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Low-carbon steel as an alternative to conventional roller-quenched, tempered steel

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SYNOPSIS

Weldable steel plate with a good combination of strength and toughness is currently produced from 0,12 to 0,28 per cent carbon low-alloy steel heat-treated by roller quenching and tempering. Alternatively, steel plate of the same strength can be produced at a lower production cost by the use of very-low-carbon steel (0,03 to 0,08 per cent carbon) processed by in-line quenching without tempering. This paper reports the results of experimental work on these steels, and compares them with the properties of conventional steel. On thinner sections, it was found that the properties of the experimental steels compare favourably with those of conventional grades.

SAMEVATTING

Hoë sterkte en taaiheid sweisbare staal plaat word tans van 0,12 tot 0,28 persent koolstof staal vervaardig en hittebehandel deur rollerblussing en tempering. As 'n alternatief kan hierdie tipe staal plaat teen laer produksiekoste vervaardig word deur baie lae koolstofstaal (0,03 tot 0,08 persent koolstof) te gebruik direk na in lyn afblussing, sonder enige tempering. In hierdie verslag word resultate van eksperimentele werk wat op hierdie tipe staal uitgevoer is, bespreek en 'n vergelyking met die eienskappe van die konvensionele staal word getref. Die eienskappe van die eksperimentele stale vergelyk op dunner seksies baie goed met dié van die konvensionele stale.

Introduction

Roller-quenched, tempered high-strength structural-steel plate with good toughness is produced locally by Iscor Ltd under the trade name of ROQ-tuf. ROQ-last is the trade name for a range of abrasion-resistant, roller-quenched, tempered steel plate. ROQ-tuf steel is roller-quenched, tempered high-strength low-alloy steel plate with good tensile strength combined with good toughness and weldability. These steels have a high hardenability, which is obtained by the addition of alloying elements carbon, manganese, silicon, and boron in the carbon grades, and molybdenum, nickel, chromium and boron in the alloy grades. Good properties are assured by the tempered martensitic microstructure.

The heat treatment of ROQ-tuf is shown schematically in Fig. 1. The plates (already rolled to size) are austenitized at approximately 900 °C. The plates pass directly from the austenitizing furnace into the roller-quenching unit, where they are subjected to a severe, high-volume water quench. During the quenching process, the plates are held flat by rollers. Subsequently, the quenched plate is charged into a tempering furnace, where the appropriate temperature is selected to give the desired combination of strength and toughness[1].

Some ROQ-last grades have a higher carbon content (up to 0,32 per cent) than ROQ-tuf (0,12 to 0,21 per cent), and are alloyed with manganese, silicon, molybdenum, nickel, chromium, and boron to confer the required hardenability. ROQ-last is produced in a similar way to ROQ-tuf, but is tempered at lower temperatures (360 to 425 °C), since the governing property is hardness rather than toughness.

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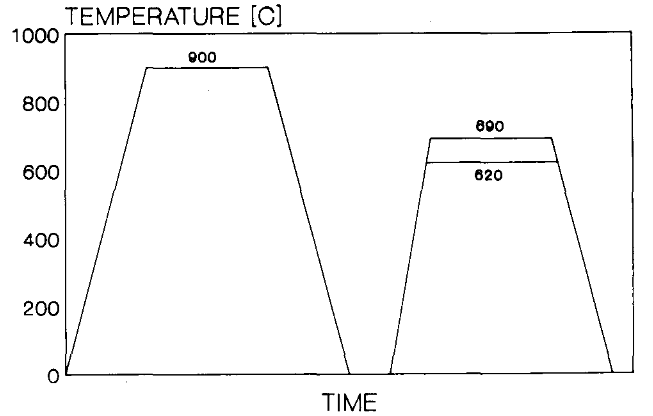

Fig. 1—Schematic illustration of the production of ROQ-tuf alloy grades

The production of roller-quenched, tempered steels involves three basic heating operations: heating for hot rolling, austenitizing, and tempering. These are major contributing factors to the production cost of these steels.

Many different ways of producing high-strength structural steel have been investigated world wide. Low-carbon (approximately 0,04 per cent) steels containing approximately 4 per cent manganese as the principal alloying element, which were controlled-rolled followed by air cooling, produced excellent tensile properties (660 to 860 MPa yield stress) with excellent toughness[2-4]. Steel of the same composition has a yield strength of 1000 to 1230 MPa if controlled rolling is followed by water quenching[5].

Various authors have experimented with low-carbon 1 to 2,5 per cent manganese micro-alloyed steels to produce high-strength plate via a bainitic microstructure[6-9]. Carbon levels of 0,07 per cent and lower were used to ensure good weldability and ductility in the heat-affected zone (HAZ) by giving a ductile low-carbon martensite in the HAZ.

In these low-carbon steels, the principal strengthening mechanism is the very fine martensitic (produced by water quenching) or bainitic (produced by air cooling) microstructure. Owing to the fairly high manganese content, sufficient hardenability is obtained to achieve this fine microstructure during water quenching (martensitic) or air cooling (bainitic), even at these low carbon levels. Depending on the required section thickness of the steel plate, the manganese content is adjusted between 2,0 and 4,5 per cent to produce the required hardenability. In some of these grades, other alloying elements like nickel, molybdenum; and chromium are added to further increase the hardenability. Manganese and chromium also serve to improve the strength through solid-solution hardening. In some grades, small amounts of vanadium, titanium, and niobium are added to produce grain refinement and additional strength through the precipitation of fine carbides during controlled rolling and subsequent cooling. Because of the low carbon content of these steels, acceptable toughness is obtained directly after water quenching, and no final tempering heat treatment is required.

This paper reports the results of four experimental melts of these low-carbon grades and compares them with ROQ-tuf and ROQ-last grades. The experimental steels were designed with the chemical compositions used by Baumgardt[6] and Massip[7] as reference. The molybdenum and nickel contents were replaced with chromium to attain sufficient hardenability. ROQ-tuf and ROQ-last are produced in thicknesses up to 100 mm and 60 mm respectively; the experimental steels were produced in a thickness of 14 mm.

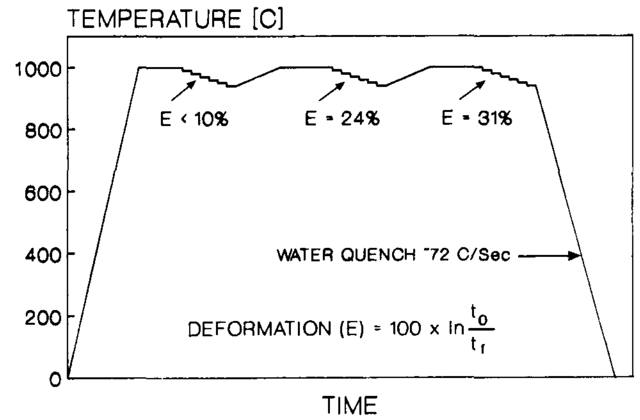

Fig. 2—Thermo-mechanical processing of the experimental casts

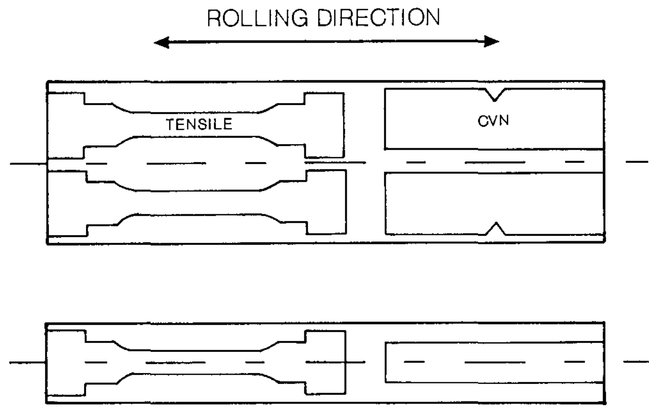

Fig. 3—Position and orientation of the test specimens

Experimental Procedure

The experimental steels were produced in a vacuum-induction furnace and were chill-cast into steel moulds. The thermo-mechanical processing to simulate in-line quenched plate is illustrated in Fig. 2. Tensile and impact tests were conducted according to BS 18 specification, and the orientation and position of the test specimens are illustrated in Fig. 3. Austenitic grain size was revealed by a special etching method[10], and was determined by the mean linear intercept method[11]. Thin foils, prepared by the standard method, were used to characterize the steels by transmission electron-microscope (TEM) metallography.

Results

The chemical composition of some typical ROQ-tuf and ROQ-last grades are given in Table I, with their mechanical properties in Table III. The chemical composition of the experimental casts are given in Table II and their mechanical properties in Table IV. The austenitic grain size of the experimental casts are given in Table V.

Discussion

Comparison with ROQ-tuf and ROQ-last

The chemical composition of the experimental steels was chosen so that the effects of carbon between 0,025 and 0,085 per cent could be studied. Adequate strength had to be obtained by the addition of solid-solution strengthening elements manganese and chromium, which also provided the required hardenability. Micro-alloying elements niobium and titanium were added for their grain-refining action and, hence, improvement of strength and impact toughness.

During the fabrication of the experimental steels in the vacuum-induction furnace, aluminium was added for deoxidation. The titanium and niobium were also added to form carbides, nitrides, and carbo-nitrides protecting the boron in the molten steel from precipitation. The total nitrogen content as determined by the LECO method was found to vary between 0,0039 and 0,0058 per cent.

The increase in carbon content from 0,025 to 0,085 per cent improves proof strength from 690 to 919 MPa, and the tensile strength from 834 to 1205 MPa (Fig. 4). This implies an improvement of 38 MPa per 0,01 per cent carbon added in proof strength, and 62 MPa increase in tensile strength per 0,01 per cent carbon added.

Fig. 5 shows that, with the increase in carbon content, no trend is observed in respect to Charpy impact energy at both 18°C and −20°C. It should be noted that the titanium-free steel (cast B) has significantly higher impact toughness than cast A with the same carbon content. This implies that the grain-refining action of the titanium was overshadowed by the embrittling effect of the titanium carbide precipitation.

In Fig. 6 the yield strengths of the low-carbon steels

TABLE I

TYPICAL CHEMICAL COMPOSITION OF ROLLER-QUENCHED AND TEMPERED STEELS

	Element, % by mass									
Grade	C	Mn	Cr	Si	Mo	P	S	Ti	Nb	B
ROQ-tuf										
C410	0,16	1,20	–	0,32	–	0,015	0,005	–	1	–
C550	0,17	1,15	–	0,27	–					0,002
C690	0,18	1,25	–	0,23	–			–	–	0,002
AD690	0,12	0,45	–	0,20	0,50	0,035	0,040	–	–	0,001
	0,21	0,70	–	0,35	0,65			–	–	0,005
ROQ-last										
C321	0,28	1,50	–	0,20	–	0,040	0,050	–	–	0,005
	(max)			0,60						(min)
C340	0,28	1,50	–	0,20	–	0,040	0,050	–	–	0,005
	(max)			0,60						(min)
AH400			0,80							
	0,32	0,50	1,15	0,30	0,20	0,035	0,040	–	–	–

TABLE II

CHEMICAL ANALYSIS OF EXPERIMENTAL MELTS

	Element, % by mass									
No.	C	Mn	Cr	Si	Mo	P	S	Ti	Nb	B
A	0,025	1,87	0,44	–	–	0,007	0,010	0,02	0,05	0,004
B	0,040	2,00	0,48	–	–	0,010	0,009	–	0,04	0,003
C	0,037	2,10	0,46	–	–	0,009	0,005	0,03	0,04	0,002
D	0,085	2,01	0,50	–	–	0,006	0,009	0,03	0,04	0,004

TABLE III

MECHANICAL PROPERTIES OF SOME ROQ-tuf AND ROQ-last ROLLER-QUENCHED AND TEMPERED STEELS[12].

Grade	Hardness Vickers no.	Proof stress MPa	Tensile stress MPa	Elongation %	vE_{18} J
ROQ-tuf					
C410	163	415	550	22	190
C550	195	550	655	18	130
AD690	250	690	760	18	100
ROQ-last					
C321	339	na	na	na	40
C340	360	na	na	na	20
C400	425	na	na	na	

na = not available

vE_{18} = Charpy impact energy at 18°C

TABLE IV

MECHANICAL PROPERTIES OF EXPERIMENTAL CASTS

No.	Hardness Vickers no.	Proof stress MPa	Tensile stress MPa	Elongation %	¾ vE_{18} J	vE_{18}* J
A	310	690	834	10,3	21	28
B	343	771	970	13,1	49	65
C	356	778	961	11,8	16	21
D	395	919	1205	10,5	19	25

¾ vE_{18} = Charpy impact energy at 18 °C as tested using ¾ size specimens

vE_{18}* = Charpy impact energy at 18 °C when corrected to specimens of standard size

TABLE V

AUSTENITIC GRAIN SIZE OF EXPERIMENTAL STEELS

No.	Austenitic grain size μm
A	32,6
B	28,3
C	36,5
D	25,0

and ROQ-tuf grades are compared with their Charpy impact energy. The diagram shows the typical penalty in impact toughness with increasing strength. Casts B and D follow the same trend as the ROQ-tuf grades. Casts A and C, however, do not conform to this trend. The more adverse toughness-to-strength ratios of casts C and D can be attributed to their larger austenitic grain size (Table V), and possibly also to the presence of titanium in these steels.

Fig. 6 demonstrates that the low-carbon experimental steels have higher strength than the commercially produced ROQ-tuf carbon grades (C410 and C550). These experimental steels show the same strength-to-toughness ratio as the ROQ-tuf steels, and could therefore be used as higher-strength steels of adequate toughness.

A comparison of the hardness of the experimental steels with that of the abrasion-resistant ROQ-last (Fig. 7) shows that they compare well with grades C321 and C340, with superior toughness in the titanium-free cast. However, the experimental steels have superior hardness to that of the ROQ-tuf grades. Steels with the composition

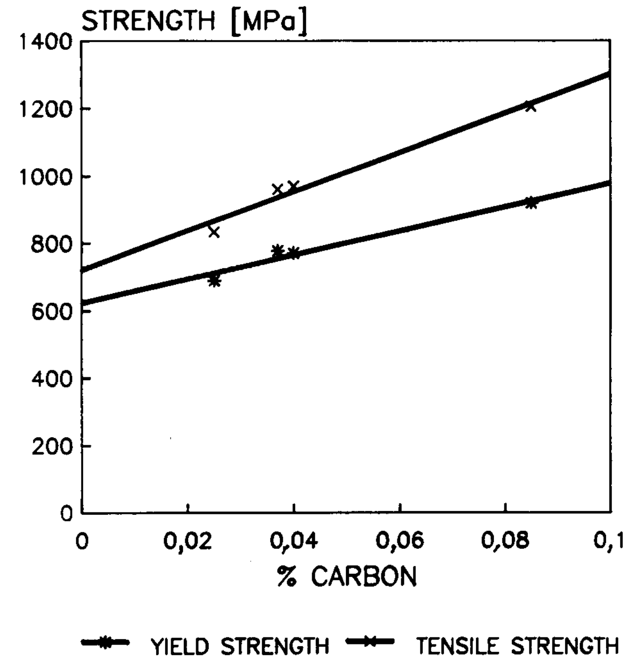

Fig. 4—The influence of carbon on the strength of the experimental steels

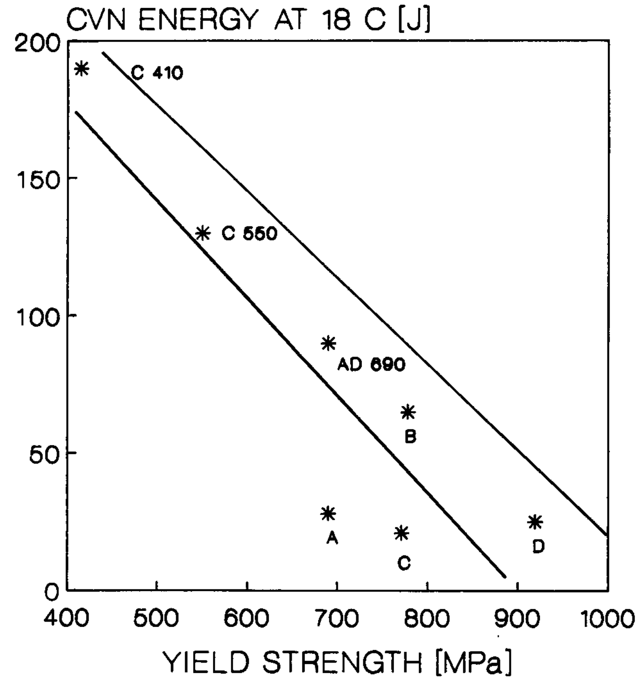

Fig. 6—Comparison of strength versus impact toughness at 18°C between ROC-tuf and the low-carbon experimental steels

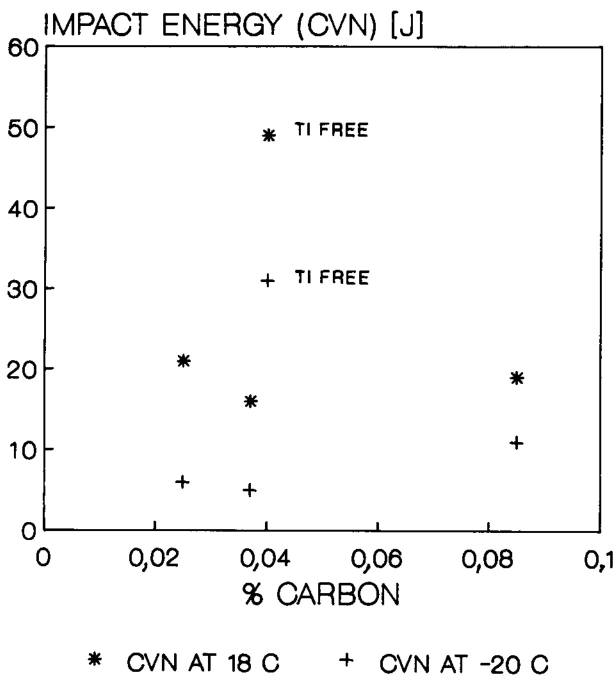

Fig. 5—The influence of carbon on Charpy impact energy

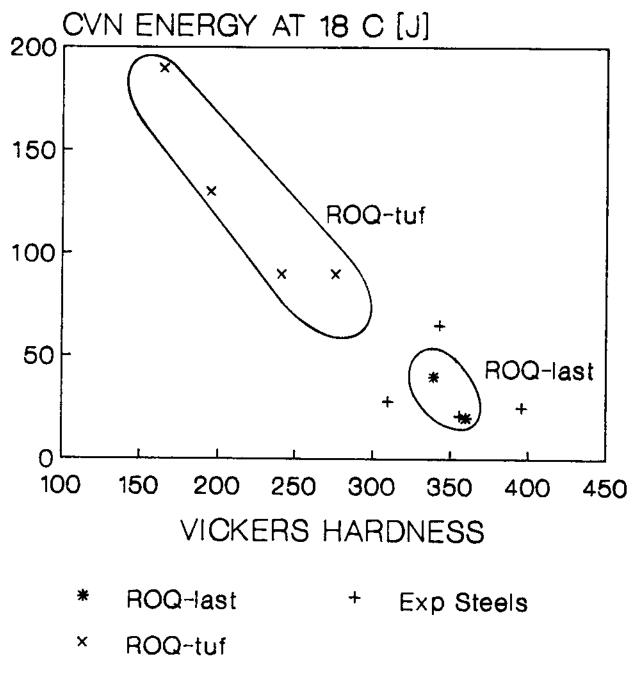

Fig. 7—Comparison of hardness versus impact toughness at 18°C between ROQ-tuf, ROQ-last, and the low-carbon experimental steels

of casts B, C, and D could replace ROQ-last Grades C321, C340, and C400, with an improvement in both strength and toughness in some cases.

The weldability of steels depends on their hardenability. In general, the higher the hardenability, the lower the weldability. Weldability can be evaluated theoretically by use of the P_{CM} value calculated according to

$$P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B.$$

The P_{CM} value of cast B is 0,164 compared with 0,277 of ROQ-tuf AD690, which has comparable strength and toughness, and 0,31 of ROQ-last C340. The higher the P_{CM} value as calculated from the chemical composition, the lower the weldability and the higher the susceptibility to hydrogen cracking[9].

The excellent weldability of these low-carbon steels makes them useful as high-strength, high-toughness structural steel. The higher carbon content still ensures superior weldability to that of the ROQ-last grades at higher hardness levels. The low processing cost and the excellent combination of properties (weldability, hardness, strength, and toughness) make these steels a viable alternative to conventionally quenched, tempered steels.

Examination of Microstructures

Very few data are available on the effect of martensitic grain size on toughness. In general, however, finer martensitic packets and laths contribute to better strength, toughness, and ductility.

The difference in impact toughness of casts B and C (41 J at 18°C) can be explained in terms of their microstructural features. In Table V the measured austenitic grain sizes indicate a significant difference between casts B and C. Fig. 8 shows the microstructure of cast B, and Fig. 9 that of cast C. A comparison of the optical micrographs in Figs. 8a and 9a indicates the coarser microstructural features (larger martensite packets) of cast C. This is confirmed by the much finer martensitic laths of cast B, as indicated by the TEM micrograph of Fig. 9b compared with that of Fig. 8b.

a

b

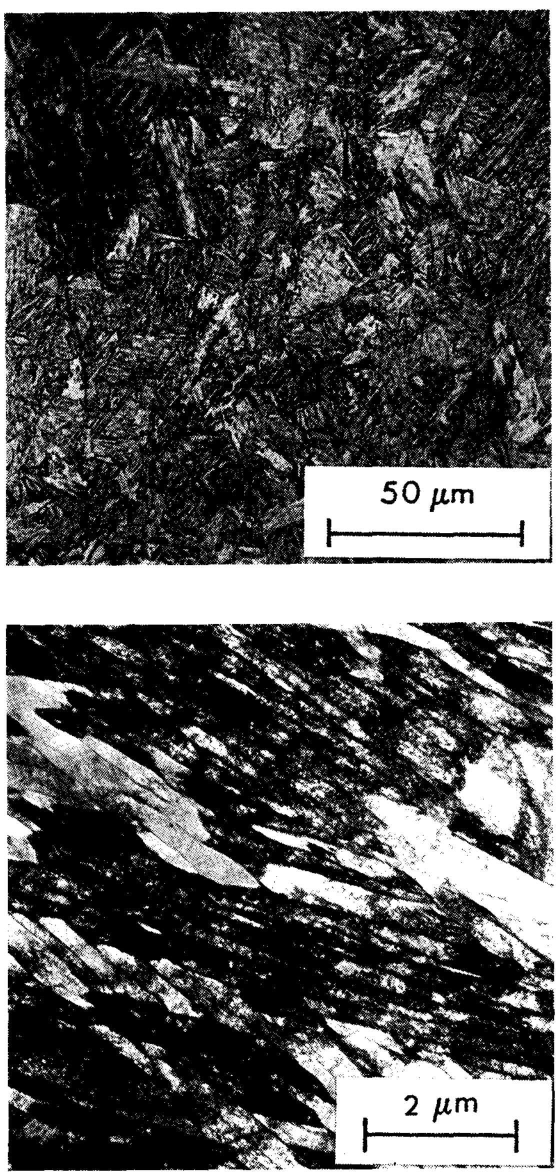

Fig. 8—Microstructures of cast B (titanium-free)

a

b

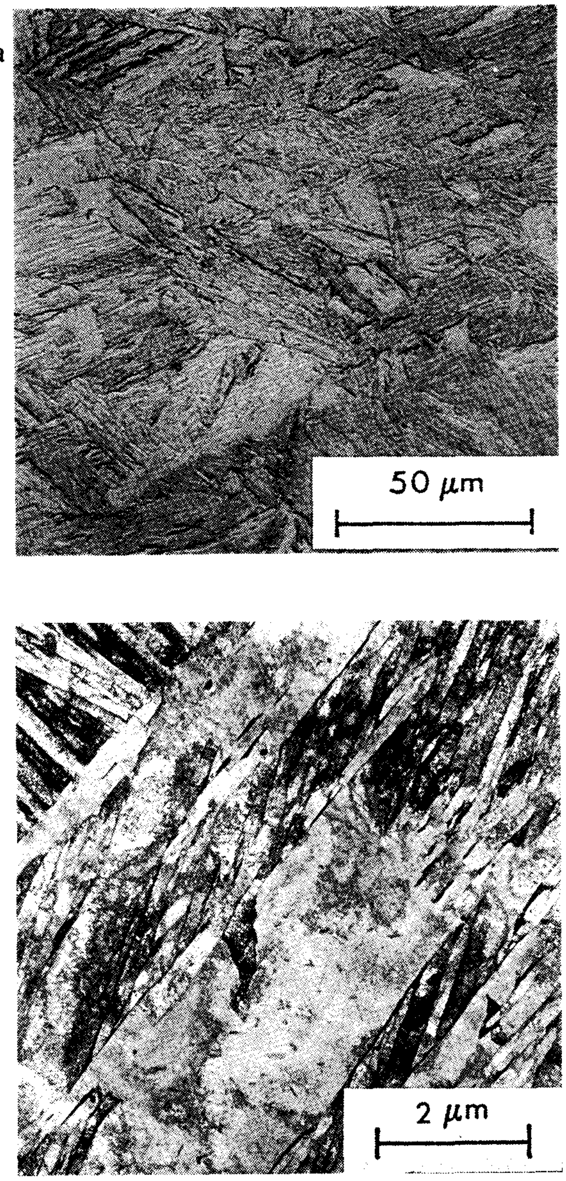

Fig. 9—Microstructures of cast C

From Tables II and V it is evident that the addition of titanium as a grain-refining element in these experiments was not successful. This could be due to insufficient soaking temperature and inadequate mechanical processing for grain refining. Better processing (as done on production lines) should produce much finer austenitic grains transforming to much finer martensitic grains and laths. The grain refining should improve the impact properties of these steels to levels comparable with high-toughness, quenched, tempered ROQ-tuf grades at higher strength levels.

The low-carbon manganese quenched steels would make the production of high-strength, high-toughness, structural-steel plate possible. Steels of higher hardenability as obtained by 0,085 per cent carbon cast steel would not go to waste since the higher strength and hardness obtained would render them useful as weldable abrasion-resistant plates.

Conclusions

The research on experimental low-carbon steels showed the following.

(1) The processing costs of ultra-low-carbon quenched steels are lower than those of conventional quenched, tempered structural steels, but the alloying costs could be higher.
(2) The strength and toughness obtained via the alternative route compares well with those obtained by the conventional route.
(3) Ultra-low-carbon (below 0,04 per cent carbon), quenched steels could satisfy the need for ultra-high-strength, high-toughness, structural-steel plate of small-section thickness.
(4) Somewhat higher carbon contents (0,04 to 0,08 per cent) produce steel plate comparable with current abrasion-resistant, quenched, tempered steels (ROQ-last) of superior weldability.
(5) The low carbon content ensures good weldability.
(6) More work needs to be done on the effects of plate thickness and processing variables on the properties of these steels.

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