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**DEVELOPMENT OF ULTRA-HIGH STRENGTH, TEMPER-
RESISTANT STEELS DESIGNED FOR IMPROVEMENT OF
FATIGUE PROPERTIES THROUGH RELIEF OF
RESIDUAL STRESS**

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FOREWORD

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ABSTRACT

Various experimental alloy steels were investigated with reference to temper resistance, which was evaluated on the basis of hardness measurements. Molybdenum was the major alloying element used for improving temper resistance in steels having carbon contents in the range of 0.30 to 0.55 per cent. Chromium, vanadium, and tungsten were utilized in minor amounts as alloying elements. It was found that austenitizing at 2200°F was required to dissolve all of the carbides and provide a fully martensitic structure upon oil quenching or air cooling. Alloys were developed capable of maintaining hardnesses of Rc 40 to Rc 59 after tempering for one hour in the range of 1250°F to 1300°F.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



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Contrails

DEVELOPMENT OF ULTRA-HIGH STRENGTH, TEMPER-RESISTANT STEELS DESIGNED FOR IMPROVEMENT OF FATIGUE PROPERTIES THROUGH RELIEF OF RESIDUAL STRESS

I. SCOPE

Research involving the study and improvement of the fatigue properties of high-strength steel has been actively carried out since 1 December 1955, when this program was initiated at the Foundation. The original phase of this program was concerned with the effects of melting practice and inclusion content on the fatigue properties of heat-treated AISI 4340 steel. It was demonstrated that melting high-strength steel under vacuum or protective atmosphere resulted in improved fatigue properties. However, the most promising development involved air-induction melted steel initially deoxidized with carbon additions, rather than silicon, and finally deoxidized with aluminum. This technique produced a steel having a Prot endurance limit to tensile strength ratio of 0.55 and a constant stress endurance limit of 148 ksi. Both of these values represented significant advances.

The present program was concerned with improving fatigue properties by means of microstress relief during high-temperature tempering. In order to accomplish this, however, the development of a temper-resistant steel was necessary -- a steel that would retain an ultimate tensile strength approaching 300,000 psi after tempering in the 1000°-1300°F range to relieve microstresses around inclusions. Several steels have been developed during this program which appear to provide the necessary resistance for retaining high tensile strengths after tempering at elevated temperatures.

The logical conclusion of these closely interrelated fatigue investigations would involve the combination of methods: the application of special carbon deoxidation techniques to the production of a high-strength, temper-resistant steel. A steel prepared in this manner would realize the advantages of both developments; fewer nonmetallic inclusions would be present, and their stress-concentrating effect would be materially reduced by tempering at high temperature. It appears that a temper-resistant steel melted under these special techniques would provide high strength coupled with significantly improved fatigue properties.

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II. INTRODUCTION

The objective of this program was to develop, produce, and evaluate the properties of a steel which can be tempered in the range of 1100° to 1300°F to strength levels approaching 300,000 psi. Other work in this field involving the correlation of the size and shape of nonmetallic inclusions with fatigue life has indicated that the cleanliness of the steel is a major factor in determining the fatigue properties. As the production of inclusion-free steel appeared impractical, it was proposed to study means of reducing the residual stress pattern at inclusion sites. Since residual stresses in structural members generally result from the hardening operation, they can be eliminated or relieved by a suitable tempering treatment. However, in the case of a low-alloy steel such as AISI 4340 the tempering range cannot exceed 400°F and maintain a high strength level. It becomes necessary to temper at higher temperatures (1000°-1300°F) in order to achieve significant or almost complete stress relief. This introduces the problem of retarding softening and loss of strength during the tempering of low- and medium-alloy steels at these temperatures.

It was desired to formulate a steel having high tempering characteristics in order to maintain a tensile strength of 300,000 psi after tempering in the range of 1100° to 1300°F. Among existing materials, even high-speed steels fall below the required strength level if tempered above 1200°F, and they are unsuitable for structural applications because of their inherent brittleness. However, tempering treatments in the 900° to 1100°F range can produce better-than-expected fatigue properties in 5 per cent chromium hot-work die steel compositions (such as Vascojet 1000). The presence of strong carbide- and nitride-forming elements -- such as chromium, molybdenum, vanadium, and tungsten -- retards the softening of steel at elevated tempering temperatures. In some instances, an increase in hardness can be obtained during tempering over a certain range of temperature. In order to develop a temper-resistant steel, alloys containing various combinations of these elements were prepared and evaluated.

III. EXPERIMENTAL PROCEDURE

A. Alloy Selection

During this program, over 30 different steels were melted and evaluated with regard to temper resistance. The alloy compositions investigated were varied systematically in order to cover the greatest range and provide the maximum information. The selection of experimental compositions was guided by present knowledge and current developments in the field of high-strength steel metallurgy. This background indicated that molybdenum has a very significant effect on the resistance to softening at tempering temperatures

above 1000°F; as a consequence, the effect of varying molybdenum concentration on the properties of a medium carbon-chromium-vanadium steel was chosen for the initial investigation.

Hardness results indicated that approximately 5 per cent molybdenum provided the greatest improvement in temper resistance. Following this, the effect of minor alloy additions in varying proportions on the properties of this particular steel were considered. Alloy development work was directed, whenever possible, toward the investigation of one alloying element at a time; this was done in order to determine the effects of a prescribed amount of alloy addition. The realization of this objective was complicated by variations in composition from one melt to another and interaction effect among alloying elements. These elements included chromium, vanadium, tungsten, niobium, cobalt, and nickel; various additions in the general ranges shown below were studied.

C	0.35 - 0.80 per cent
Cr	0 - 1.50
V	0.50 - 2.00
W	0 - 2.00
Nb	0 - 2.00
Co	0 - 3.00
Ni	0 - 2.00

The carbon range was necessarily limited: a minimum carbon content was required to insure the formation of austenite at elevated temperature, and the upper limit was restricted by the brittleness associated with high-carbon steels. Chromium, vanadium, and tungsten are strong carbide-formers and could be expected to contribute to temper resistance through the formation of complex carbides. Niobium was studied to determine its ability to inhibit grain growth at the temperatures required to dissolve complex carbides. Cobalt was considered as a ferrite strengthener, while nickel was reported to increase ductility and extend the austenite field.

A similar series of alloys was planned based on preliminary results obtained using tungsten as the major constituent; however, lack of time prevented completion of this work. Only one series of alloys of this type was prepared and tested. The carbon contents ranged from 0.40 to 0.55 per cent while molybdenum, vanadium, and nickel, in similar amounts to those studied previously for molybdenum alloys, comprised the secondary alloying elements.

B. Melting

The steels investigated during this program were melted by two different techniques. The majority of alloys were melted in air by induction melting. Standard aluminum deoxidation was employed, and refractory hot tops were utilized in all cases. This practice enabled reasonably close control to be maintained on chemical composition.

Several alloys were induction-melted in a similar furnace under a partial vacuum. A rod of AISI 4150 steel was used as melting stock, and alloy additions including carbon were made in the crucible. However, due to limitations in furnace design, it was difficult to obtain the desired analysis, especially carbon content, in this manner; and this method of melting was discontinued.

C. Hot Working

Ingot breakdown was performed initially by hot upsetting. The majority of the ingots were approximately 3 in. in diameter by 10 in. long (without the hot top). In general, the hot tops were cut off after annealing, and the ingots were cut transversely into two cylindrical sections of approximately equal weight. The sections were heated at 2000 to 2200°F in a carbon monoxide atmosphere and upset (in the direction of the cylindrical axis) in one or two passes to a disc having a thickness of about 3/4 in. Later in the program this technique was modified to eliminate the cutting operations. Using the same forging temperature, the ingots were press-forged in the transverse direction (perpendicular to the cylinder axis) to a slab having a thickness of about 1 in., in one or two passes. The forged ingots then were annealed to facilitate the preparation of heat-treating samples, and the hot tops were cut off at this time.

D. Heat Treatment

After the forging operation, all of the ingots were annealed; this treatment consisted of furnace cooling from 1650°F in a Vapocarb atmosphere. A cooling rate of about 100°F per hour was utilized. This softened the steels sufficiently to permit bandsawing the samples preparatory to heat-treating. Rectangular blocks, approximately 1 1/2 in. x 1 in. x 3/4 in. were used for heat-treating purposes.

Austenitizing at relatively high temperatures was required for the alloy steels studied in this program. High temperatures, coupled with molybdenum contents up to 10 per cent, resulted in excessive decarburization unless special precautions were taken. A procedure was developed to eliminate the necessity for grinding after heat treatment and minimize the effects of decarburization. The rectangular blocks described above were austenitized in an Inconel muffle using an atmosphere of purified argon. After quenching, the blocks were split on a cut-off wheel, and hardness measurements were taken in the central areas of the cut surfaces.

Quenching was performed initially by air cooling. The original molybdenum-vanadium steels were treated in this manner. However, subsequent work on these steels showed that a higher as-quenched hardness could be attained by oil quenching. As a result, this procedure was adopted and, with only a few exceptions, all of the other experimental alloys were hardened by oil quenching.

E. Hardness Measurements

Heat-treated and tempered samples were prepared for hardness testing to insure clean parallel surfaces. In the case of samples split after austenitizing, only the opposite surfaces were cleaned up as the cut-off operation provided a good surface. Sufficient coolant was used during cutting in order to avoid overheating. Four to five Rc hardness measurements were made on each sample; additional readings were taken if a close agreement in values was not obtained on the first trial.

IV. RESULTS

A. Chemical Composition of Experimental Steels

The initial composition used in this program was a medium carbon-vanadium steel to which varying amounts of molybdenum were added systematically. The compositions of the steels prepared using this base composition are shown in Table I. Additional alloys were prepared based upon data derived from investigation of the initial compositions. The chemistry of these alloys is shown in Table II.

B. Hardness Data

The alloys described above were austenitized at various temperatures, quenched in air or oil, and tempered for one hour at various temperatures. In some cases double tempering treatments were used. The heat treatments and resultant hardnesses of the initial set of molybdenum alloys are shown in Tables III to VI. These results showed that a minimum austenitizing temperature of 2000°F was required to harden these steels, and the effect of molybdenum addition appeared to be the greatest at about 5 per cent (Table V). In view of this, additional studies were made on alloy No. 5. Austenitizing temperatures in the range of 1900° to 2200°F were investigated. The results of this study (Table VI) indicated that an austenitizing temperature of 2200°F resulted in higher hardnesses in both the as-quenched and tempered condition. The heat-treating samples used to determine the hardness values given in Table VI were found to be partially decarburized. This explains, to a large extent, the lower hardnesses recorded here as compared to Tables III, IV, and V. However, this apparently did not mask the effect of austenitizing temperature on tempered hardness.

The effect of single and double tempering on the hardness of alloy No. 5 is illustrated in Figure 1. As the effect of double tempering was detrimental, at least in so far as hardness was concerned, further work was limited to single-tempering treatments.

Based on the promising results obtained with molybdenum-vanadium steels, further efforts were directed toward developing increased temper resistance. The data provided by the study of additional alloys (whose compositions are given in Table II) are shown in Table VII. Steel compositions were developed which provided hardnesses as high as Rc 59 after tempering for one hour at 1250°F to 1300°F. Several of the more promising steels were tempered at 1250°F. Pronounced softening was noted with the exception of alloy V which maintained a hardness of Rc 47.5 after this treatment. Tempering data are presented in graphical form in Figures 2 to 5.

V. DISCUSSION OF RESULTS

The results of this program indicate that alloying additions of molybdenum, chromium, vanadium, and tungsten can be used to prepare temper-resistant steels having carbon contents of 0.30 to 0.60 per cent. It was rather difficult to make direct comparisons of the effect of alloying elements because of the variations in alloy content from one composition to another. However, molybdenum appeared to be the chief contributor to temper resistance. This is shown in Figure 2 by the tempered hardness of alloy A; this alloy has the following base composition:

<u>C</u>	<u>Mo</u>	<u>V</u>
0.46%	4.99%	0.48%

After tempering at 1300°F for one hour, this steel has a hardness of Rc 47; this represents a considerable increase in tempered hardness as compared to a plain-carbon steel of equivalent carbon content (Rc 10-20) or a commercial hot-work die steel (about Rc 30) tempered in a comparable manner.

The effect of carbon content is also very important. A comparison of eight of the experimental steels of varying composition studied during this program indicated that the tempered hardness (after tempering at a given temperature) was proportional to the carbon content. This is shown in Figure 6. These curves appear to define a linear relationship, especially at lower tempering temperature, although considerable scatter is present. These results point to the conclusion that in a given range of alloy content (such as we are considering here) the tempered hardness is dependent upon carbon content.

The effect of the other alloying elements is not as definitive. Although the more highly alloyed steels tend toward higher tempered hardnesses, the carbon contents of these steels also tend to be higher. It would require very close control of composition to evaluate the effects of alloying elements, but the general tendency of increased temper resistance with additions of tungsten, chromium, and vanadium appears to be indicated in this work.

Tungsten appears to have an effect similar to that of molybdenum when it is used as the principal alloying element, as in alloy N.

Figures 2 to 5 show that, to some degree, tempered hardness is dependent on the as-quenched hardness. This was not investigated to any great extent; however, austenitizing temperatures and quenching media were selected to give as high a value of as-quenched hardness as was practicable. Hardness measurements and metallographic techniques were utilized to guide the selection of austenitizing temperature.

The effect of retained austenite on these steels was apparently slight. Steels A, C, D, and E were cooled directly in liquid nitrogen after air-cooling to about 200°F. No significant differences in hardness were noted either in the as-quenched or tempered condition.

It was desired to dissolve the principal alloy carbides during the austenitizing treatment. This criterion resulted in the high temperatures used (e.g., 2200°F), as well as a very large grain size. While it was known that a large grain size would adversely affect the mechanical properties, this objection was waived at the time in order to develop a temper-resistant composition. The addition of niobium appeared to have a favorable effect on grain size, however. Relatively minor additions resulted in the retention of carbides that were incompletely dissolved even after austenitizing at 2200°F, and the presence of these particles apparently restricted grain growth to a considerable degree. Although only a few niobium-bearing steels were examined, they demonstrated a markedly smaller average grain size (after austenitizing at 2200°F), with only occasional large grains. This effect of niobium can be seen by comparing Figures 7 and 8; these particular samples were hot-rolled to minimize the grain size.

VI. SUMMARY

Various medium-carbon steels have been developed which can be tempered in the range of 1200° to 1300°F to hardness levels approaching Rc 62. Molybdenum, tungsten, and carbon appeared to be the major contributors to temper resistance; these elements combined with varying amounts of other alloy additions, chiefly chromium and vanadium, formed a series of temper-resistant steels. Within a tempering range of 1100° to 1300°F, compositions can be selected providing tempered hardnesses ranging from Rc 39 to Rc 62. Even after tempering at a temperature of 1350°F, several alloys having hardness values over Rc 40 are available.

While this research program has resulted in a series of temper-resistant alloy steels, this represents the initial stages in the development of a useful material. An optimum set of melting, working, and heat-treating procedures must be designed in order to realize the full potential

of these steels. The first step in this direction appears to be the elimination of the excessive grain growth associated with high austenitizing temperatures. This will undoubtedly detract significantly from tensile strength and ductility; however, these effects are susceptible to modification. Two techniques are available to gain this objective. The first involves a more intensive hot-working operation. While hot upsetting was suitable for the needs of this particular program, it provided little in the way of grain refinement. Hot rolling, for example, has been shown to produce a finer grain size. The second technique employs additions of niobium. Although this was not extensively investigated, it appears very promising. Only a fraction of the increased temper resistance developed here need be coupled with adequate tensile strength and ductility to produce a temper-resistant, ultra-high strength steel.

VII. CONCLUSIONS

Several important conclusions are indicated by the experimental results obtained during this program. These conclusions are listed below; however, they can be considered valid only for steels having similar chemical and metallurgical characteristics.

1. A series of experimental medium-carbon steel compositions containing molybdenum, chromium, vanadium, and tungsten were developed capable of maintaining Rc hardnesses of 62 to 48 after tempering in the range of 1100°-1300°F.

2. Carbon appeared to have a strong effect in conferring temper resistance; this was relatively independent of composition for the range of steel compositions investigated.

3. Molybdenum and tungsten produced a significant increase in temper resistance in the presence of sufficient carbon; these elements caused the occurrence of a secondary hardening peak during tempering in the range of 1000°-1250°F.

4. In order to obtain the maximum effect of alloying on temper resistance, the austenitizing treatment must be such as to dissolve essentially all of the carbon; one hour at 2200°F was found to be satisfactory for the steels developed during this investigation.

5. Minor additions of niobium produced relatively fine-grained structures after austenitizing treatments at temperatures up to 2200°F.

6. Refrigeration treatments following air quenching techniques had no significant effect on either quenched or tempered hardness.

7. Double-tempering treatments resulted in slightly decreased hardnesses.

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TABLE I
COMPOSITION OF MOLYBDENUM STEELS

Designation	Alloy Content, per cent			
	C	Cr	V	Mo
1	0.45	1.29	0.52	1.02
2	0.44			1.99
3	0.44			3.02
4	0.42			3.36
5	0.47	1.28	0.55	4.54
6	0.45			5.46
7	0.44			6.80
8	0.44			7.58
9	0.44			8.48
10	0.57	1.17	0.58	9.18

Note: These steels were derived from the same heat by adding molybdenum progressively; additional carbon was added to alloy No. 10; nominal analysis of steels: 0.79% Mn, 0.48% Si; 0.035% S, 0.010% P.

TABLE II
COMPOSITION OF ALLOY STEELS

Designation	Alloy Content, per cent					Other Elements
	C	Cr	Mo	V	W	
A	0.46	—	4.99	0.48	—	
C	0.42	1.29	4.00	0.45	0.40	
D	0.53	1.25	4.88	0.94	0.47	
E	0.57	1.14	3.80	0.89	0.77	
G	0.37	1.16	5.28	1.10	—	
I	0.34	1.18	4.24	0.55	1.00	
J	0.41	1.08	4.27	0.45	—	2.20 Nb
M	0.45	1.17	5.89	0.56	—	2.96 Co
N	0.54	—	0.84	0.50	1.26	
N-1	0.37	0.07	6.50	1.03	—	
P	0.44	—	—	0.54	5.15	
Q	0.43	—	6.00	0.41	—	
R	0.41	—	6.92	0.39	—	
S	0.50	1.23	6.70	0.39	—	1.99 Ni
T	0.61	1.35	5.30	0.87	0.76	
U	0.61	1.35	5.40	0.90	0.93	0.14 Nb
V	0.62	1.25	5.06	0.84	0.88	0.19 Nb, 2.02 Ni
AA	0.41	—	1.08	0.55	1.04	
BB	0.44	—	1.08	0.55	2.06	
CC	0.48	—	2.03	0.50	2.91	
FF	0.49	—	2.02	0.50	3.24	

Note: All alloys were air-melted except G, I, and M;
Nominal minor alloy and impurity content: 0.80% Mn; 0.50% Si;
0.035% S; 0.010% P.

TABLE III
HARDNESS OF MOLYBDENUM STEELS
AUSTENITIZED AT 1600°F

Air-cooled after austenitizing
Double-tempered 1 hr each as shown

Composition No.	Mo Content %	Rockwell C Hardness									
		As-quenched	900°F Temper		1000°F Temper		1100°F Temper		1200°F Temper		
			First	Second	First	Second	First	Second	First	Second	
1	1.02	45	43	42	42	42	42	42	39	37	
2	1.99	42	43	41	42	40	42	41	40	36	
3	3.02	39	40	39	36	37	40	40	37	35	
4	3.36	37	39	37	37	39	39	39	31	31	
5	4.54	40	40	39	39	39	41	41	39	36	
6	5.46	38	40	39	36	36	37	37	38	35	
7	6.80	35	33	32	39	40	36	37	30	30	
8	7.58	29	30	29	29	30	28	28	27	27	
9	8.48	27	27	27	28	26	28	26	26	25	
10	9.18	27	28	27	25	26	26	28	27	26	

TABLE IV
HARDNESS OF MOLYBDENUM STEELS
AUSTENITIZED AT 1800°F
Air-cooled after austenitizing
Double-tempered 1 hr each as shown

Composition No.	Mo Content, %	As-quenched	Rockwell C Hardness							
			900°F Temper		1000°F Temper		1100°F Temper		1200°F Temper	
			First	Second	First	Second	First	Second	First	Second
1	1.02	42	40	39	38	38	39	38	34	32
2	1.99	40	40	38	38	39	36	35	36	35
3	3.02	35	33	33	31	32	32	32	30	29
4	3.36	31	30	30	30	30	32	32	28	27
5	4.54	36	35	35	33	35	36	37	32	28
6	5.46	33	34	31	30	30	31	29	29	27
7	6.80	30	30	31	29	29	27	26	28	25
8	7.58	26	28	26	25	25	26	26	25	24
9	8.48	24	26	24	25	25	23	23	22	21
10	9.18	24	26	25	25	25	24	24	23	22

TABLE V
HARDNESS OF MOLYBDENUM STEELS
AUSTENITIZED AT 2000°F

Air-cooled after austenitizing
Double-tempered 1 hr each as shown

Composition No.	Mo Content, %	Rockwell C Hardness									
		As-quenched	900°F Temper		1000°F Temper		1100°F Temper		1200°F Temper		
			First	Second	First	Second	First	Second	First	Second	
1	1.02	51	50	48	47	46	51	51	48	48	
2	1.99	52	53	50	53	51	52	51	51	50	
3	3.02	47	52	52	48	48	51	51	51	50	
4	3.36	50	50	50	55	56	55	55	53	50	
5	4.54	53	49	51	55	54	55	57	56	53	
6	5.46	51	50	49	51	54	56	55	54	52	
7	6.80	51	50	50	53	54	55	57	55	52	
8	7.58	47	47	47	48	52	52	51	50	47	
9	8.48	45	46	46	44	48	51	50	51	59	
10	9.18	49	47	47	53	54	55	54	49	48	

TABLE VI
EFFECT OF AUSTENITIZING TEMPERATURE
ON THE HARDNESS OF STEEL NO. 5

Austenitized as shown, air-cooled
Tempered for one hour each time as shown

Austenitizing Temperature, °F	Rockwell C Hardness			
	As-quenched	1200°F Temper	1275°F Retemper	1342°F Retemper
1900	44	44	39	32
2000	50	47	42	35
2100	45	46	42	34
2150	50	50	46	38
2200	56	51	45	39

TABLE VII
AS-QUENCHED AND TEMPERED HARDNESSES
OF EXPERIMENTAL STEELS
Austenitized at 2200°F
Tempered for one hour as shown

Designation	As-quenched Hardness, Rc	600°F	800°F	1000°F	1200°F	1250°F	1300°F	1350°F
A	59	56	57	59	56	53	47	--
C	57	55.5	56	59	55	49	45	--
D	59	58	59	62	59	54	48	--
E	60	60	60	63	60	55.5	51.5	--
G	57	55	55	57	52	50.5	42.5	--
I	56	55	55	58	51	48	40	--
J	57.5	54	56	57	46	44	41	--
M	61	57.5	57	61	55	49	43.5	--
N	64	57	55	56	54	52.5	47.5	42
N-1	55	56	58.5	60	51.5	45	35.5	38
P	61.5	54	53	52	55	55	50	38
Q	58	54	53	55	52.5	44	39	--
R	58	55.5	56	57.5	53	43	35.5	--
S	63	57	57	60	53	50	46.5	--
T	65	58	57	61	61.5	59	52	42
U	63	59	58	61	60.5	58	52	40
V	62.5	56	58	62	59	57	49	47.5

TABLE VII (Cont'd)
AS-QUENCHED AND TEMPERED HARDNESSES
OF EXPERIMENTAL STEELS
Austenitized at 2200°F
Tempered for one hour as shown

Designation	As-quenched Hardness, Rc	Rockwell C Hardness after Tempering at:					
		600°F	800°F	1000°F	1200°F	1250°F	1300°F
AA	54.5	--	50	48.5	50	47	48
BB	58	--	50.5	51	52.5	51.5	51.5
CC	54.5	--	--	54.5	55.5	--	53
FF	58	--	54	52	57	51	51

Alloys C, D, and E were air-cooled; all other alloys were oil quenched.

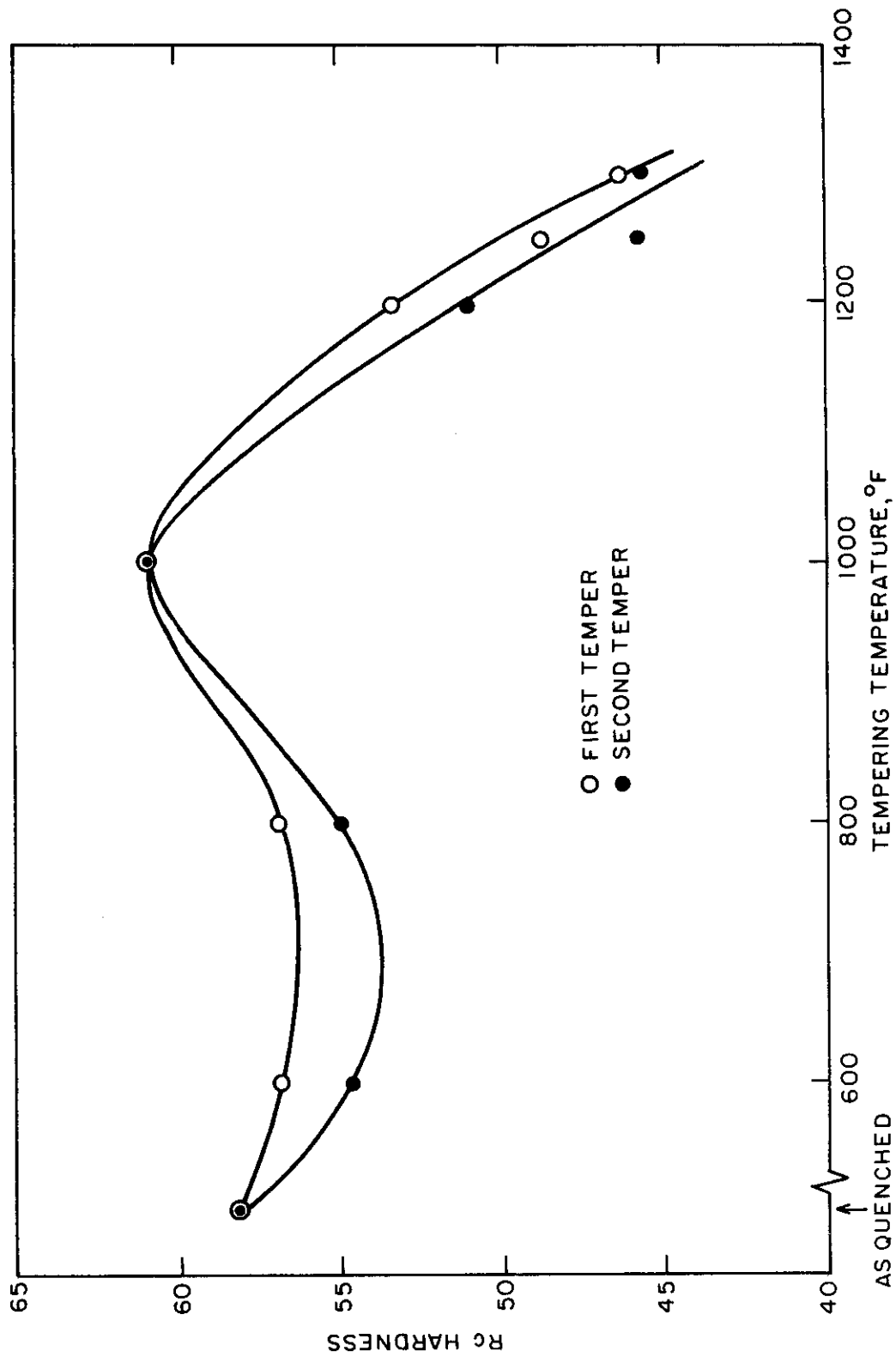


FIG. 1 - TEMPERED HARDNESS OF STEEL NO. 5 CONTAINING 0.47% C, 4.54% Mo, 1.28% Cr, AND 0.55% V, AUSTENITIZED AT 2200°F, AIR COOLED, AND TEMPERED FOR ON HOUR AS SHOWN.

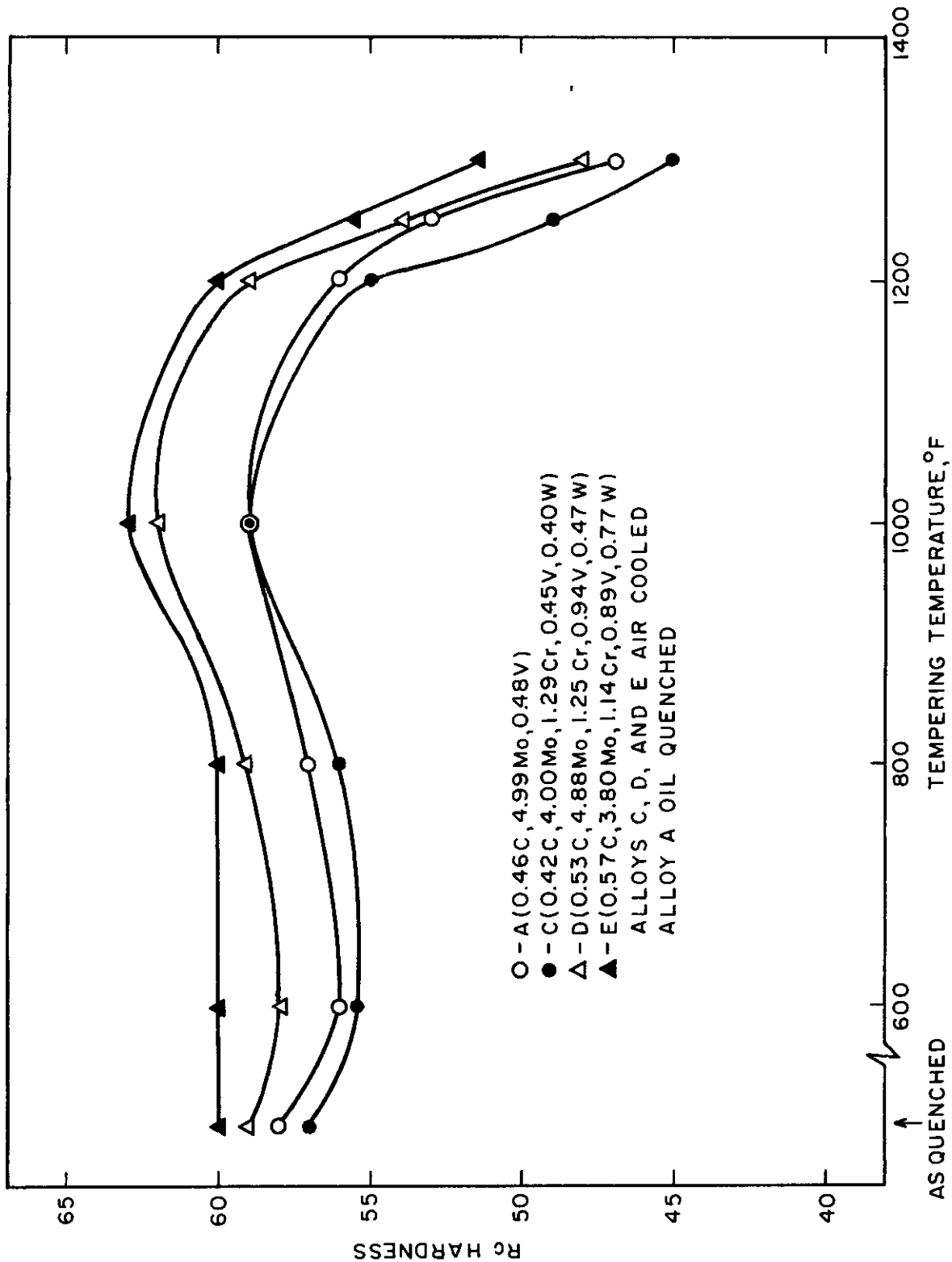


FIG. 2 - TEMPERED HARDNESS OF VARIOUS ALLOY STEELS AUSTENITIZED AT 2200°F, AND TEMPERED FOR ONE HOUR AS SHOWN.

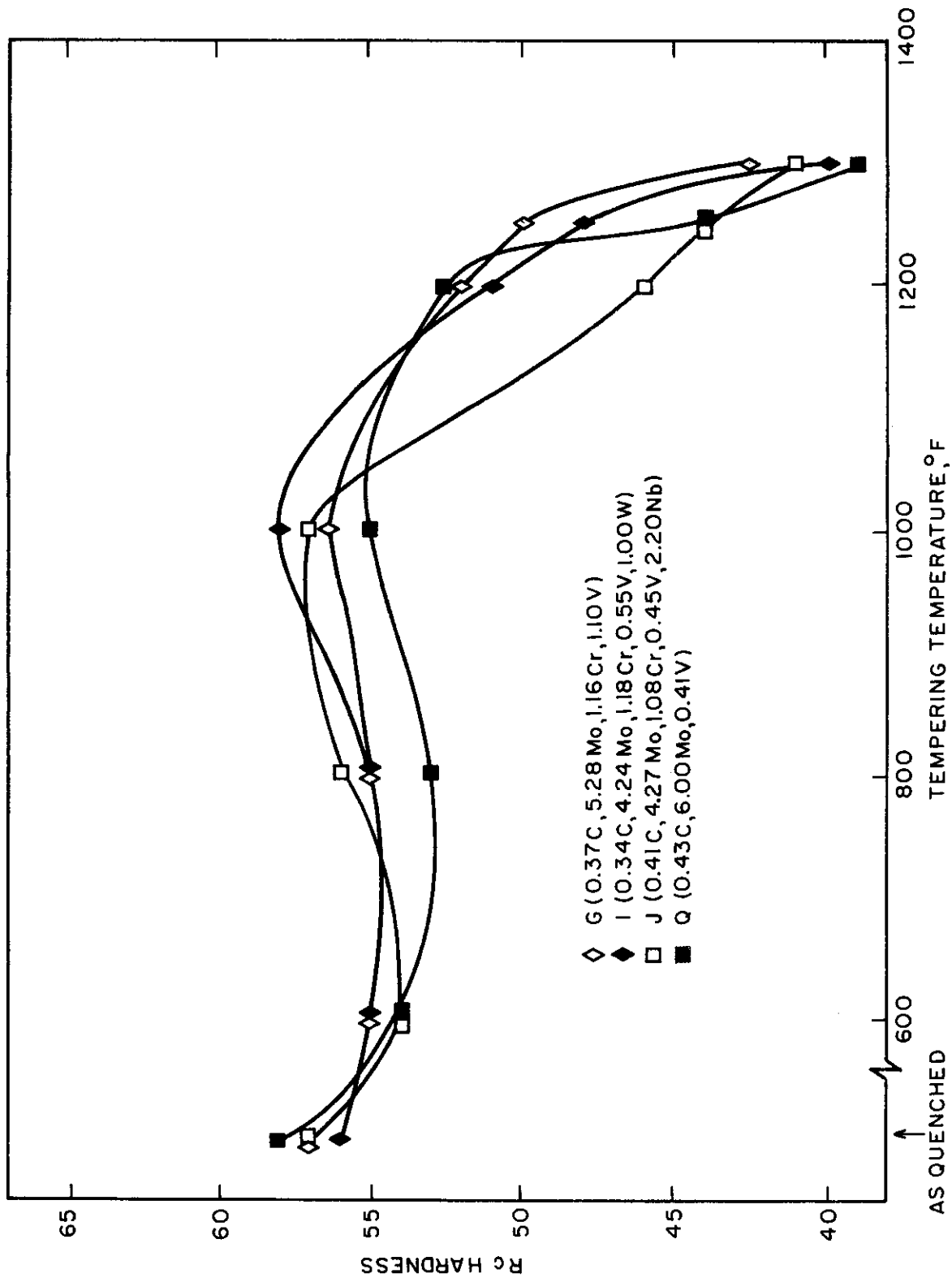


FIG.3-TEMPERED HARDNESS OF VARIOUS ALLOY STEELS AUSTENITIZED AT 2200°F, OIL QUENCHED, AND TEMPERED FOR ONE HOUR AS SHOWN.

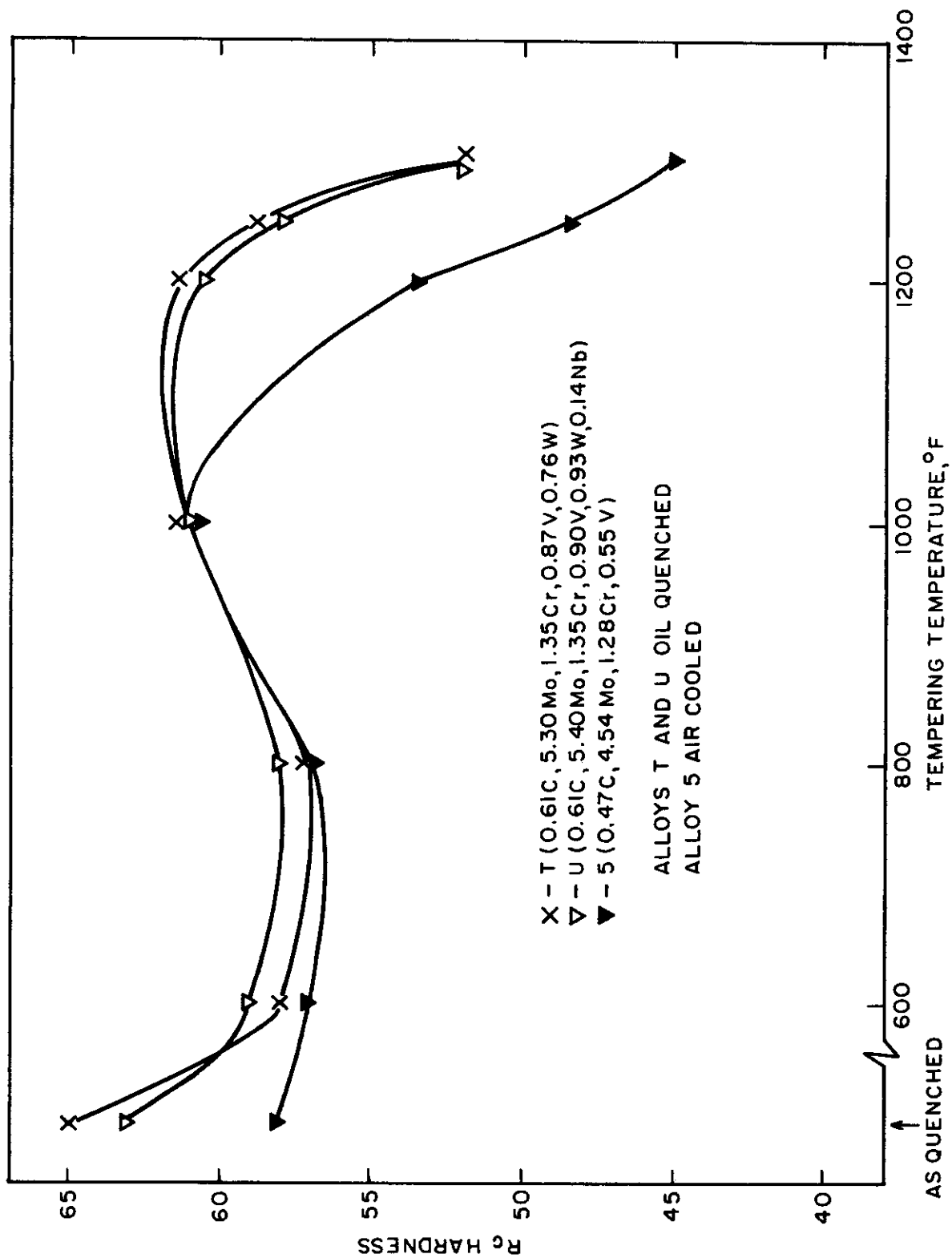


FIG. 4-TEMPERED HARDNESS OF VARIOUS ALLOY STEELS AUSTENITIZED AT 2200°F, AND TEMPERED FOR ONE HOUR AS SHOWN.

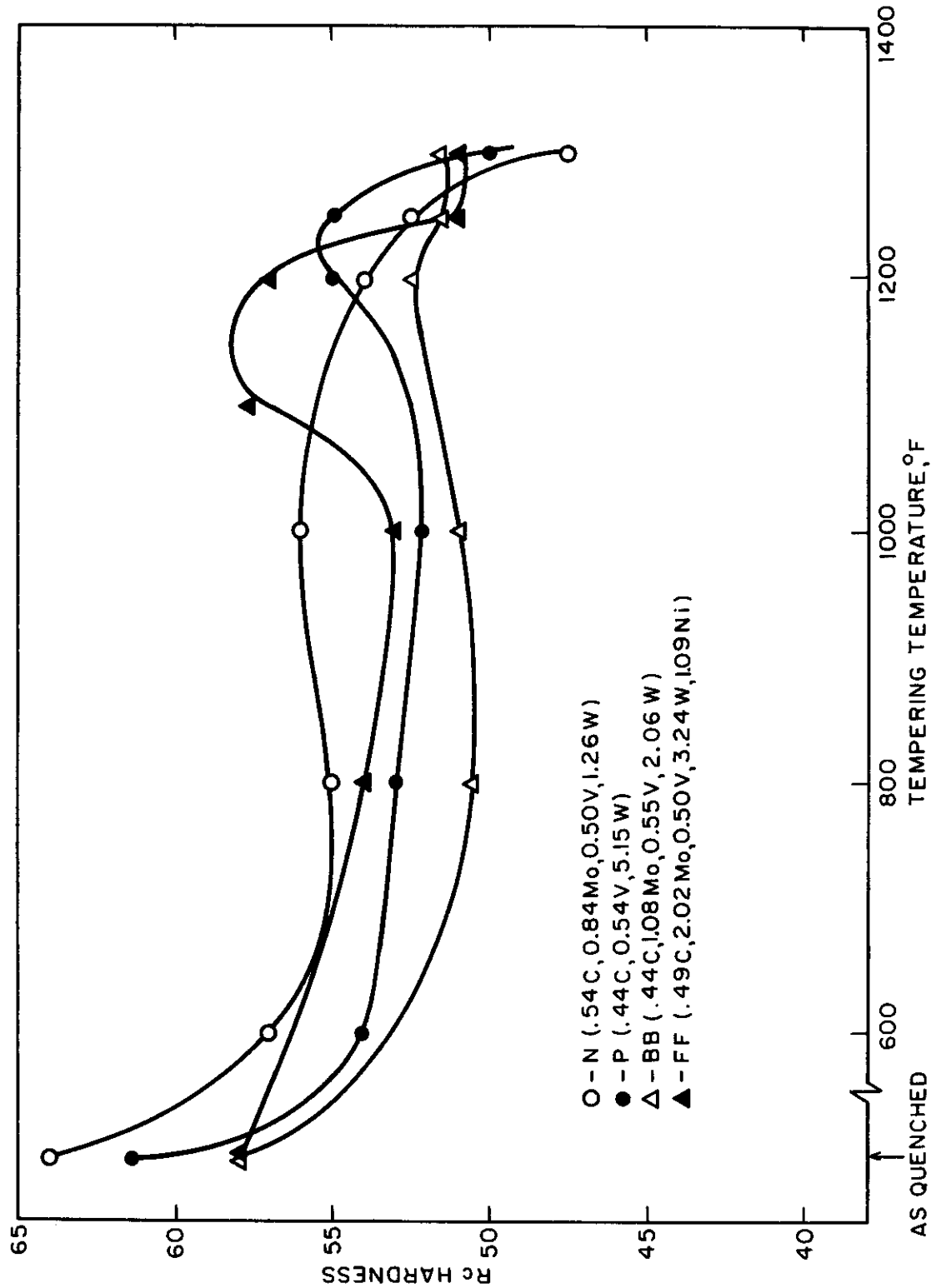


FIG. 5- TEMPERED HARDNESS OF VARIOUS ALLOY STEELS AUSTENITIZED AT 2200°F, OIL QUENCHED, AND TEMPERED FOR ONE HOUR AS SHOWN.

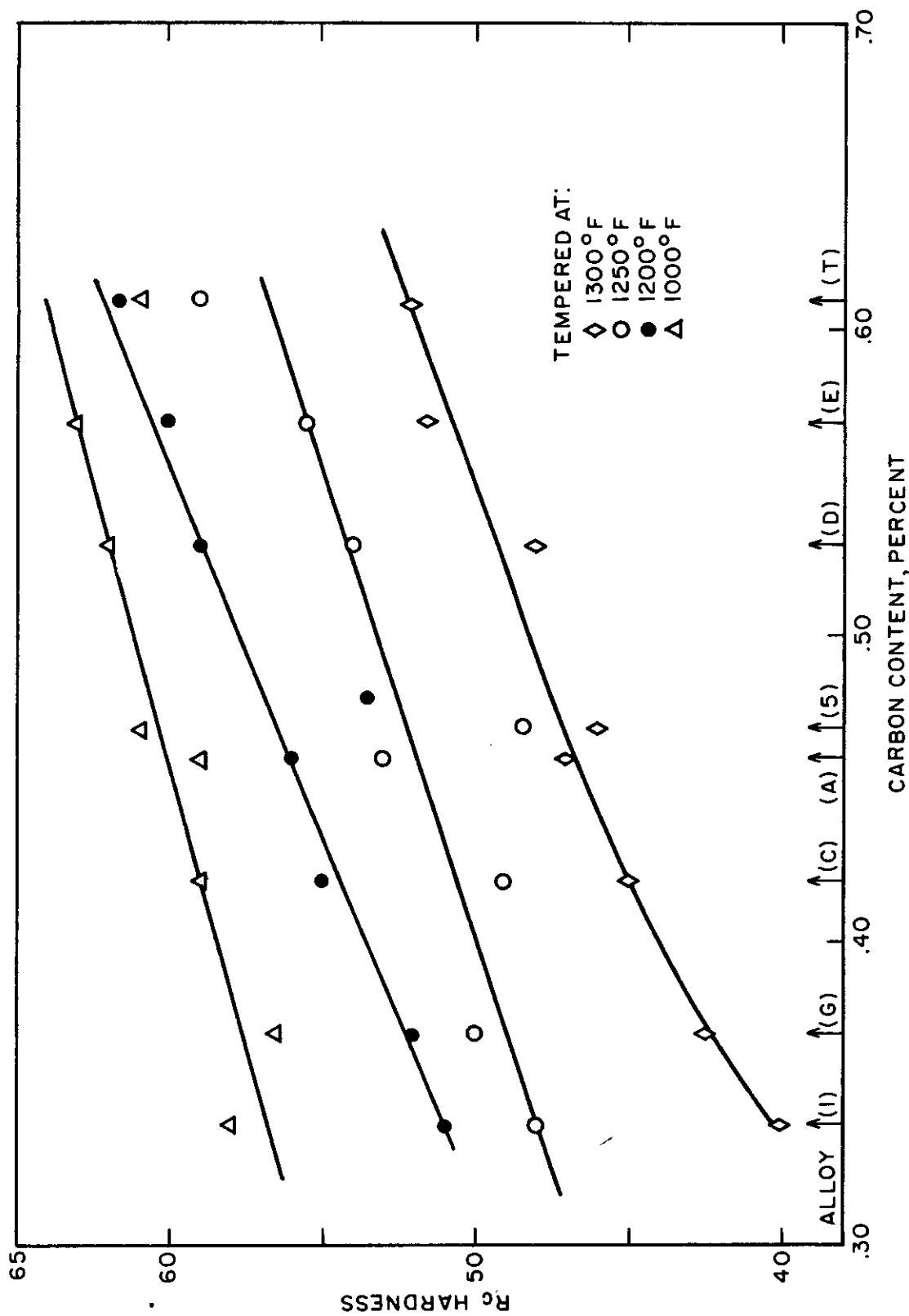
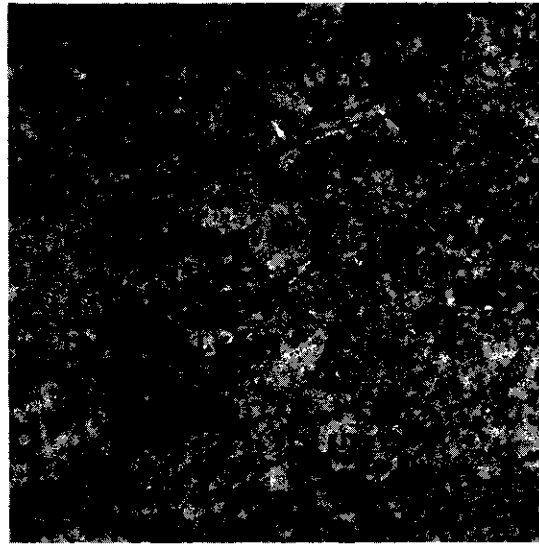


FIG.6 -THE EFFECT OF CARBON CONTENT ON THE TEMPERED HARDNESS OF EIGHT ALLOY STEELS.



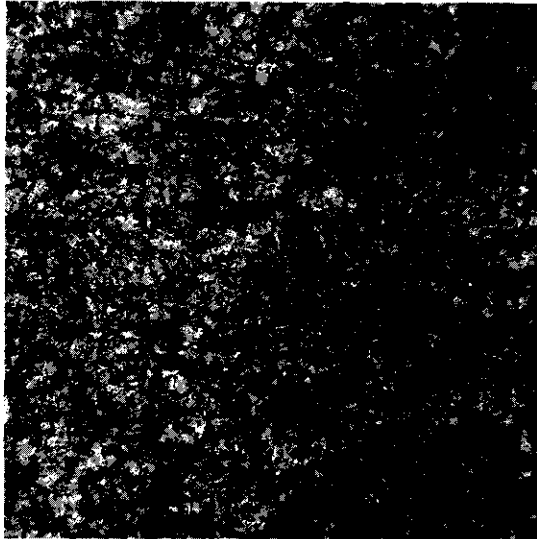
Neg. No. 17997
Etchant: 2% nital

100X

Fig. 7 Microstructure of Steel T,
Quenched and Tempered

Austenitized at 2200°F

Composition:	<u>C</u>	<u>Mo</u>	<u>Cr</u>	<u>V</u>	<u>W</u>
	0.61	5.30	1.35	0.87	0.76



Neg. No. 17998
Etchant: 2% nital

100X

Fig. 8 Microstructure of Steel U,
Quenched and Tempered

Austenitized at 2200°F

Composition:	<u>C</u>	<u>Mo</u>	<u>Cr</u>	<u>V</u>	<u>W</u>	<u>Nb</u>
	0.61	5.40	1.35	0.90	0.93	0.14

Contrails