THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

HARDENABILITY OF SILICON-MANGANESE SPRING STEEL (250A58 and 250A61)

by

P. Gray, B.Sc.

Report No. 280

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SUMMARY AND CONCLUSIONS

Seven samples of silicon-manganese spring steel, all having slight differences in composition, have been tested by the Jominy method in order to determine their hardenability. Tensile and hardness tests have been carried out on each sample after tempering at various temperatures between 375 and 550°C.

The slight variations in mechanical properties, hardness and hardenability were analysed in order to determine whether there was any correlation with the variations in chemical composition of the steels. It was found that, over the range of compostions investigated, hardenability was insensitive to small changes in carbon and residual element contents. There was, however, a difference in as-quenched hardness and hardness after tempering which could be attributed to the difference in carbon content. The mechanical properties after tempering in the range 400 to 550°C were found to be insensitive to compositional changes over the range of compositions investigated.

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1. INTRODUCTION

The objective of this work was to investigate the effect on hardenability of small changes in composition within the British Standard specification for silicon-manganese spring steel. Seven batches of steel were used with carbon contents in the range 0.55 to 0.63 per cent. Hardenability was determined by the "Jominy" method and both tensile properties and hardness were determined at several tempering temperatures in the range 375 - 550°C. An attempt was made to correlate the variations in hardenability and the mechanical properties with the variations in the concentrations of the nine elements.

Use was made of previous work on the hardenability of silicon-manganese spring steel, and other steels, where relevant, to substantiate the findings of the present work.

2. EXPERIMENTAL METHODS

2.1 Material

Bar stock having diameters between 26.2 and 38.1 mm, of seven different batches of steel, were used. The chemical composition, including the three main elements, C, Si and Mn, plus six residual elements are given in Table I. Microscopical examination of samples taken from the bars indicated, in each case, that the steel had a satisfactory level of cleanness, being less than level 1 on the J.K. chart for 60 x 100 fields.

The prior-austenite grain size in the initial condition was estimated to be 6 in each case, as examined in accordance with BS 4490. In five of the seven batches, sufficient pro-eutectoid ferrite was present to enable the prior-austenite grain size to be identified by heavy etching in 2% nital. Some of the samples, including the remaining two, showed a small quantity of decarburisation at the bar surface from which the grain size could also be estimated. Similar grain size estimates were obtained in those samples for which both methods could be employed.

2.2 Sample Preparation

2.2.1 Hardenability test samples

The samples were prepared in accordance with BS 4437, being machined from the stock bar to the standard 25.4 mm diameter and 100 mm length. Two samples from each batch were prepared and were held for 30 minutes at 920°C in a muffle furnace with an estimated temperature accuracy of ±5°C. Small pieces of graphite were placed in the furnace with the bars for the full 30 minute period in an attempt to minimise decarburisation. Each bar, after soaking for 30 minutes at 920°C, was quenched at one end by a water jet using a "Metaserve" end quench unit set up to conform to the procedure outlined in BS 4437. The essential features of the apparatus are illustrated schematically in Fig. 1 and shown in use in Fig. 2.

Two parallel flats were subsequently ground (using a copious supply of coolant) along the length of each bar to a depth of 0.4 mm and hardness determinations were made at regular intervals (i.e. 1.5, 3, 5, 7...... mm etc.) from the quenched end using a Vickers hardness tester (HV 30) in accordance with Method 1 in BS 4437.

2.2.2 Tempering test samples

Bars 13 mm in diameter by 50 mm long were machined from the stock bar and quenched in oil from 920°C after soaking for 30 minutes at temperature. The same furnace and decarburisation precautions were used as described in section 2.2.1. A hardness determination was made using the Vickers hardness tester (HV30) after grinding and polishing a 0.4 mm deep flat on the cylindrical surface. Sufficient sample bars were made available so that, for each batch of steel, one bar was tempered for 1 hour at temperatures differing by 25°C in the range 375 - 550°C inclusive. The tempering was carried out in an air circulation furnace with an estimated accuracy of ±5°C.

After tempering, a new 0.4 mm deep flat was prepared on each sample bar and a hardness (HV30) value determined. A hardness value was also determined from the centre of a polished transverse section of each sample bar, sectioned using a water cooled, metallographic slitting machine.

2.2.3 Tensile test samples

Tensile test samples were machined from the stock bar to about 14.32 mm diameter on the gauge length, thus allowing 0.5 mm to be removed after heat treatment to eliminate any decarburisation or other surface effects. The final diameter of the gauge length was 13.82 mm ± 0.77 mm for all tensile test specimens, other dimensions being in conformity with BS 18: Part 2 (1971).

The test pieces so prepared were held at 920°C for 30 minutes, using the same furnace and applying the same decarburisation precautions as described in section 2.2.1, and then quenched in oil.

Sufficient test samples were made so that, for each batch of steel, one sample was tempered for 1 hour at temperatures differing by 50°C in the range 400-550°C inclusive. This tempering was carried out, where relevant, with the samples of section 2.2.2, in the same furnace.

All tensile tests were performed on a 300kN Amsler, hydraulically powered tensile testing machine. Elongation, in all cases but one, was measured by means of a 50 mm Baldwin electronic extensometer with an automatic graph plotting facility.

3. RESULTS

3.1 Hardenability

The hardness determinations are presented in Figs. 3 - 9 which include for each steel the points for four separate longitudinal traverses from the quenched end to up to 30 mm from the end of the bar, from two parallel 0.4 mm deep longitudinal flats from each of two samples of each batch of steel. In each figure a curve is drawn through one of the four sets of data.

3.2 Hardness results after tempering

The hardness results after tempering for one hour at a temperature in the range 375 - 550°C inclusive are presented in Table II. Two sets of results are given, one from a flat filed and polished on the circumference of the bar and the other from transverse sections, cut using a metallographic slitting machine and then polished. Statistical analysis of the two sets of results showed no significant difference between them, indicating that no undue heating of the transverse surface had occurred during sectioning.

Also included in Table II are some hardness results obtained from samples in the as-quenched condition. Two sets of samples were tested for hardness prior to tempering. Statistical tests showed that any differences between the two groups were not significant, indicating that both the quenching efficiency and chemical homogeneity of the material were satisfactory.

3.3. Mechanical Properties

The tensile properties for the seven steels investigated, at four tempering temperatures, are given in Table III.

4. DISCUSSION

4.1 Hardenability

The curves given in Figs. 3 - 9 for the hardenability of the seven steels studied have been redrawn in Fig. 10, to illustrate the close spacing of the curves. Figs. 3 - 9 each give an idea, from the spread of the points themselves, of the kind of uncertainty that exists for each curve. If this is taken into account in Fig. 10, it is evident that there is little significance in most of the differences in the positions of the hardenability curves.

From the Jominy curve results, by suitable calculations, the diameter of bars which will give the same hardness at the centre as that at some specific point from the quenched end of the Jominy bar can be determined, as long as the efficiency of the quenching medium is known(1,2).

If the quenching medium is assumed to be 100% efficient (H value ∞) then an "Ideal Diameter - D_I" can be calculated which is purely a function of the compositions of the steel.

In practice, however, silicon-manganese spring steels are quenched in agitated oil which has a heat transfer index, "H", of approximately 0.35.

The curves for both D_I and the bar diameter quenched in oil as a function of the distance from the water cooled end of the Jominy test piece are given in Fig. II. From this graph equivalent D_I and DH=0.35 values have been determined for the Jominy distances corresponding to 650 HV30 from the curves in Figs. 3 - 9 for each steel; the results are presented in Table IV.

These results confirm the generally accepted view that silicon-manganese spring steel can be adequately hardened in oil up to a bar diameter of about 30 mm. Steels 4 and 6 seem to have significantly better hardenability than the others at a hardness of 650 HV; this does not, however, seem to correlate with any of the compositional variations in Table I.

It is often the practice to relate critical diameters such as those given in Table IV to the point at which a specific proportion of martensite is present at some point along the Jominy bar. For two practical reasons a hardness criterion (i.e. 650HV30) has been chosen instead. Firstly, it proved difficult to distinguish, in silicon-manganese spring steel, between martensite and bainite in the Jominy specimens and the accuracy of locating the point at which, say, 90% of the structure was martensite was subject to considerable error.

Secondly, it was felt that, for springs, the overriding requirement was fora suitable strength (i.e. hardness) level, even if the microstructure at the centre of the bar was partly bainitic. It is well appreciated that fatigue failure initiates at or near the surface, which is in any case still fully martensitic, and that the torsional stress levels as the centre of the bar is approached decrease to zero. In any case bainite, when tempered, still has an appreciable strength.

4.2 Hardness results before and after tempering

From the results in Table II, the tempering curve in Fig. 12 has been derived, each point on the curve being the mean hardness for the seven batches of steel. The dotted lines are confidence limits based on two standard deviations from the mean of each group of data and represent a 0.95% probability of an individual hardness determination (after a 1 hour temper) being within the limit shown.

The individual sets of hardness values for each batch of steel were analysed statistically to determine whether there was any significant difference in hardness between one batch and another. The differences in hardness between each value and the mean for that temperature were taken as the basic data and the means and standard deviations were calculated for these values from the complete range of temperatures for each individual steel. Using steel No. 3, which had the highest mean hardness difference as the control, Student's "t" tests were performed on the remaining batches to determine whether the differences between the two extremes in hardness levels were significant. It was shown that: steel No. 2 had a lower range of hardnesses which were significant at 0.2% (i.e. in only 1 time in 500 such situations could the difference be due to chance alone); steel No. 7 was significantly different to a level of greater than 0.1%; and steel No. 4 had a very highly significant difference, being much greater than 0.1%. The difference between steel No. 3 and the remaining batches of steel were found not to be significant. The as-quenched hardness values in Table II are plotted in Fig. 13 as a function of carbon content (from Table I) for each of the seven batches of steel.

Linear analysis of the data gives a correlation coefficient of 0.807 which, by performing a Z-transformation(3) was found to be a highly significant trend. This is not, of course, a particularly surprising result(5) and it can be seen that the effect of carbon content also persists after tempering since, as explained in the previous few paragraphs, a significant lowering of the tempering curve occurs to an increasing degree in steels 2, 7 and 4 respectively; this corresponds to the order of placement of these batches in Fig. 13, with the exception of batch 3 which has a tempering curve which is displaced to a higher hardness than would have been predicted by the remaining data. One possibility for this anomaly may be ascertained from Table I; it can be seen that this particular batch, steel No. 3, has a residual Cr content of 0.32%, compared with 0.22 ±0.03% Cr in other batches. Cr is known to confer improved temper resistance in high carbon steels(5).

4.3 Mechanical Properties

At first sight, from Table III, there may appear to be some relationship between the tensile properties (after tempering in the range 400 to 550°C) to the carbon contents of the steels investigated but statistical tests proved there was no correlation between the two factors. The reduction of area is of interest in steel No. 6; this is quite different from the mean reduction of area of the rest of the tensile specimens at every tempering temperature used. Statistical test in all cases show that the difference is highly significant.

4.4 Unexplained Anomalous Results

Steels Nos. 4 and 6 show differences from the normal behaviour which are not immediately obvious from the data as presented here. Both steels 4 and 6 show mathematically significant (though not necessarily significant in a production context) improvements in hardenability, as illustrated in Fig. 10 and Table IV, steel No. 6 showing a marked drop in ductility or toughness as represented by the reduction of area in a tensile test. The relatively high hardenability of steel No. 4 may be explained by the fact that this steel has, coincidentally, the highest Mo, Ni, and one of the highest Mn contents, all of which elements, particularly Mo, are known to increase the hardenability of high carbon steels(6).

The situation with respect to steel No. 6, which has an increased hardenability and also a low toughness is more intriguing, and at this stage no satisfactory explanation can be given.

CONCLUSIONS

1. The hardenability of silicon-manganese steel is not sensitive to small changes in carbon, alloy and residual element contents within the composition ranges investigated. The ranges were confined to a band of composition within the current British Standard 970, 250A58/61 range within which silicon-manganese spring steel is currently being manufactured by British steelmakers.

2. Much of the difference in as-quenched hardness and hardness response to tempering, can be attributed to differences in carbon content. A tempering curve is given based on the results from the seven silicon-manganese steels studied.

3. Mechanical properties are not sensitive to small changes in composition within the band of compositions investigated.

6. RECOMMENDATIONS FOR FUTURE WORK

1. Some further examination of the tensile fractures and microexaminations of suitable sections of the specimens, particularly the Jominy test samples, may provide further information to explain some anomalous results which were found during the course of the work. Some impact testing may also be of value in this respect.

7. REFERENCES

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3. Moroney, M.J., "Facts From Figures", Penguin (1951).

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6. Jatczak, C.F., "Hardenability in High Carbon Steels", Met. TRANS, 1973, October.

7. Iron and Steel Institute Publication 56. "Isothermal Transformation Diagrams".

8. Iron and Steel Institute Publication 36. "Symposium on the Hardenability of Steel" (1946), pp. 89-92, 99-113, 164-168, 353-354.

TABLE I COMPOSITION OF THE SEVEN SILICON-MANGANESE SPRING STEELS INVESTIGATED.

SAMPLE No.	C %	Si %	Mn %	S %	P %	Cr %	Ni %	Mo %	V %
1	0.62	1.88	0.84	0.034	0.018	0.20	0.28	0.03	0.04
2	0.58	1.83	0.84	0.026	0.017	0.22	0.25	0.02	0.03
3	0.55	1.81	0.91	0.036	0.019	0.32	0.28	0.03	0.03
4	0.55	1.88	0.91	0.032	0.017	0.20	0.30	0.04	0.03
5	0.60	1.85	0.92	0.020	0.024	0.23	0.19	0.02	0.01
6	0.63	1.75	0.87	0.028	0.018	0.20	0.25	0.02	0.01
7	0.56	1.85	0.86	0.030	0.020	0.25	0.28	0.03	0.01

TABLE II HARDNESS DETERMINATIONS (HV30) ON STEEL SAMPLES AFTER TEMPERING FOR 1 HOUR AT INDICATED TEMPERATURE.

TEMPERING TEMPERATURE °C		SAMPLE NO.						
		1	2	3	4	5	6	7
BEFORE TEMPER		789	774	752	735	760	808	740
375	ON FLAT	650	644	637	613	642	642	637
	ON SECTION	652	622	650	614	646	648	624
BEFORE TEMPER		805	799	772	744	775	812	775
400	ON FLAT	600	593	597	575	611	616	601
	ON SECTION	588	583	602	571	602	594	581
425	ON FLAT	550	536	540	533	561	549	533
	ON SECTION	550	548	564	537	568	554	543
450	ON FLAT	525	527	522	508	512	518	521
	ON SECTION	523	514	528	499	525	521	508
475	ON FLAT	500	-	490	485	486	494	486
	ON SECTION	484	-	496	473	495	492	480
500	ON FLAT	455	457	457	450	452	465	457
	ON SECTION	467	453	478	446	470	465	451
525	ON FLAT	437	442	442	427	437	441	433
	ON SECTION	436	429	454	427	454	439	432
550	ON FLAT	420	413	424	406	415	413	410
	ON SECTION	411	403	426	402	427	422	413

TABLE III TENSILE PROPERTIES OF STEEL SAMPLES AFTER HARDENING AND TEMPERING

SAMPLE NO.	Rm N/mm^2	L of P N/mm^2	Rpo.05 N/mm^2	Rpo.1 N/mm^2	Rpo.2 N/mm^2	Z (r of A) %	A (El) %
	TEMPERING TEMPERATURE 400°C						
1							
2	1990	1520	1830			11.6	7.0
3							
4	1910	1350	1670	1720	1750	17.9	9.4
5							
6	1950	1000	1640	1710	1760	1.9	3.1
7	1960	1470	1730	1760	1780	18.4	8.6
	TEMPERING TEMPERATURE 450°C						
1	1740	1090	1550	1570	1580	14.2	10.9
2	1670	1130	1450	1470	1500	14.2	11.7
3	1670	1050	1480	1510	1520	13.6	10.1
4	1630	1060	1450	1470	1490	15.3	11.7
5	1700	1070	1490	1510	1530	13.6	10.9
6	1680	1310	1480	1500	1520	6.3	10.1
7	1610	-	1440	1470	1480	17.4	10.1
	TEMPERING TEMPERATURE 500°C						
1	1540	950	1340	1350	1360	12.8	13.3
2	1500	1070	1310	1320	1340	14.7	16.4
3	1510	950	1350	1370	1380	12.6	11.7
4	1440	1050	1290	1310	1320	17.2	12.5
5	1500	940	1340	1350	1360	10.9	11.7
6	1490	940	1320	1330	1340	7.0	9.4
7	1580	950	1290	1300	1320	12.8	10.1
	TEMPERING TEMPERATURE 550°C						
1	1320	-	1130	1140	1150	16.8	14.1
2	1320	890	1130	1150	1170	18.6	17.2
3	1340					15.2	14.1
4	1300	1030	1130	1140	1160	17.6	15.6
5	1330	880	1170	1190	1190	12.4	14.1
6	1330	870	1150	1160	1170	9.2	12.5
7	1300	810	1140	1150	1160	18.5	14.1

TABLE IV JOMINY DISTANCES FROM THE QUENCHED END OF THE BAR CORRESPONDING TO THE POSITION AT A HARDNESS OF 650 HV30 WITH CORRESPONDING VALUES OF D_I AND $D_H = 0.35$ FOR THE SEVEN SAMPLES OF STEEL.

SAMPLE NO.	JOMINY DEPTH FOR 650 H_V (mm)	D_H=0.35 (mm)	D_I (mm)
1	11.0	28	67.0
2	11.1	28	68.0
3	10.8	28	66.5
4	12	31	71.0
5	10.5	27	65.0
6	12.4	32	72.0
7	10.8	28	66.5.

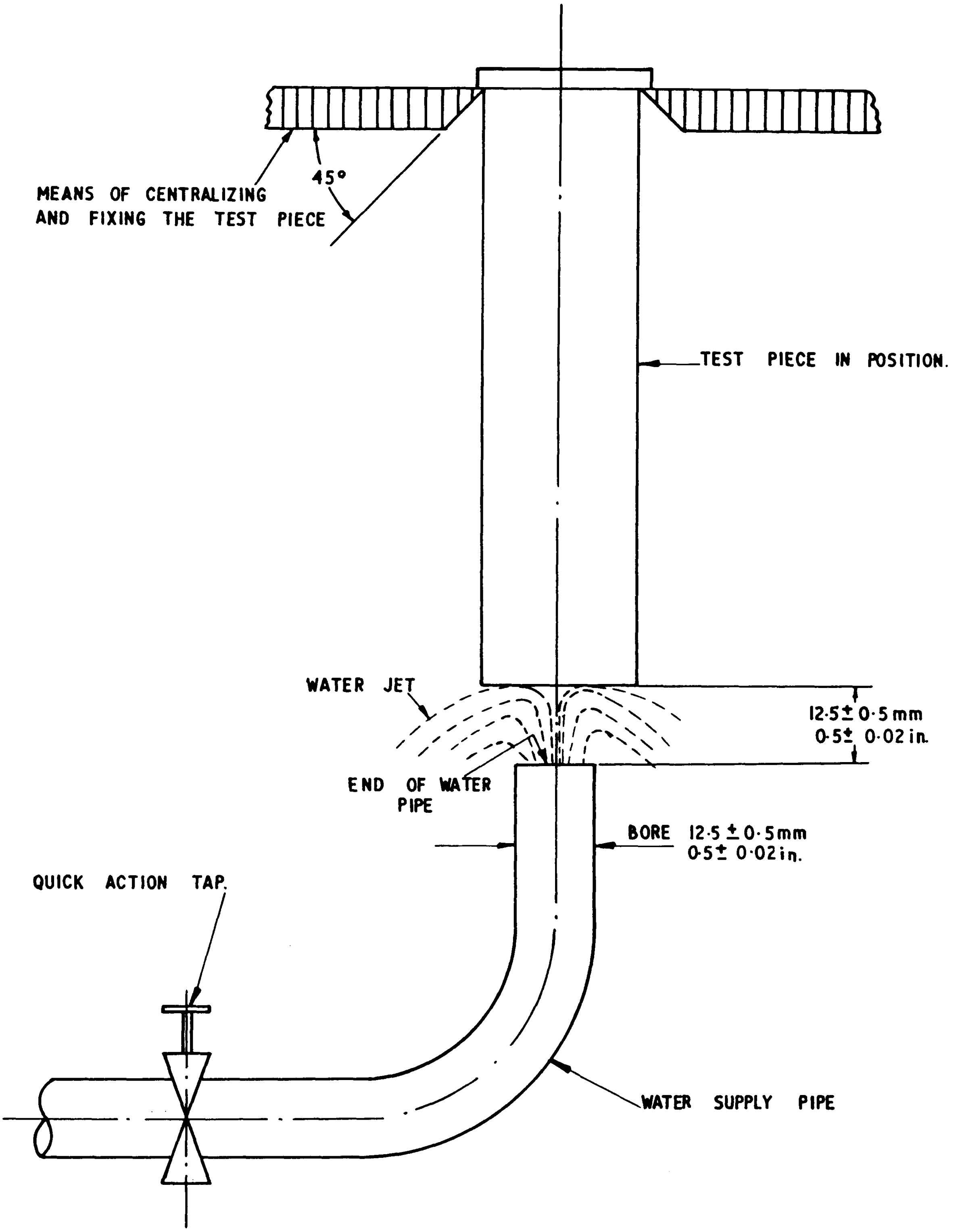

FIG. 1 SCHEMATIC DIAGRAM OF HARDENING APPARATUS.

Fig. 2 Jominy End Quench Apparatus

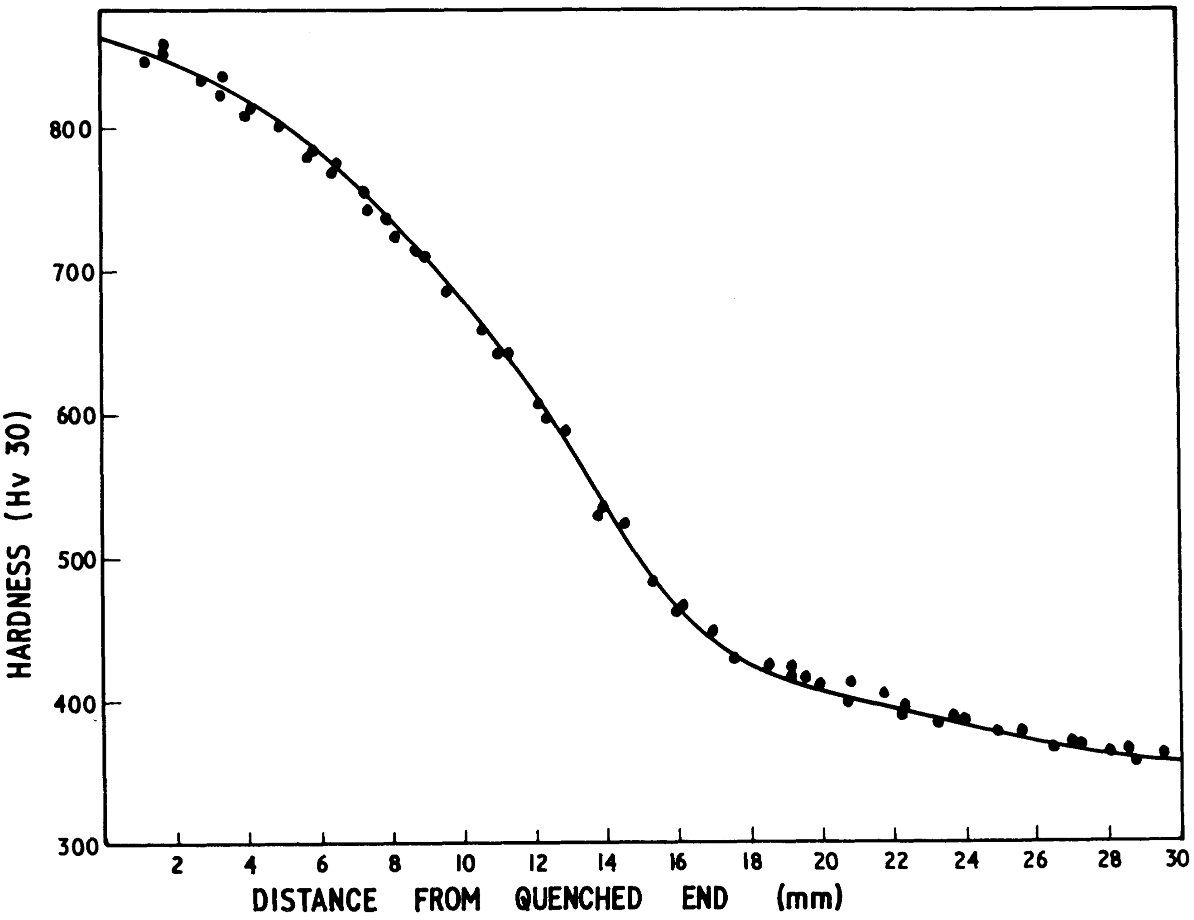

FIG. 3 JOMINY END QUENCHED HARDENABILITY CURVE FOR STEEL No.1. (- POINTS FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES - LINE DRAWN THROUGH ONE SET OF DATA.)

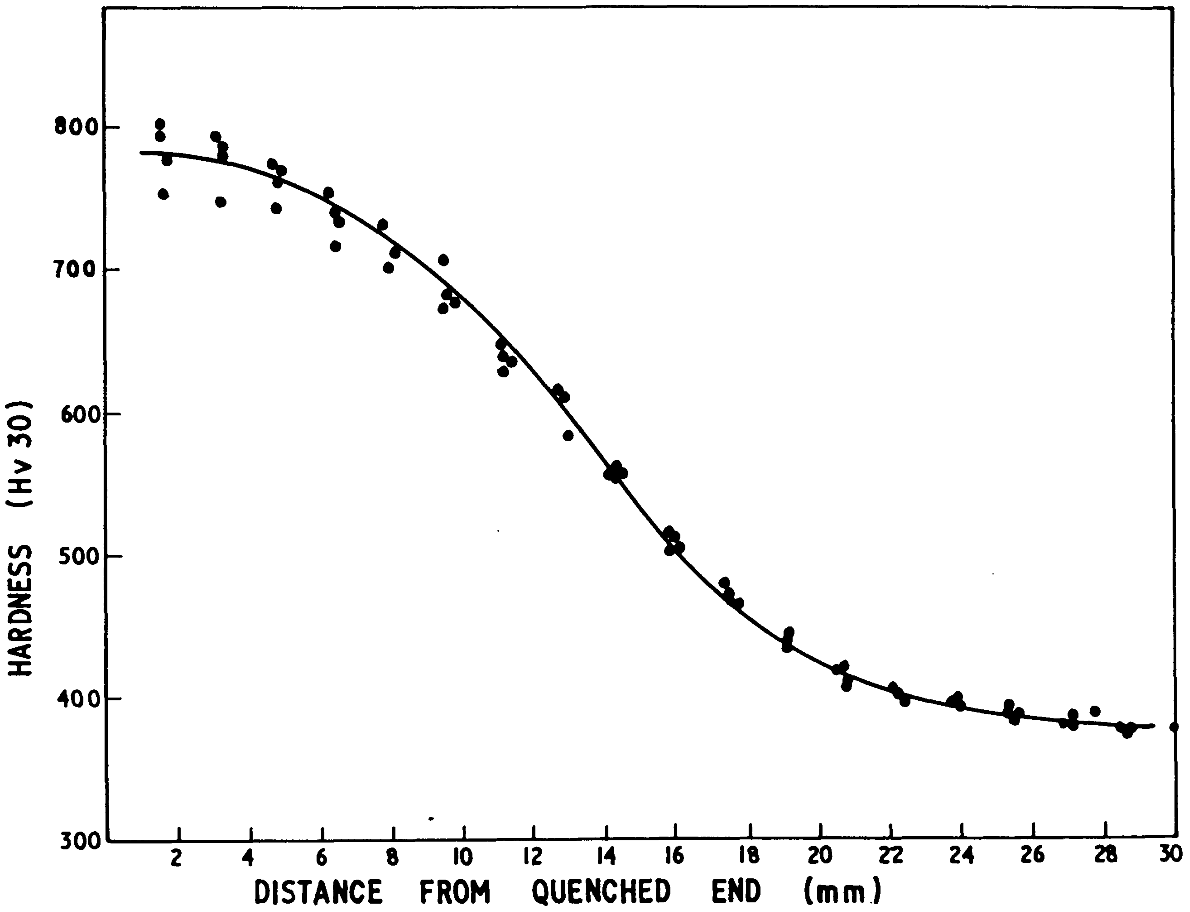

FIG. 4 JOMINY END QUENCH HARDENABILITY CURVE FOR STEEL No. 2. (POINTS FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES – LINE DRAWN THROUGH ONE SET OF DATA.)

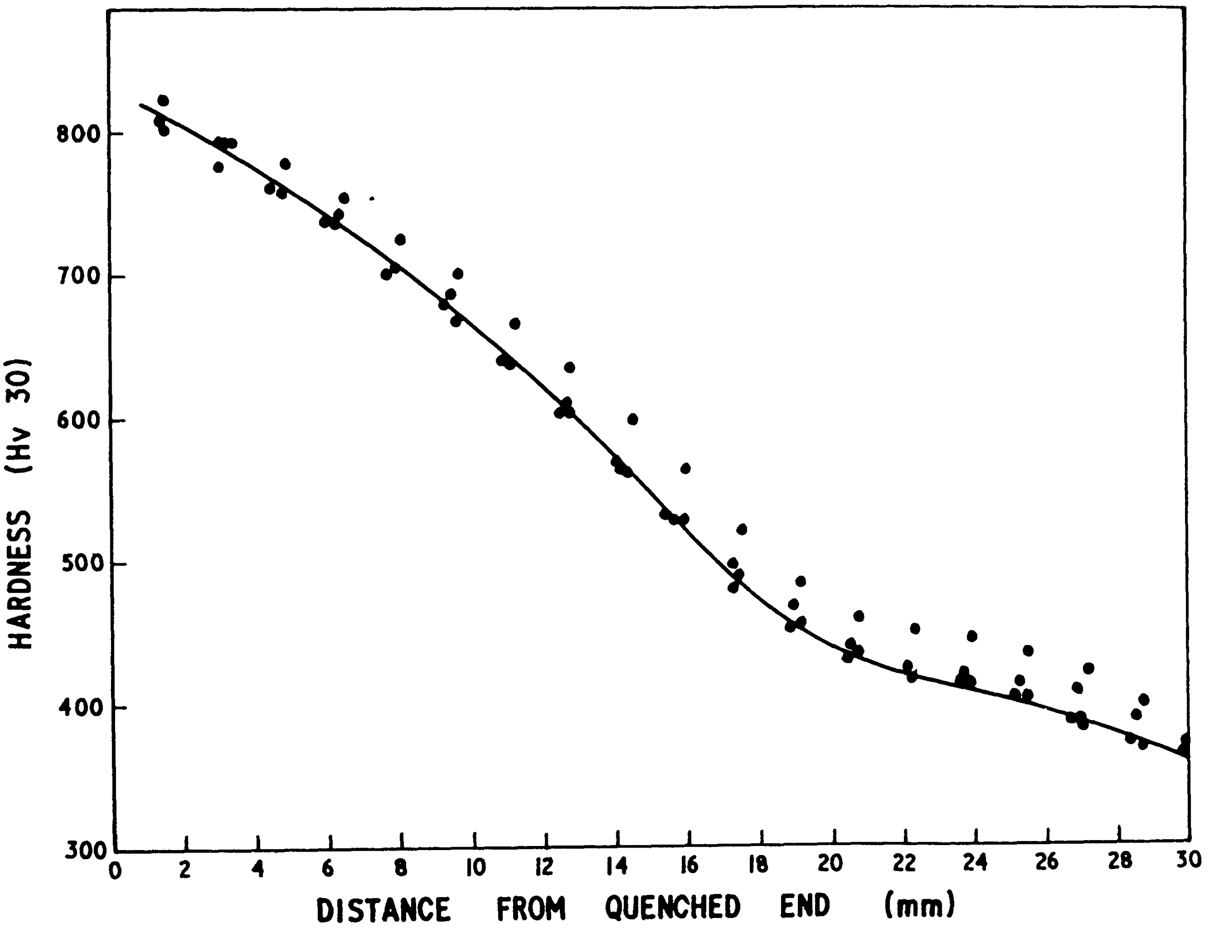

FIG. 5 JOMINY END QUENCH HARDENABILITY CURVE FOR STEEL No.3. (POINTS ARE FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES – LINE DRAWN THROUGH ONE SET OF DATA.)

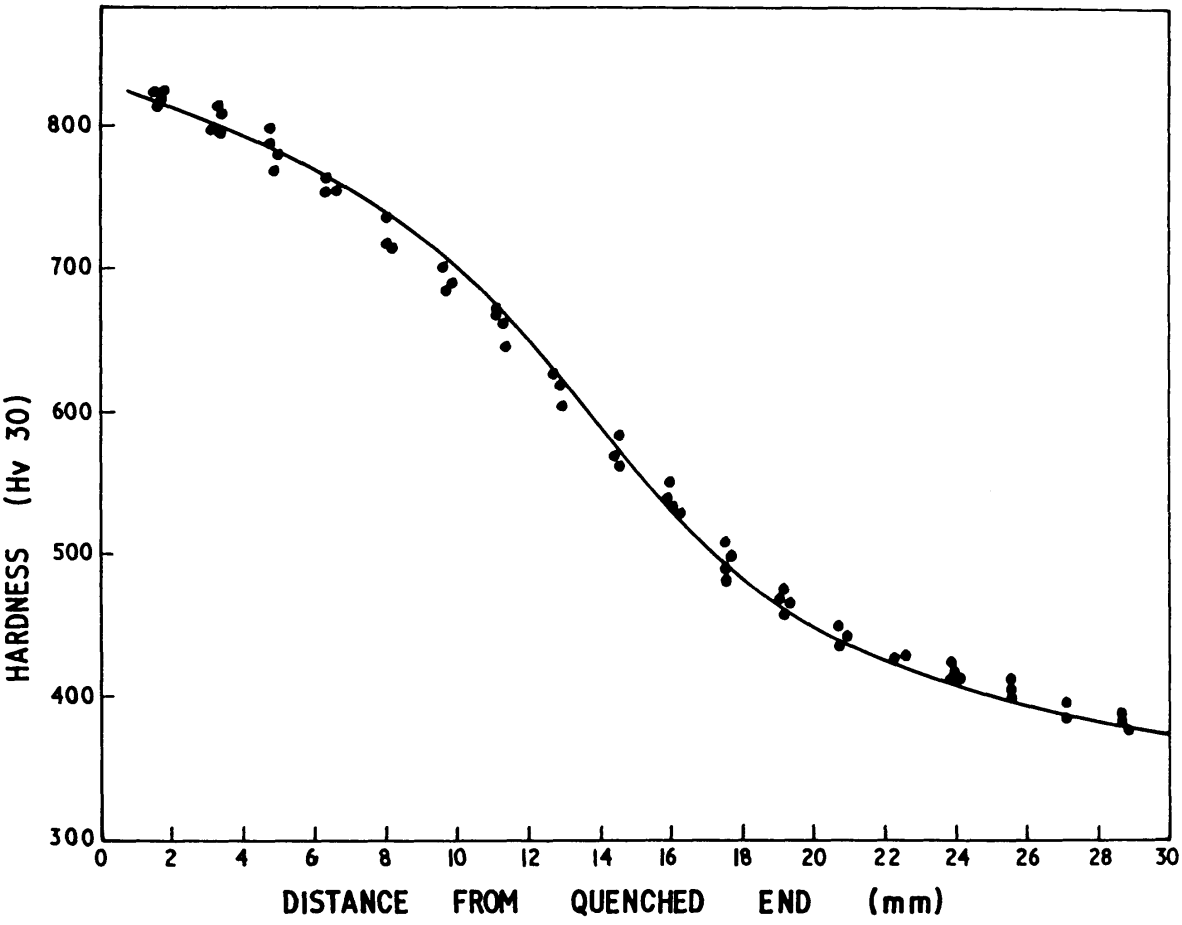

FIG. 6 JOMINY END QUENCH HARDENABILITY CURVE FOR STEEL No. 4. (POINTS ARE FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES – LINE DRAWN THROUGH ONE SET OF DATA.)

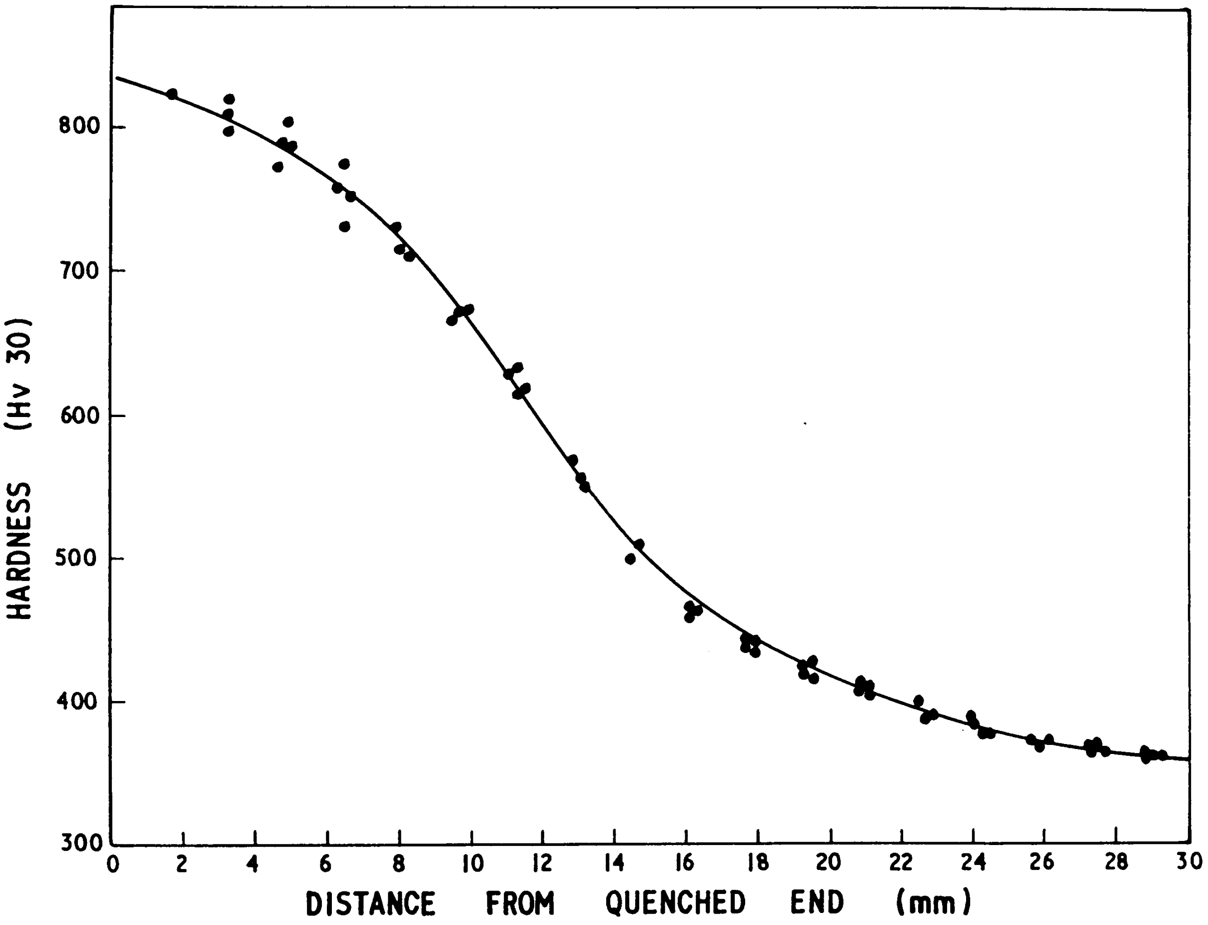

FIG. 7 JOMINY END QUENCH HARDENABILITY CURVE FOR STEEL No.5. (POINTS ARE FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES – LINE IS DRAWN THROUGH ONE SET OF DATA.)

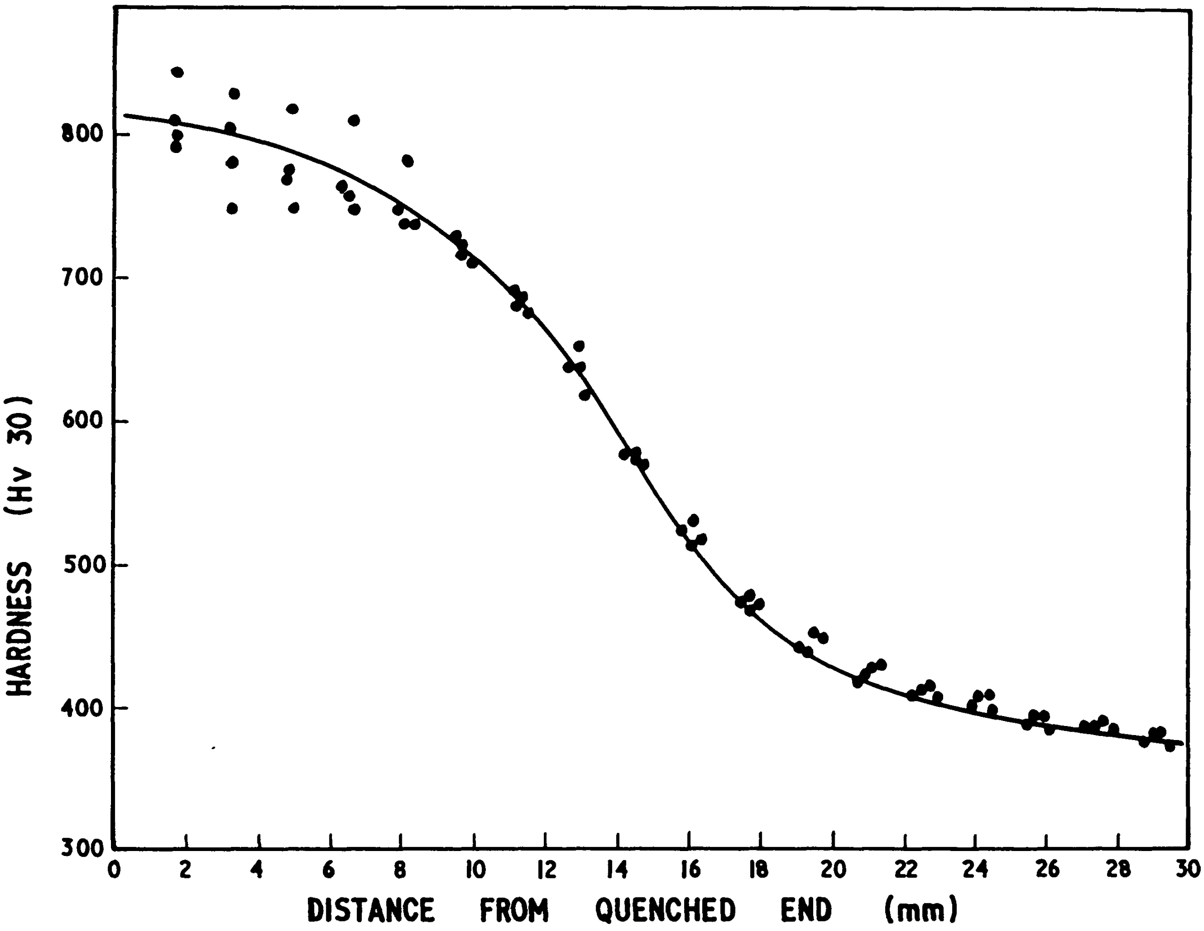

FIG. 8 JOMINY END QUENCH HARDENABILITY CURVE FOR STEEL No. 6 (POINTS ARE FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES – LINE IS DRAWN THROUGH ONE SET OF DATA.)

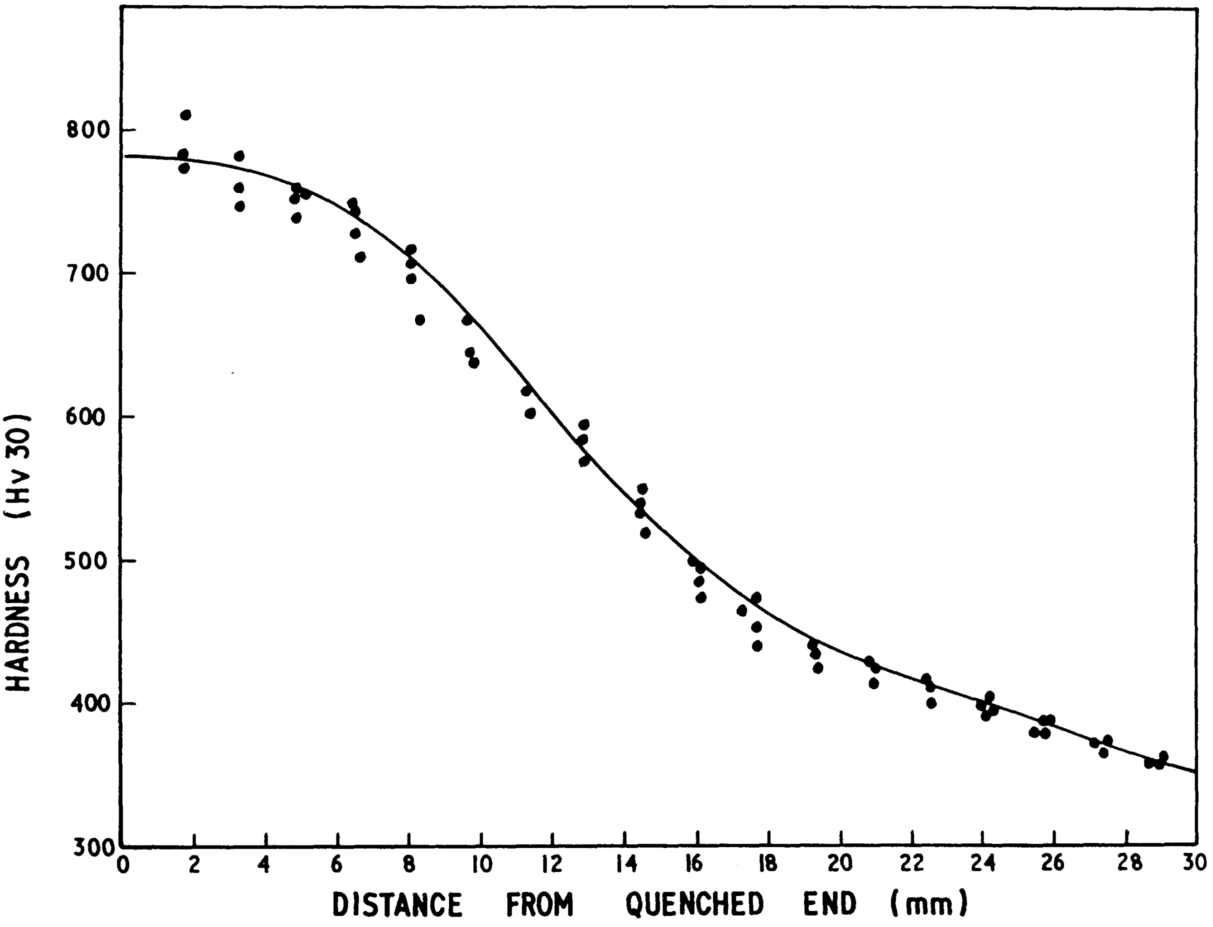

FIG. 9. JOMINY END QUENCH HARDENABILITY CURVE FOR STEEL No. 7. (POINTS ARE FOR FOUR SETS OF DATA, TWO SETS FROM EACH OF TWO TEST PIECES — LINE IS DRAWN THROUGH ONE SET OF DATA.)

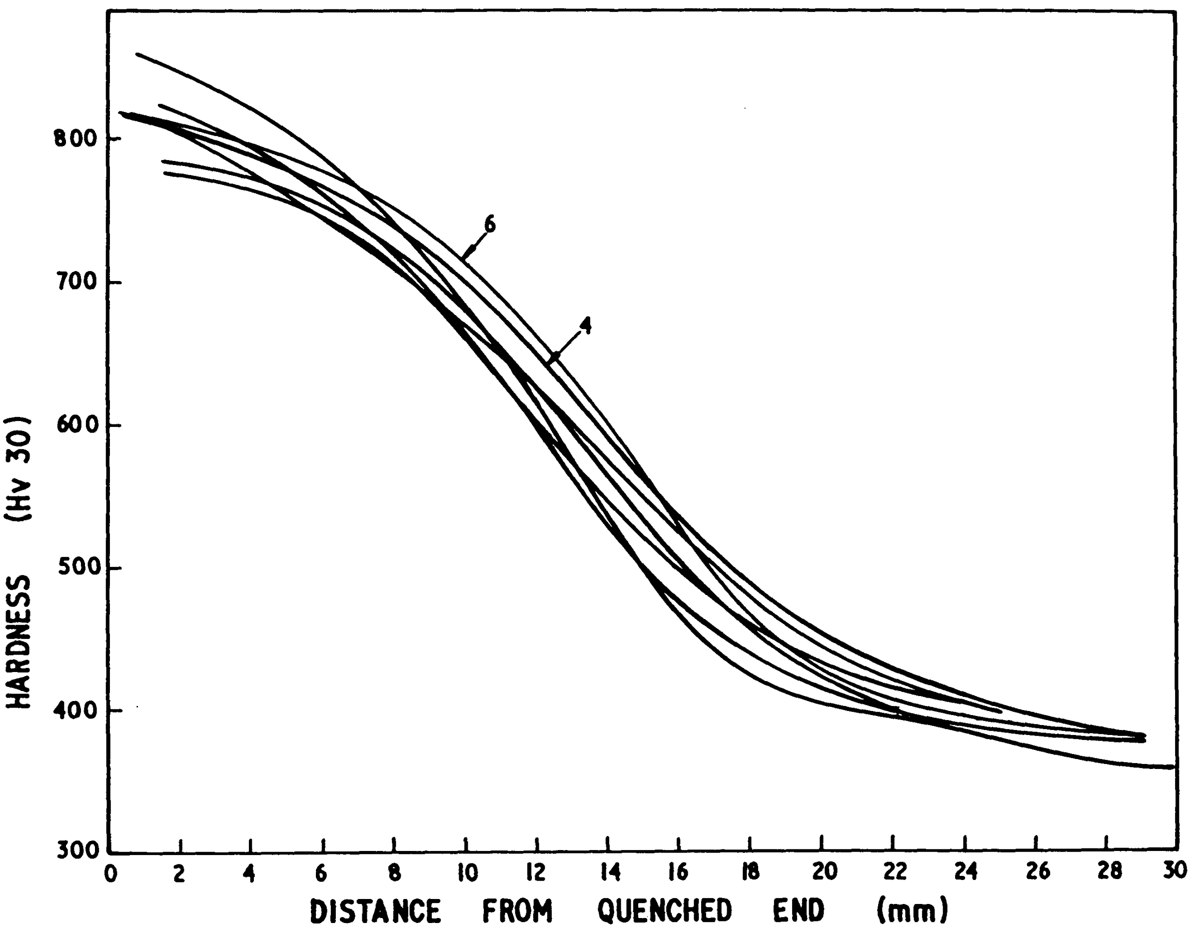

FIG. 10 JOMINY END QUENCH CURVES FROM FIGS. 3-9 FOR COMPARISON.

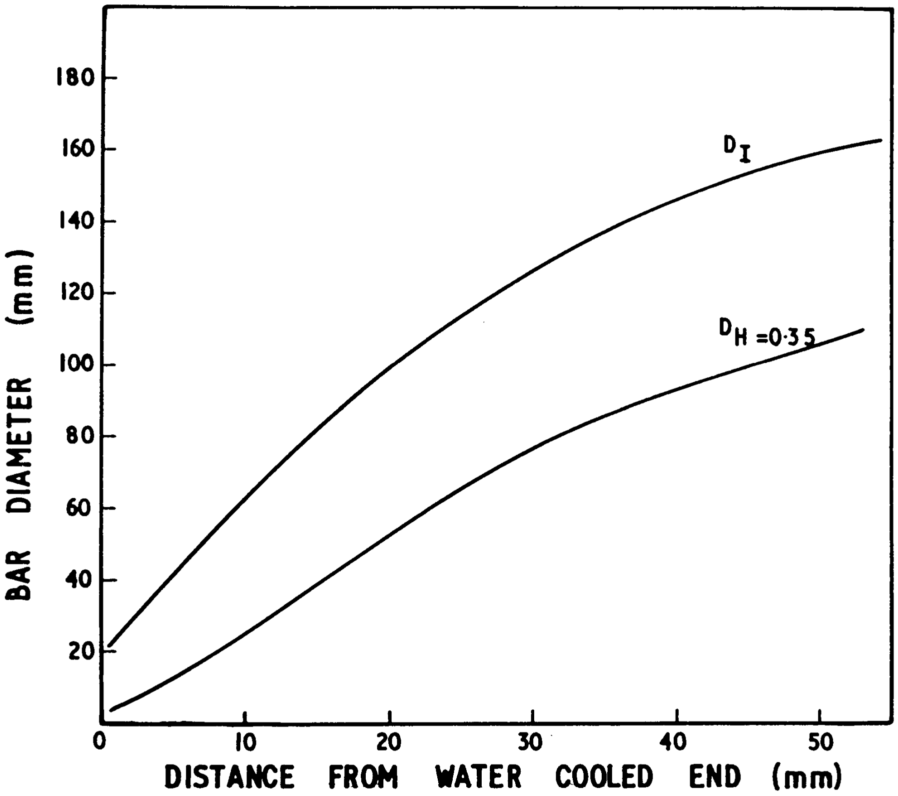

FIG. 11. RELATIONSHIP BETWEEN JOMINY DISTANCE, D_I AND $D_{H = 0{\cdot}35}$ (1,2)

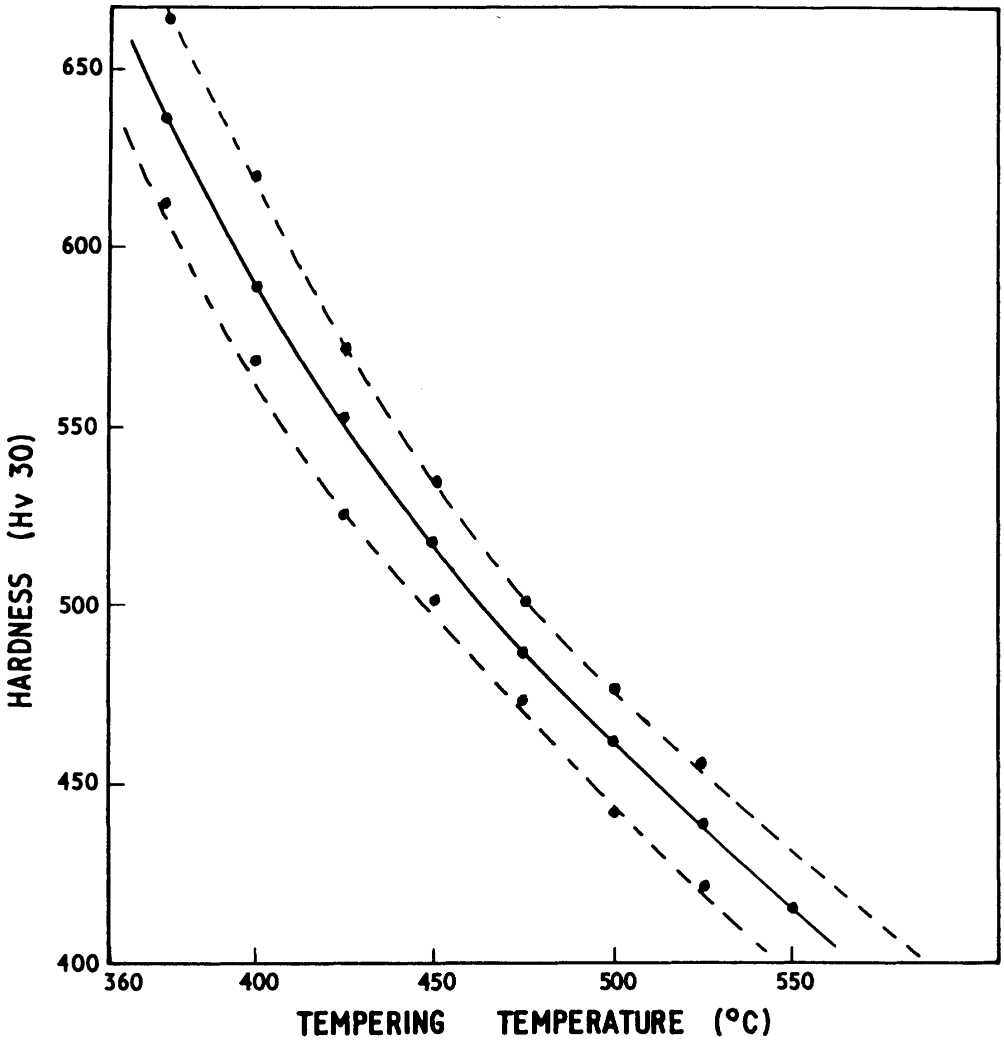

FIG. 12. TEMPERING CURVE FOR SILICON - MANGANESE SPRING STEEL BASED ON SEVEN BATCHES OF STEEL.

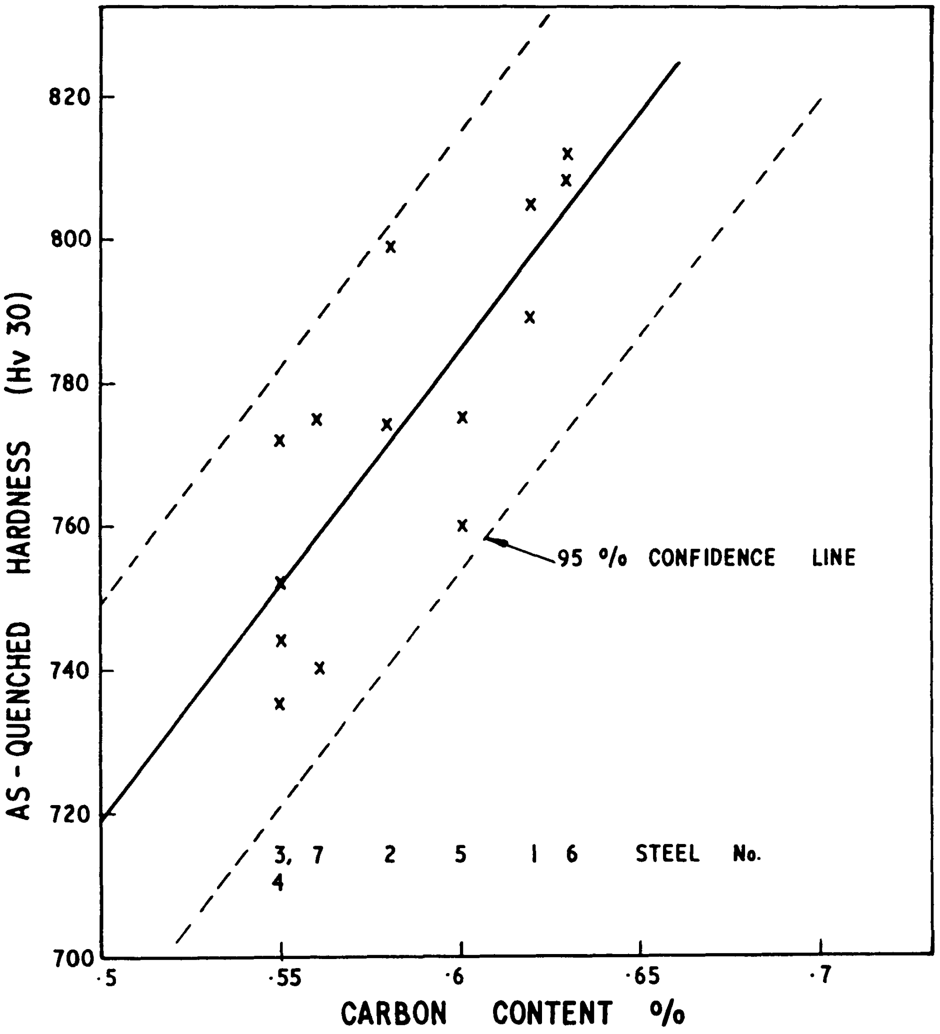

FIG. 13 VARIATION OF AS-QUENCHED HARDNESS WITH THE CARBON CONTENT OF SILICON-MANGANESE SPRING STEEL.