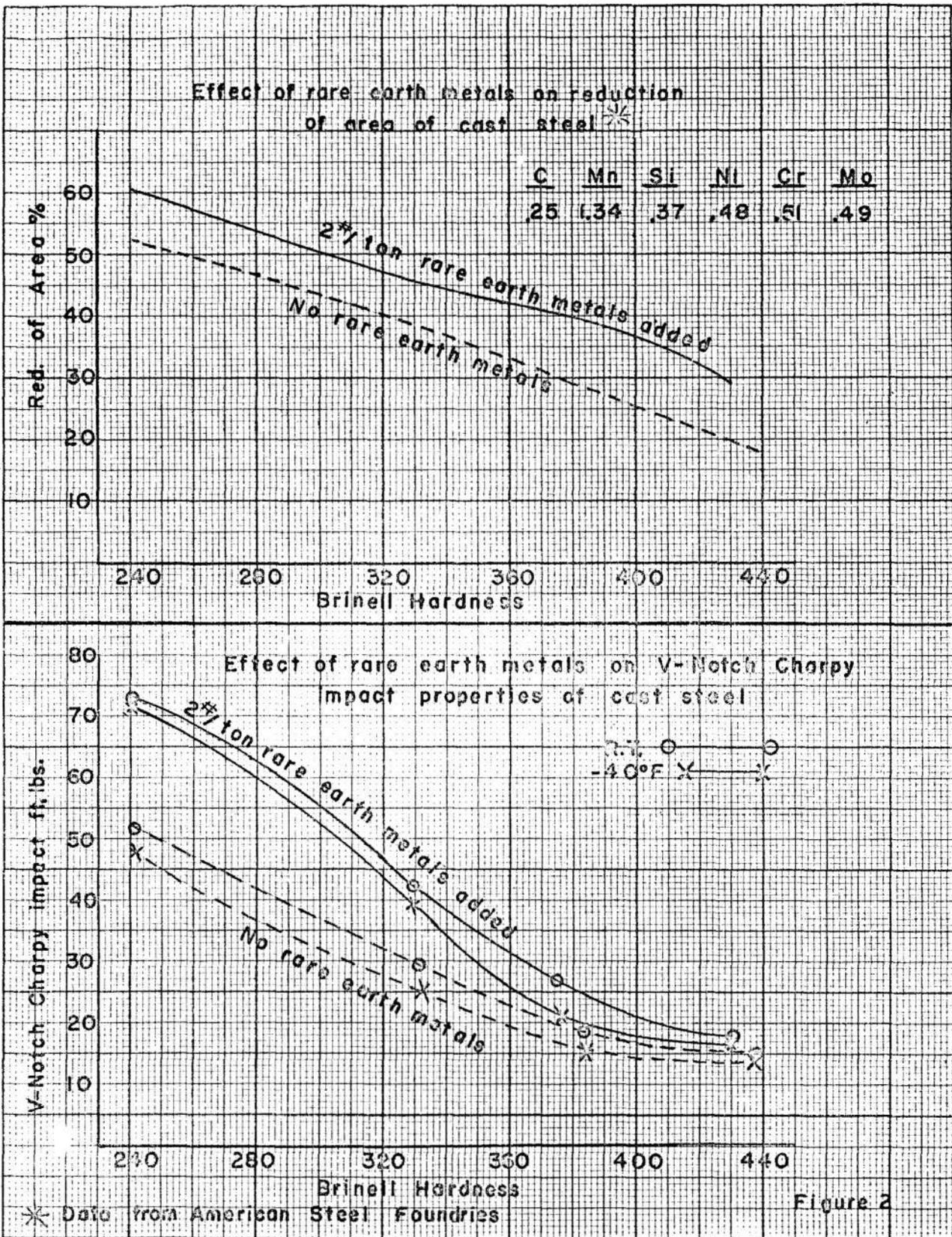
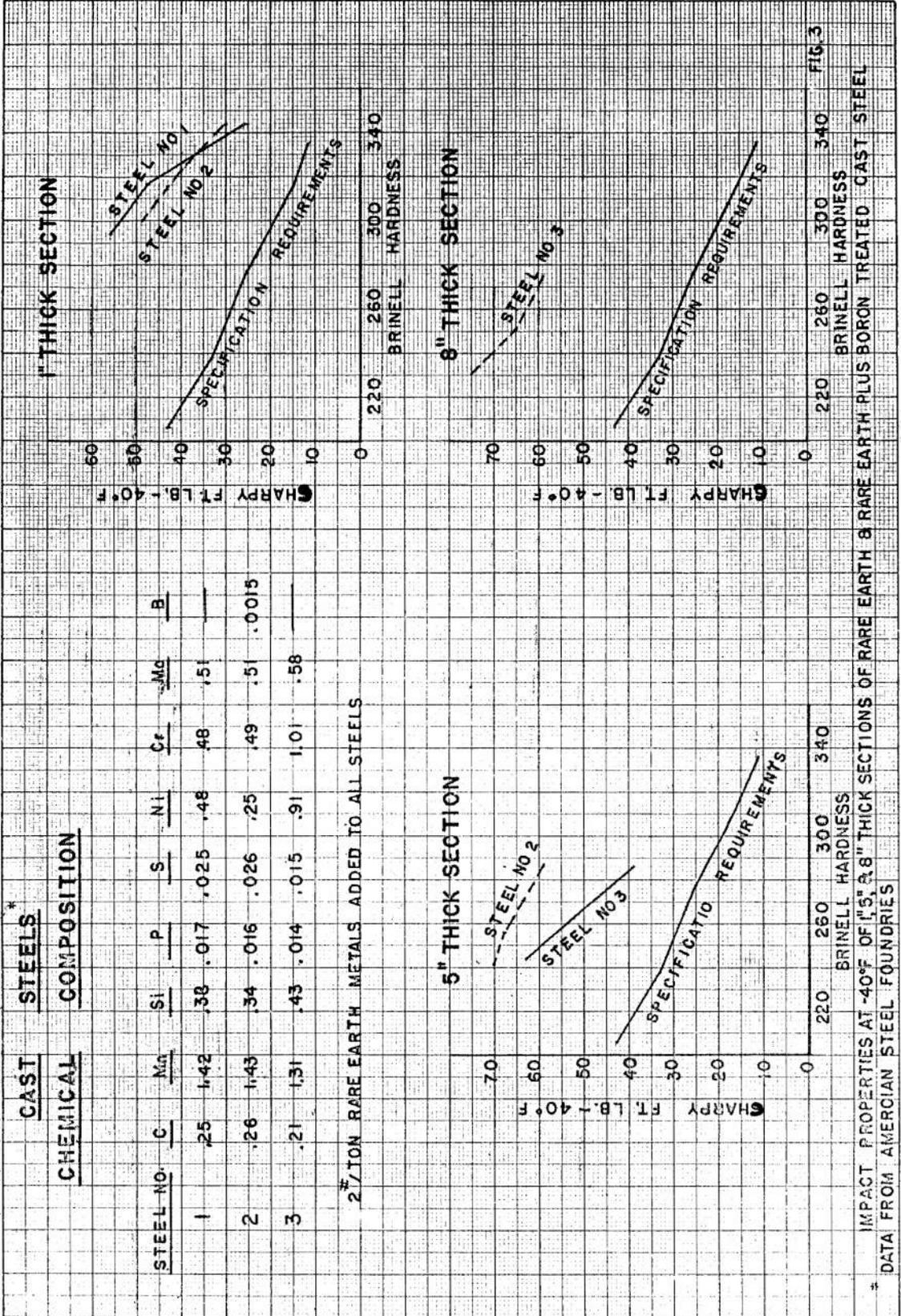
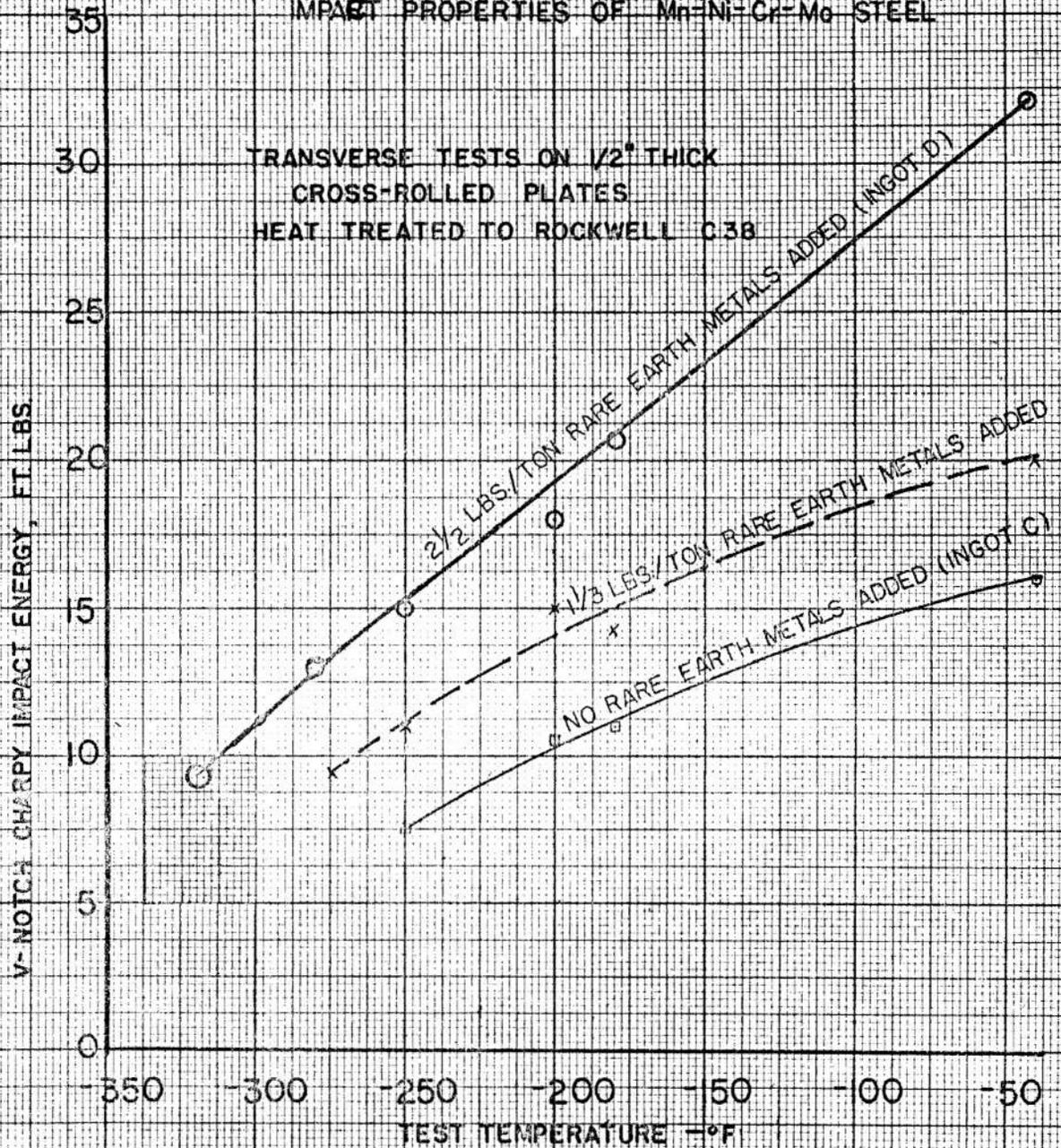


Figure 2



IMPACT PROPERTIES AT -40°F OF 1", 5", & 8" THICK SECTIONS OF RARE EARTH B RARE EARTH PLUS BORON TREATED CAST STEEL DATA FROM AMERICAN STEEL FOUNDRIES

EFFECT OF RARE EARTH METALS ON LOW TEMPERATURE
IMPACT PROPERTIES OF Mn-Ni-Cr-Mo STEEL*



*DATA FROM UNITED STATES STEEL CORP.

FIGURE 4.

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