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Hardenability: an alternative to the use of grain size as calculation parameter

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Several austenizing treatments carried out on different types of quench-temper and carburizing steels confirm the relationship which exists between austenitic grain size and the treatment time and temperature parameters. A relationship has been established between the three variables, a regression plane linking them being obtained. A mathematical model is proposed which permits the treatment parameter P to be calculated theoretically, and making it possible to obtain from only chemical composition and austenizing temperature the data required to obtain the Jominy curve. The experimental results for diverse steels and the resulting structures agree with those obtained theoretically. A calculation programme has been developed in accordance with the model we present for both manufacture and quality control. Its industrial use has been widely verified.

1. Introduction

The correct and adequate use of low-alloy steels increasingly demands from users full knowledge of their technological possibilities. Steel hardenability and more, in particular, austenitic grain size are essential data for determining the quality of any type of steel; in addition, grain size is a parameter constantly used in the various theoretical methods for hardenability calculation.

Experimental grain size determination, however, involves long-duration tests which also do not provide a continuous variable objectively related to it.

An attempt has been made in this report to replace this discrete variable by another continuous one which allows its use alternatively in all practical cases with a reasonable degree of assurance. It should be emphasized that the aim is not so much a higher accuracy than that obtained in tests, nor a general law of indefinite field, but to try finding a sufficient precision for the usual range of times and heat treatment temperatures for this type of steel.

2. Experimental method

Commercial melts of steel in the chromium, Cr–Mo, Cr–Ni–Mo series were used for the research. Other special melts to which a grain size growth inhibitor had been added were also employed.

Let us consider the results obtained for the first family of steels, namely those of commercial manufacture. They were subjected to various austenizing treatments and later to water quenching. The grain size corresponding to each treatment were then determined. The results are shown in Table I.

The aim is to study variation of grain size in terms of temperature and time of treatment. The linear relationship is the most simple one, consequently n is represented against time t and temperature T. The curves obtained together with considerations on the phenomena under study [1–3] and their mechanics induced us to represent n against $\ln t$ and $1/T$, there being then obtained points which follow lines of identical slope as shown in Figs 1 and 2. This double linearity makes it possible to assume the existence of a single law enabling the three variables under study to be linked.

This induced us to consider the two variables simultaneously so that they could be linked by a relationship made up of the linear combination of the two previous ones, that is a plane whose particular sections for the values of T and t studied would provide the former straight lines; their equation, if it exists, would be of the type

$$n = aT^{-1} + C \ln t + b \qquad (1)$$

The graphical representation of this hypothesis using our experimental results is given in Fig. 3.

3. Mathematical verification

In order to establish any calculation model, it is imperative to check the mathematical validity of this representation or, in other words, to calculate the regression plane for the grain size variable against $a(1/T)$ and $\ln t$ which, as seen in the representation, fits the phenomenon under study.

In our particular case we have

$$r^2 = 0.9$$

$$n = 30\,715.21 \quad T^{-1} - 0.571\,925 \ln t - 19.7$$

$$a = 30\,715.21 \quad C = -0.571\,925 \quad b = -19.7 \qquad (2)$$

Taking into consideration the multiple correlation obtained it can be asserted that the error made, when

TABLE I ASTM grain size obtained in different treatments

t (h)	T (K)*						
	1073	1098	1123	1148	1173	1198	1223
0.5	10 (1) 9.5 (2) 9 (6) 8.5 (1)	9 (5) 8.5 (3) 8 (2)	9 (1) 8.5 (2) 8 (6) 7.5 (1)	8 (2) 7.5 (7) 7 (1)	8 (1) 7.5 (2) 7 (6) 6 (1)	7 (2) 6.5 (5) 6 (3)	7 (1) 6 (7) 5.5 (2)
1	9 (6) 8.5 (3) 8 (1)	9 (2) 8.5 (5) 8 (3)	8 (5) 7.5 (5)	8 (1) 6 (1) 7.5 (1) 7 (6) 6.5 (1)	7 (2) 6.5 (5) 6 (3)	6.5 (1) 6 (7) 5 (2)	6 (3) 5.5 (4) 5 (3)
2	9 (2) 8.5 (5) 8 (3)	8.5 (2) 8 (6) 7.4 (2)	8 (2) 7.5 (6) 7 (2)	7.5 (3) 7 (4) 6.5 (2) 6 (1)	7 (1) 6.5 (1) 6 (6) 5.5 (2)	6 (1) 5.5 (3) 5 (6)	6 (1) 5 (7) 4 (2)
4	8.5 (3) 8 (7)	8 (1) 7.5 (6) 7 (3)	8 (3) 7 (6) 6 (1)	7 (2) 6.5 (6) 6 (1) 5 (1)	6 (5) 5.5 (5)	6 (1) 5.5 (1) 5 (6) 4 (2)	5.5 (1) 5 (4) 4.5 (2) 4 (3)

*Bracketed figures stand for the number of times each value is repeated. Sample: ten casts. Normalized T = austenizing temperature.

grain size was calculated by this theory, is acceptable and may be used for subsequent calculations with a satisfactory degree of assurance.

This, of course, applies within the usual temperature limits which in practice make it possible to assume also the non-existence of duplex grains.

As already mentioned, the steels studied were commercial melts where aluminium acts as a grain growth moderator in low-alloy steelmaking.

Four melts of different steels with a higher percentage of aluminium, or to which some other grain growth inhibitor had been added (niobium in this case in the proportion we considered correct) were made. Table II shows the small variation undergone by grain size upon an increase of temperature, as well as its greater fineness. In this case the direct calculation of the regression plane by the method formerly used would mean the introduction of a high margin of error. For this reason its equation was obtained by solving the system of equations corresponding to the experimental data attained by the least-squares method, whose solution is

$$n = 9644.468\, T^{-1} - 0.142\,56 \ln t + 1.158 \quad (3)$$

and in this case

$$a = 9644.468 \quad C = -0.142\,56 \quad b = 1.158$$

The smaller slopes indicate the effect of the inhibitors

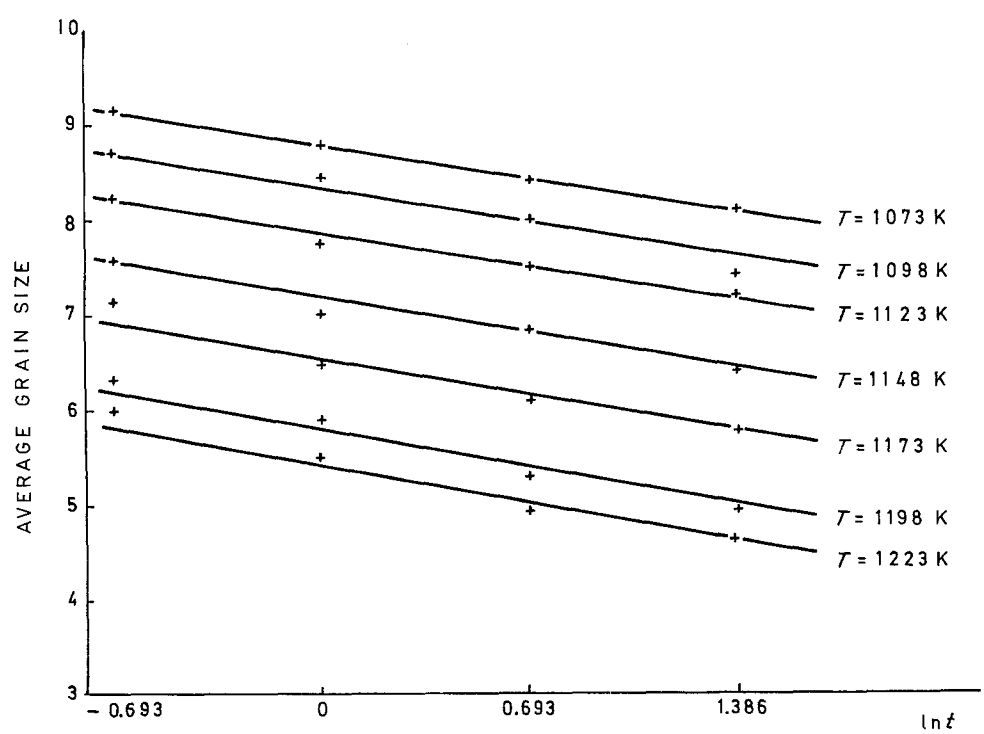

Figure 1 Variation in average grain size $\bar{n}$ with ln t (h).

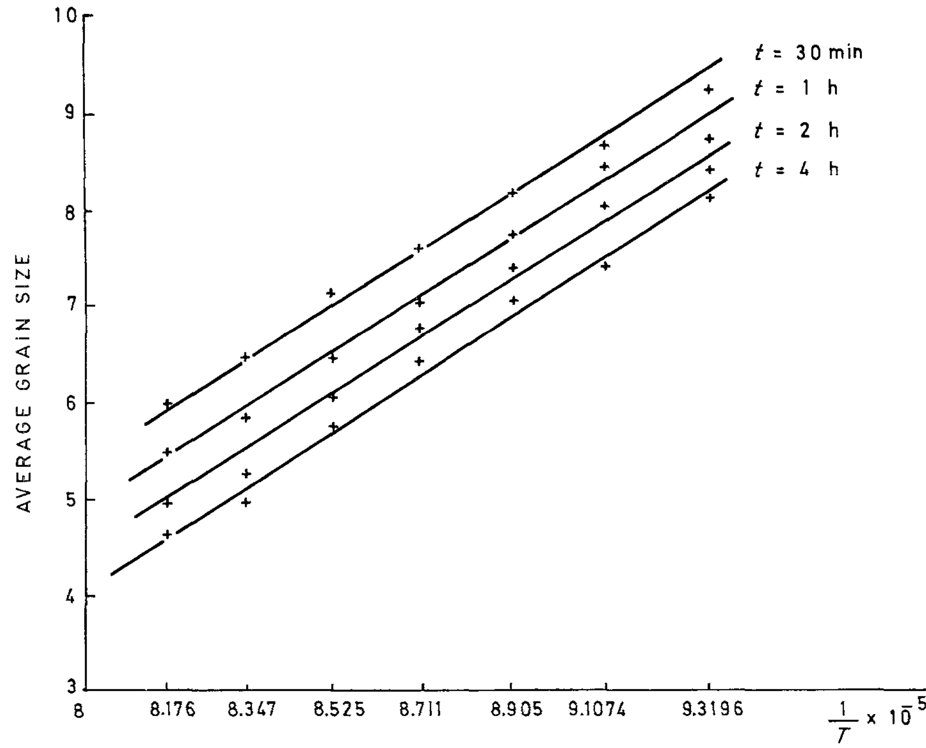

Figure 2 Variation in average grain size $\bar{n}$ with $1/T$ (K).

used, as corresponding to the experimental values given in Table II.

As is well known, aluminium produces segregation which can become a serious problem. For this reason it is not advisable to increase its amount in steel beyond the limits laid down in the relevant standards. To avoid this difficulty it was decided to use niobium as inhibitor, bearing in mind also that its proportion must be very precise in order to eliminate the appearance of complex carbide chains on grain boundaries which might cause embrittlement.

In conclusion, two mathematical expressions were obtained which enable the austenitic grain size produced by any austenizing treatment to be calculated theoretically. The validity of the results have been verified on more than 500 test specimens corresponding to different types of steel.

This grain size, obtained theoretically, makes it possible to work with the various hardenability calculations available. For our part, we have developed a calculation method which provides additional information on other interesting aspects of steel quality,

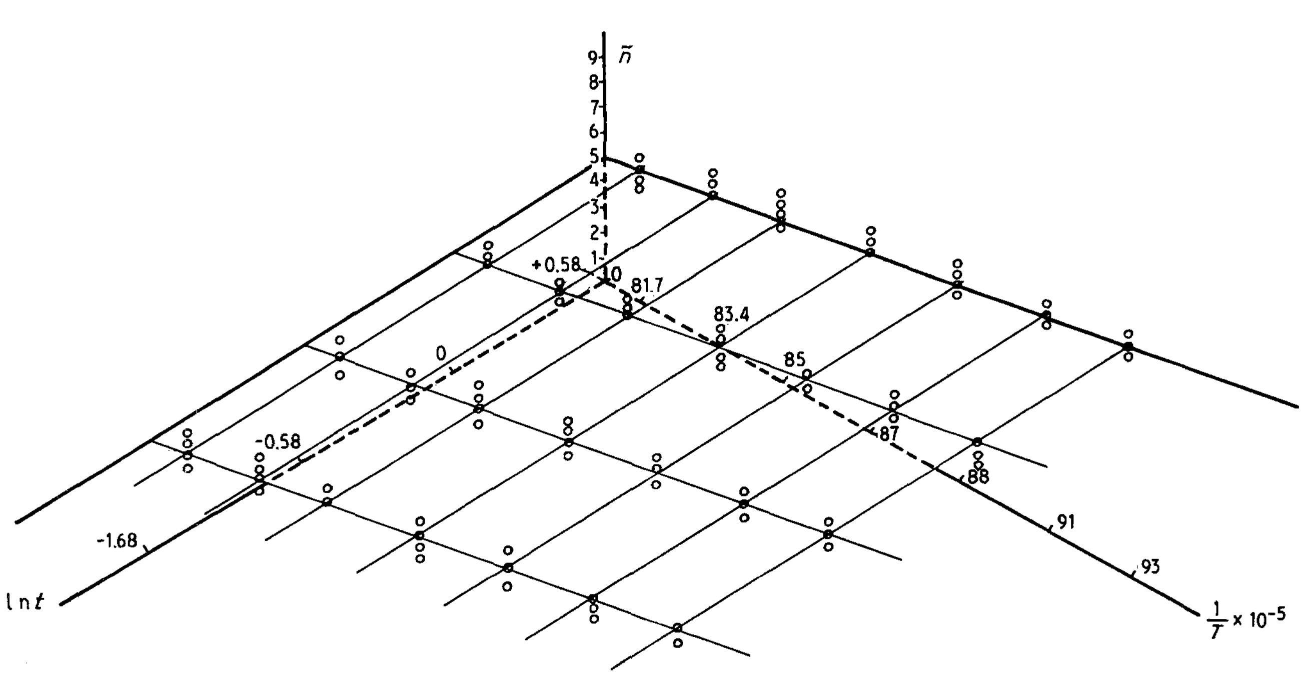

Figure 3 Average grain size $\bar{n}$ against ln t and $1/T$.

TABLE II ASTM Grain sizes for melts with grain growth inhibitor

t (h)	T (K)			
	1073	1123	1173	1223
0.5	10.5	10	10	9.5
1	10	10	10	9.5
2	10	10	9.5	9.0
4	10	9.5	9.5	9.0

such as phases and structures existing at different temperatures and at different cooling rates.

4. Calculation method

The proposed method consists therefore of a mathematical model which provides, in addition to the classical data on hardenability, others which determine the different metallographic structures obtained from any austenizing treatment.

To this end, the chemical composition of the steel and the treatment to which it was subjected were taken as initial data. Since two variables are involved in the austenizing treatment, namely time and temperatures, their interrelationships will be considered so that with the use of a single parameter we can study the process and compare it to any other.

Grain size is the variable required for our purpose, together with composition, in order to carry out the commercial melts and their correct treatment. This means that two different treatments which provide the same grain size are equivalent, and it is thus possible to establish that if one of them was carried out at temperature T_1 and time t_1, the second at temperature T_2 and time t_2, the equality $n_1 = n_2$ (where n is the grain size obtained) will be verified, which implies

$$\frac{a}{T_1} + C\ln t_1 + b = \frac{a}{T_2} + C\ln t_2 + b \qquad (4)$$

$$\frac{a}{T_2} = \frac{a}{T_1} + C(\ln t_1 - \ln t_2) \qquad (5)$$

$$\frac{1}{T_2} = \frac{1}{T_1} + \frac{C}{a}(\ln t_1 - \ln t_2) \qquad (6)$$

$$T_2 = \left(\frac{1}{T_1} + \frac{C}{a}\ln\frac{t_1}{t_2}\right)^{-1} \qquad (7)$$

If we consider a standard treatment of 1 h duration we get finally

$$P = \left(\frac{1}{T} + \frac{C}{a}\ln t\right)^{-1} \qquad (8)$$

where P is the treatment parameter corresponding to time t and a temperature T(K).

In the case of steels without inhibitor of grain growth we shall for values of C and a calculated previously

$$P = \left[\frac{1}{T} - (1.862\,02 \times 10^{-5})\ln t\right]^{-1} \qquad (9)$$

When inhibitors are added, with the corresponding values for C and a in this case it follows that

$$P = \left[\frac{1}{T} - (1.478\,15 \times 10^{-5})\ln t\right]^{-1} \qquad (10)$$

As the aim is, apart from providing reliable information on hardenability, to obtain data on the metallographic structures corresponding to each treatment, the cooling rate should be involved since this will influence the final product. On the other hand, we must not forget the objective in mind, namely to determine hardenability, whose most characteristic representation is the Jominy curve. The UNE 7279 standard (ASTM A225, DIN 50 191) specifies the conditions for carrying out this test, and establishes the agreement between the various points in the test specimen and its cooling rate at 700° C.

We shall now concern ourselves with the study of various standard rates at this temperature, using them to prepare a table which will enable us to ascertain the corresponding metallographic structure at these rates with accuracy.

From the data existing in several cooling diagram atlases (Max Planck Institute, BS and ASTM, IRSID, Benelux steels and CENIM standards [5–10]) the following ten basic rates were calculated:

- V_1 Limit rate (°C h^{-1}) in order to obtain a fully martensitic structure.
- $V_1(90)$ Rate for 90% martensitic structure.
- $V_1(50)$ Rate for 50% martensitic structure.
- $V_1(10)$ Rate for 10% martensitic structure.

TABLE III Cooling rates (°C h^{-1})

	Cte	C	Mn	Ni	Cr	Mo	P (°C)
$\log V_1$	9.81	4.62	0.78	0.41	0.8	0.66	0.0018
$\log [V_1(90)]$	8.76	4.04	0.86	0.36	0.69	0.97	0.001
$\log [V_1(50)]$	7.77	1.75	0.79	0.42	0.77	0.94	0.001
$\log [V_1(10)]$	9.8	3.3	-0.25 Mn $+2.1\ (\mathrm{Mn})^{1/2}$	0.46	0.8	1.16	0.002
$\log V_1$	8.56	1.5	1.61	0.6	1.24	1.46	0.002
$\log V_2$	10.55	4.8	0.8	0.62	1.17	1.58	0.0026
$\log [V_2(10)]$	9.06	4.11	0.9	0.5	1.1	2	0.0013
$\log [V_2(50)]$	8.64	3.4	1.15	0.96	1.1	2	0.0014
$\log [V_2(90)]$	8.4	2.8	1.51	1.03	1.1	2.31	0.0014
$\log V_3$	8.56	1.5	1.84	0.78	1.24	$2\ (\mathrm{Mo})^{1/2}$	0.002

$\log V = \mathrm{Cte} + \Sigma K_i P_i$; P_i = % C, % Mn, % Ni, % Cr, % Mo, P.

TABLE IV Hardness value equations (wt %)

H_V (martensite)	=	$902.6\,C + 121.15 + 26.68 \log V$
M_V (bainite)	=	$-323 + 185\,C + 330\,Si + 153\,Mn + 65\,Ni + 144\,Cr + 191\,Mo + \log V\,(89 + 53\,C - 55\,Si - 22\,Mn - 10\,Ni - 20\,Cr - 33\,Mo)$
H_V (ferrite–pearlite)	=	$-437 + 3300\,C - 5343\,C^2 + \log V\,(1329\,C^2 - 744\,C + 15\,Cr + 4\,Ni + 135.4)$

V_1' Minimum rate for martensite to appear.

V_2 Rate at which ferrite or pearlite start to appear.

$V_2(10)$ Rate at which 10% of ferrite–pearlite is obtained.

$V_2(50)$ Rate for 50% of ferrite–pearlite.

$V_2(90)$ Rate for 90% of ferrite–pearlite.

$V_3(100)$ Rate for 100% of ferrite–pearlite.

Table III was prepared from a total of 187 diagrams, the equation system obtained being solved with the help of the experimental data shown in them.

According to the same diagrams used formerly and with the data obtained in other tests carried out by us, the corresponding hardness for each metallographic structure was calculated in terms of composition and cooling rate, shown in Table IV, so that if their properties are taken to be additive and once the percentages involved are known, it will be possible to calculate from Table III the total hardness corresponding to each cooling process.

Although the calculations do not pose any difficulty we have undertaken the complete study of a steel so that it may serve as a practical example:

Steel	*Melt*	*Austenizing*
25CD4	6968	860° C; 0.5 h (heating time not included)

Chemical composition (wt %)

0.24 C 0.33 Si 0.73 Mn 0.94 Cr 0.24 Ni 0.26 Mo

$$P = \left[\frac{1}{860 + 273} - 1.86202 \times 10^{-5} \ln 0.5\right]$$

$$= 1116.67\,K \simeq 844°\,C$$

$$n = \frac{30\,715.25}{860 + 273} - 0.571\,925 \ln 0.5 - 19.7 = 7.8$$

According to Table III,

$$\log V_1 = 9.81 - (4.62 - 0.24) - (0.78 - 0.73) - (0.41 \times 0.24) - (0.8 \times 0.94) - (0.66 \times 0.26) - (0.0018 \times 844) = 5.59$$

$$\log V_1(90) = 5.33$$

$$\log V_1(50) = 4.86$$

$$\log V_1(10) = 4.54$$

$$\log V' = 3.64$$

$$\log V_2 = 4.96$$

$$\log V_2(10) = 4.64$$

$$\log V_2(50) = 4.02$$

$$\log V_2(90) = 3.56$$

These values are included in Fig. 4.

According to Table IV, the Vickers hardness values calculated for the various points which correspond to the quenched ends of the Jominy test pieces and the corresponding structures are as given in Table V.

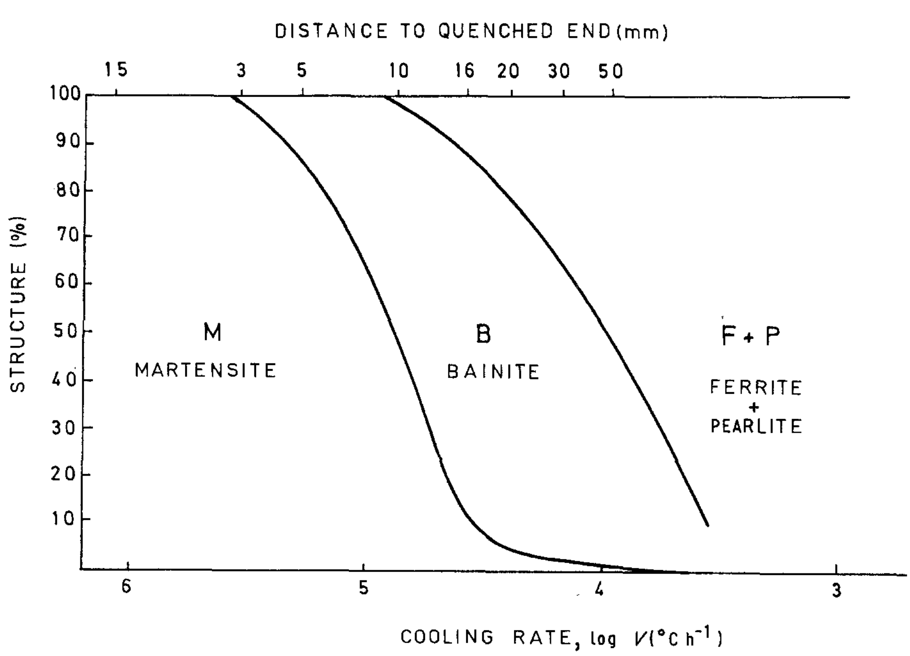

Figure 4 Estimated structures for different cooling rates.

TABLE V Hardness values and structures

Distance to quenched end (mm)	1.5	3	5	10	15	20	25	30
$\log V$ (°C h^{-1})*	6	5.6	5.25	4.85	4.55	4.36	4.25	4.16
Martensite (%)	100	100	86	47	10	4	4	3
Bainite (%)	–	–	14	49	75	71	63	57
Ferrite + pearlite (%)	–	–	–	4	15	25	33	40
Vickers hardness	498	487	459	390	321	300	290	283
HRC hardness	48	47.5	45	39.5	32.5	29	28	27.5

*UNE 7279 standard-DIN 50 191 [4].

Hardness values are given by

$$\text{Martensite} = 337.8 + 26.68 \log V$$
$$\text{Bainite} = 142.6 + 37.73 \log V$$
$$\text{Ferrite + pearlite} = 47.2 + 48.45 \log V$$

In order to calculate the hardness corresponding to a given point, the following procedure should be observed: let it be J_{10} (Jominy distance, 10 mm) for example.

$$\log V = 4.85$$
$$H_V \text{ (martensite)} = 337.8 + 26.68 \times 4.85 = 467.19$$
$$H_V \text{ (bainite)} = 142.6 + 37.73 \times 4.85 = 325.59$$
$$H_V \text{ (ferrite + pearlite)} = 47.2 + 48.45 \times 4.85 = 282.18$$

and taking their percentages into consideration

$$H_V \text{ (martensite)} = 467.19 \times 0.47 = 219.58$$
$$H_V \text{ (bainite)} = 325.59 \times 0.49 = 159.53$$
$$H_V \text{ (ferrite + pearlite)} = 282.18 \times 0.04 = 11.28$$
$$H_V \text{ (total)} = 390.39$$

By working analogously with the other points in the Jominy test piece the values in Table V, shown in Fig. 5, will be obtained.

By experiments on the test piece itself for distances of 1.5, 10, 15 and 25 mm from the quenched end, the presence of the various phases as well as the real hardness at each point has been verified quantitatively. The results obtained are given in micrographs in Fig. 6.

Even with the possible errors in this type of determination, agreement between the theoretical and the practical results is good and within acceptable error. In other low-alloy steel types, carburizing steels, and

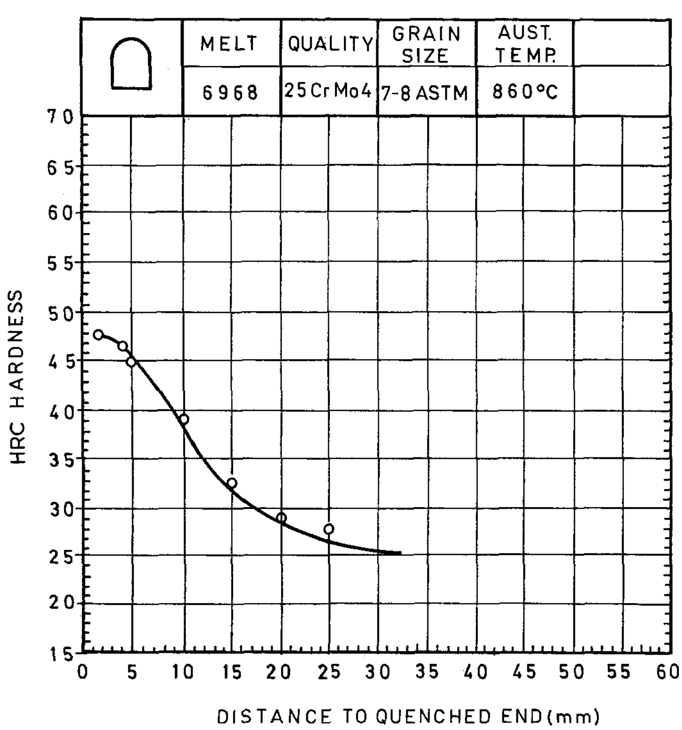

Figure 5 Jominy curves for a 25Cr–Mo4 steel: (O) calculated, (——) experimental. Melt analysis (wt %): C 0.24, Mn 0.73, Si 0.33, P 0.020, S 0.029, Cr 0.94, Ni 0.24, Mo 0.26.

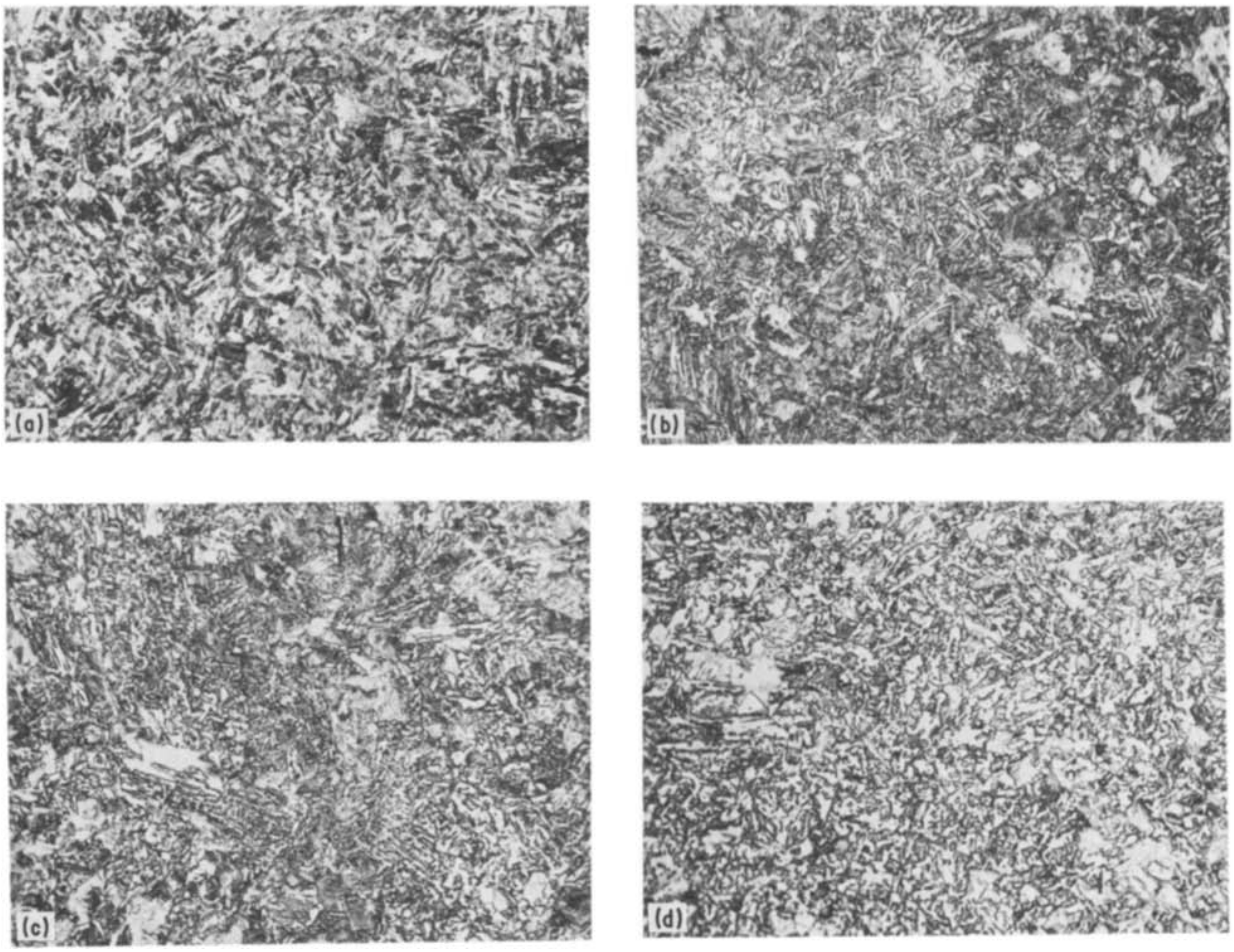

Figure 6 Structures for different points on Jominy test piece (25Cr–Mo4) steel (×400). (a) $J_{1.5}$, HRC 48, 100% M; (b) J_{10}, HRC 39, 51% M, 44% B, 5% (F+P); (c) J_{15}, HRC 32, 8% M, 72% B, 20% (F + P); (d) J_{25}, HRC 28, 4% M, 6% B, 36% (F + P).

quench-temper steels, of those used in the automotive industry, agreement between the theoretical and the experimental results with regard to the Jominy curve is also excellent and the same is the case upon a quantitative examination of the phases present.

5. Computer calculations

The model now proposed made it possible for us to prepare a computer program which carries out the foregoing calculations so that the Jominy test results may be had within a few seconds.

Basically, the program into which the calculation forms corresponding to the effect of the various alloy elements have been fed, in accord with the flow chart shown in Fig. 7, first carries out the calculation of the treatment parameter and then, bearing in mind chemical composition, austenizing temperatures and treatment time, calculates the structure diagram, that is the curves defining martensite, bainite and ferrite–pearlite zones. In the log(cooling rate)–structure diagram thus defined and for specific cooling rates for the defined Jominy distances, it determines the corresponding percentages and, as a function of the latter, calculates Vickers hardness, transforming it afterwards into HRC, which is used in the usual representation. In a few seconds there appears on the screen a six-column table with the results for distances to quenched end (Jominy distance), percentages of martensite, bainite and ferrite + pearlite, Vickers hardness and HCR hardness. This permits the classical Jominy curve to be plotted immediately. A printer helps to obtain at will, on paper, the mentioned table and the corresponding graph for HRC hardness distance to quenched end.

Evidently in this type of theoretical calculations the correct chemical analysis of the steel studied becomes important and it is essential for comparing the results of the mathematical model with the experimental ones. The calculation program shown in the flow chart (Fig. 7) may be used for any type of computer, including a personal type, and can be integrated with the necessary links when chemical analysis instrumentation is available. This is frequently the case in industrial laboratories as an additional datum regarding the quality of the product, and it can be worked out on-line with the same computer if provided with the required calculation capacity.

Some examples of low-alloy steels calculated by the programme we present are given in Figs 8a and 9a. They are low-alloy Cr–Ni and Cr–Ni–Mo steels normally used by the automobile industry wherein the percentage of alloy elements is 3%. Figs 8 and 9 also show the micrographs corresponding to different distances from the quenched end, where the percentages of the different structures present and the HRC hardness obtained in them was estimated by optical microscopy. An excellent agreement between the

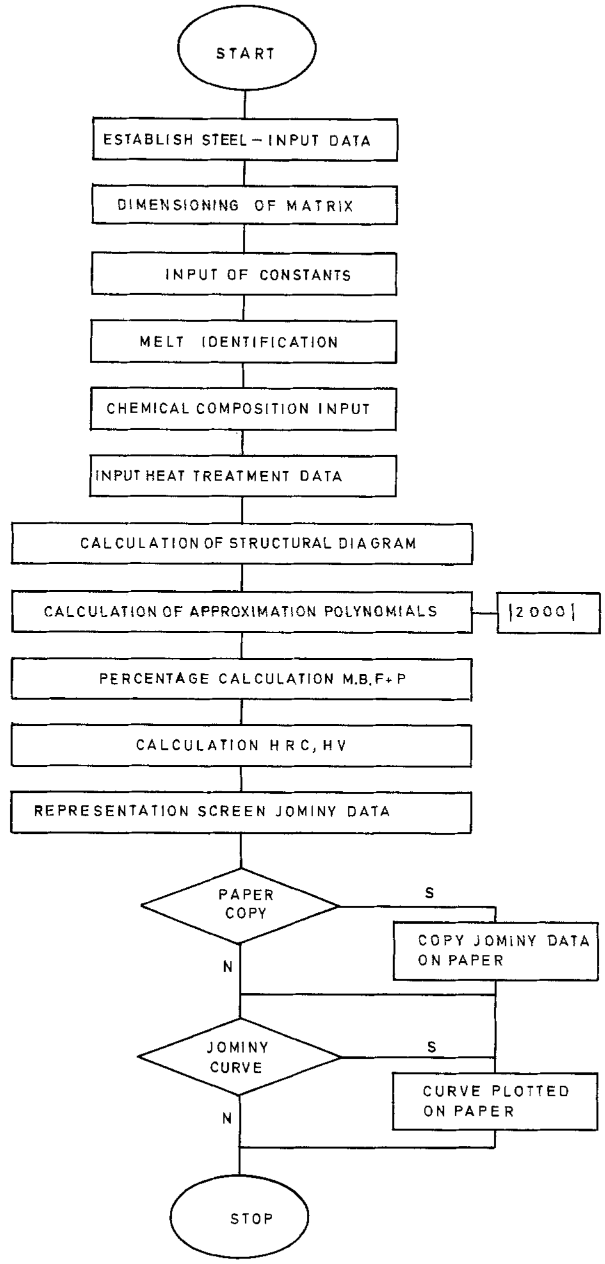

Figure 7 Flow chart for the theoretical calculation of Jominy curve.

experimental and the theoretical results was obtained.

In the case of higher-alloy steels (5% total alloy elements) the hardenability is high and it is theoretically difficult to calculate the martensitic hardness and the bainitic value; it would be necessary to introduce corrections in the calculation forms that have not been taken into account in this program. Something similar occurs when boron is considered as an element which increases hardenability, since no reliable data are available with regard to the chemical analysis that would enable a sure multiplying factor to be adopted. In such cases the diagram for constituent-cooling rates is difficult to analyse with the theoretical model and the scatters, as compared to the experimental results, are significant.

This would compel corrections to be made for each type or family of steels which might perhaps take place later on, if we should have sufficient experimental results available.

The use of a computer program, taking as base the mathematical model under study, would help to make the calculations easier and they provide the Jominy curve for the steel under consideration with sufficient assurance, thus pointing out the importance of having a reliable quantitative chemical analysis to hand.

The possibility of using the method for quality control both in manufacture and use of steel should be highlighted [11–13].

6. Conclusions

Bearing in mind the experimental results, it has been verified mathematically that it is possible to calculate by theory, with sufficient reliability, the austenitic grain size in low-alloy steels without grain growth inhibitors.

This variable can be introduced in models for the theoretical calculation of hardenability and, in particular, for the mathematical model herein proposed with complete assurance.

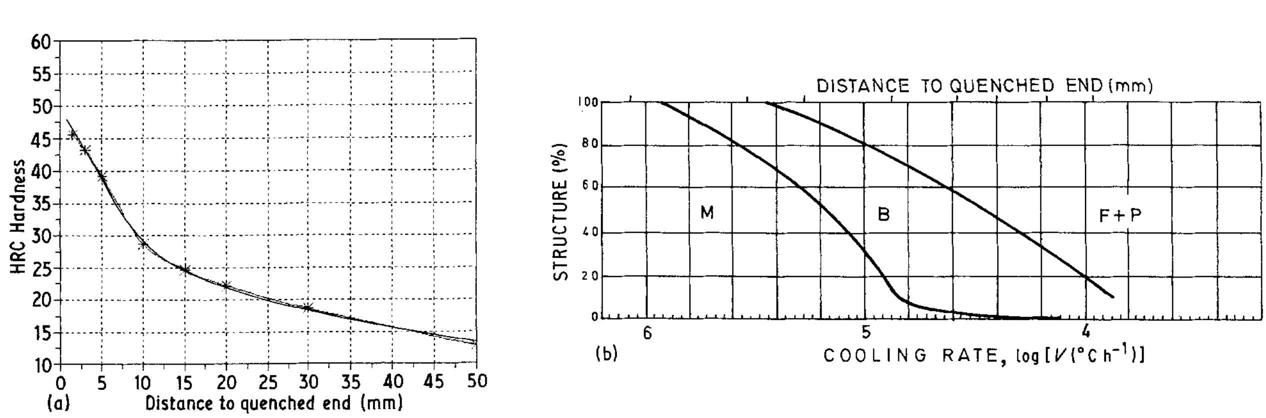

Figure 8 (a) Hardenability test, computer calculations for SAE 8620 H steel (melt 6711): (*) calculated, (——) experimental. (b) Estimated structures for different cooling rates. (c–f) Structures corresponding to different points of Jominy test piece (× 400): (c) $J_{1.5}$, HRC 45.5, 100% M; (d) J_3, HRC 43, 82% M, 18% B; (e) J_{15}, HRC 25, 6% M, 53% B, 41% (F + P); (f) J_{25}, HRC 21, 3% M, 36% B, 61% (F + P).

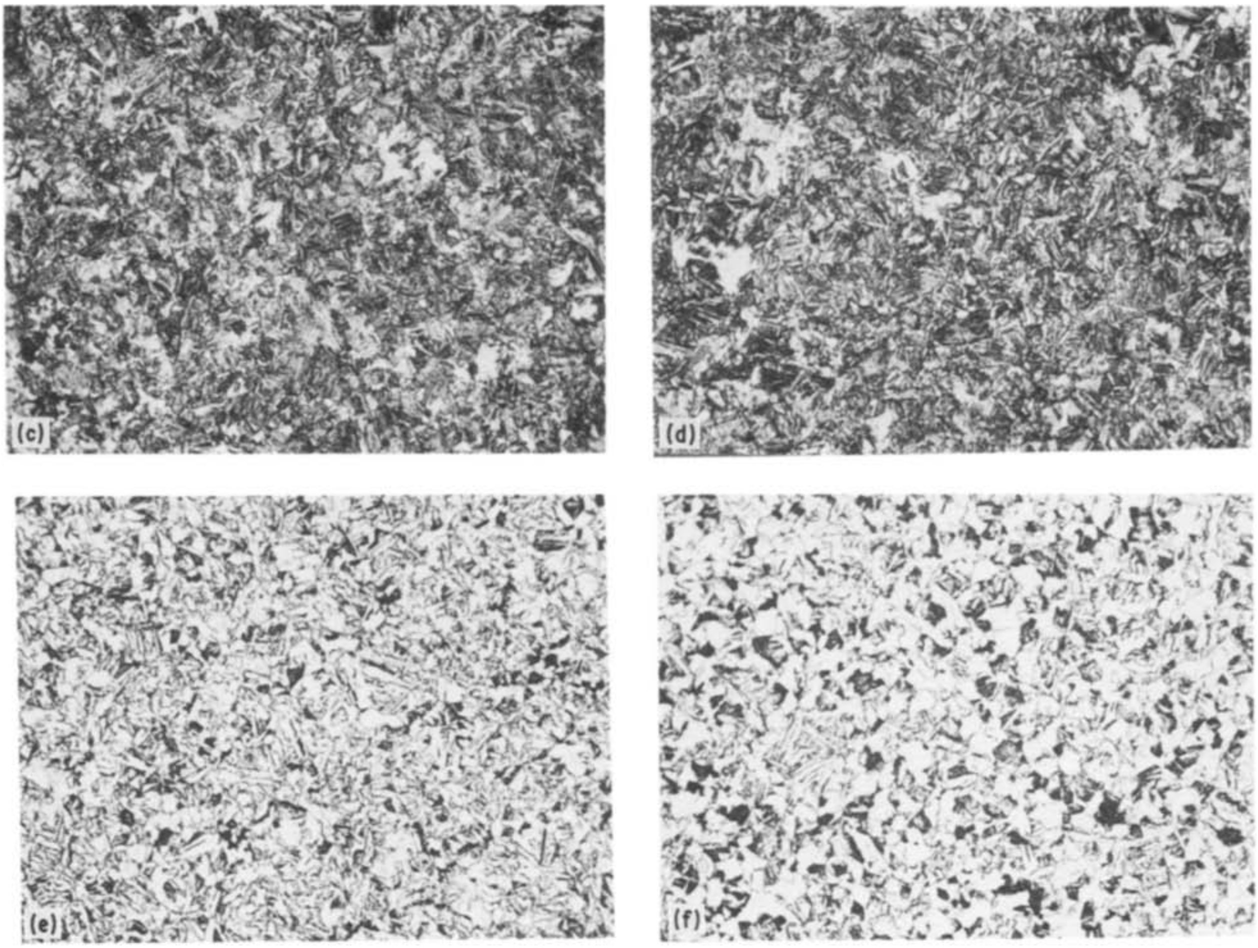

Figure 8 Continued.

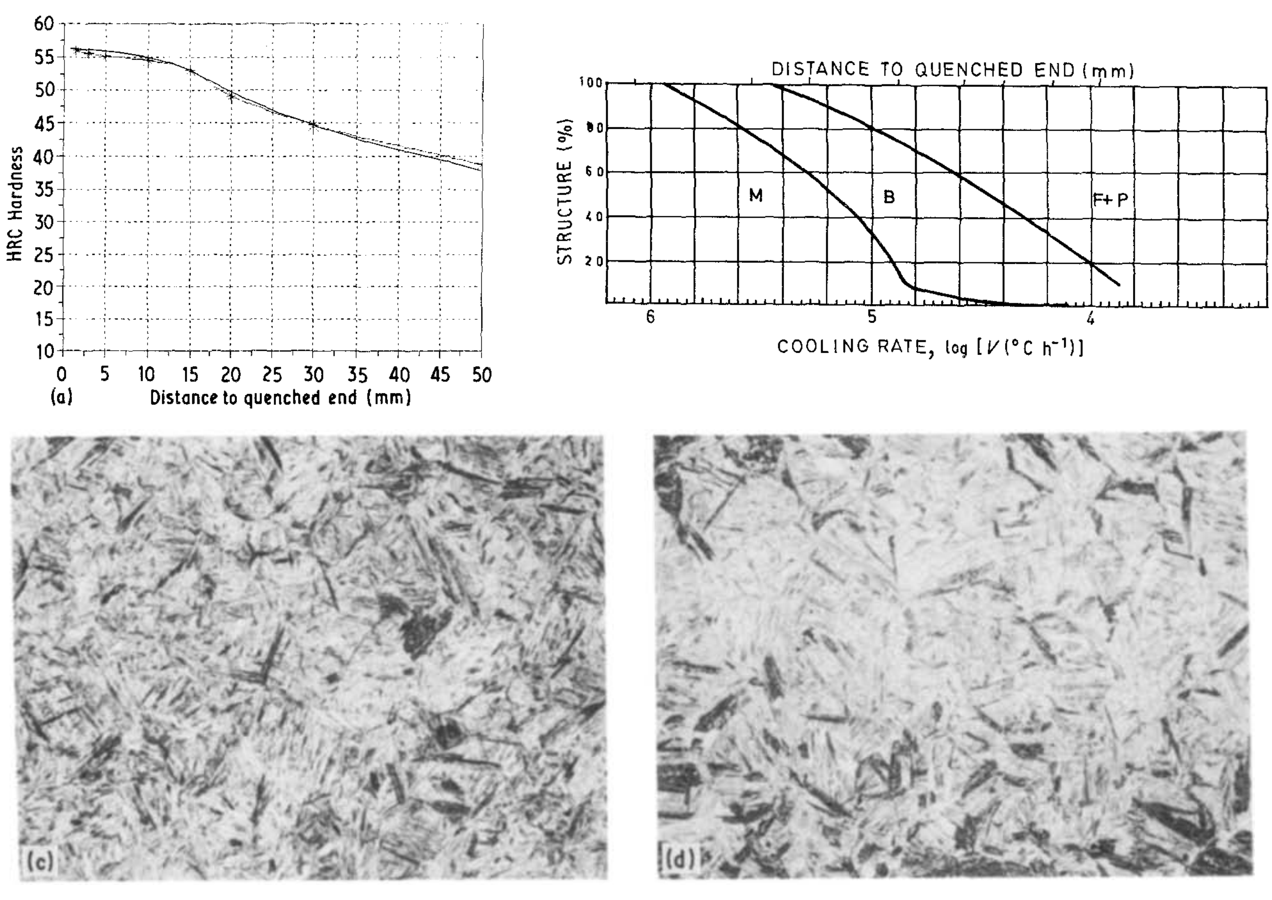

Figure 9 (a) Computer calculation of the hardenability test for EN 19C steel (melt 7109): (∗) calculated, (——) experimental. (b) Estimated structures for different cooling rates. (c–f) Structures corresponding to different points on Jominy test piece (× 400): (c) J_3, HRC 56, 100% M; (d) J_{10}, HRC 55, 95% M, 5% B; (e) J_{20}, HRC 49, 60% M, 40% B; (f) J_{25}, HRC 47.5, 46% M, 54% B.

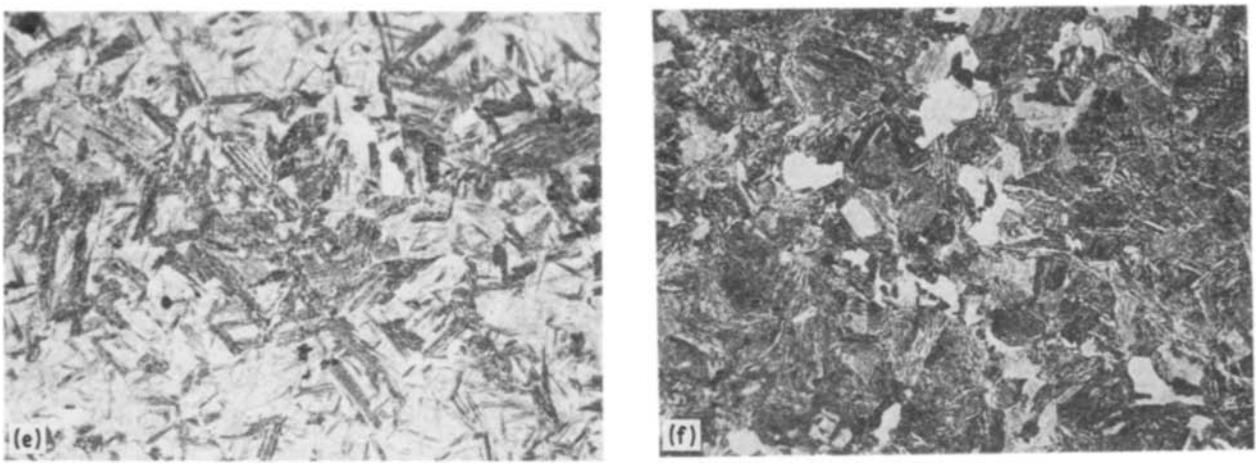

Figure 9 Continued.

This model, besides the Jominy curve, provides information on the microstructure at each point, in accord with the cooling process.

Experimental checking by optical microscopy, for the types of steels under consideration, especially for low-alloy steels, shows the value of the method and the possibility of using it in the normal conditions of the standardized Jominy test. Such a verification was carried out on the Jominy test piece itself and on a large number of commercial melts of very diverse kinds of steel.

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