THE MOLYBDENUM-BORON STRUCTURAL STEEL

J. F. SEWELL & W. E. BARDGETT

Introduction

THE production, properties and applications of alloy and special steels form a very wide subject. The decision to select the comparatively small area of this vast field, covered by the patented[1] low-carbon ½ per cent molybdenum-boron steel first described by Bardgett and Reeve[2], was made in the expectation that, during the early stages of improving the status of alloy steels in your country, you would wish to employ, as far as possible, existing facilities for steel production. It, therefore, seemed reasonable that this low-alloy structural steel which can be manufactured in the form of flat products or sections in the same plant which is used for the familiar plain carbon product and yet possesses a very much higher tensile strength without any sacrifice in other properties should have wide appeal. Although this steel is designed for applications similar to those of the familiar high-tensile low-alloy steels popular in Britain and the United States of America, it has particular properties which make it uniquely attractive and interesting. Outstanding among these is the level of tensile strength obtainable in a steel which is free from hard zone cracking in welding. Compared to a yield point of the order of 15 tons/sq. in. typical of the conventional carbon structural steels in the sections normally used, the American type steels meet a specification which demands a minimum yield point of 50,000 lb. per sq. in., i.e. 22·8 tons/sq. in., while this newer ½ per cent molybdenum-boron steel has one in the region of 30 tons/sq. in. This comparison is brought out clearly in the stress-strain curves reproduced in Fig. 1 which is an adaptation of that published by

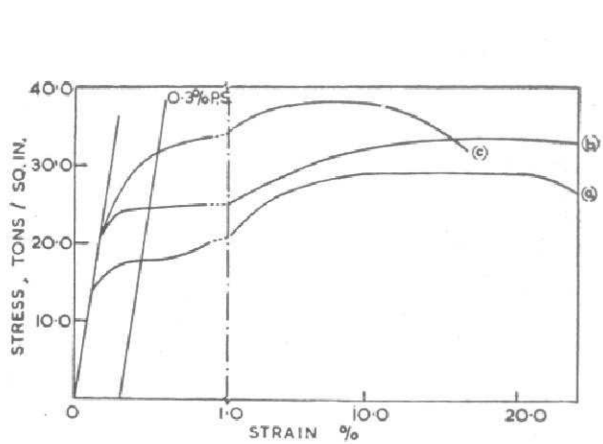

FIG. 1 — STRESS/STRAIN CURVES FOR STRUCTURAL STEELS: (a) MILD STEEL; (b) AMERICAN LOW-ALLOY TYPE; (c) ½ PER CENT Mo-B STEEL

Reeve[3], who has been responsible for much of the production development work on this steel. Thus in effect the ½ per cent molybdenum-boron steel represents the next stage of progress beyond this American group of steels, in the development of high-tensile low-alloy structural steels. It should, therefore, be regarded as complimentary to them rather than looked upon as a possible alternative. While from the composition viewpoint, all these steels come strictly within most national definitions of alloy steels, they are not considered as such in the U.S.A. because they are used almost exclusively in the hot-rolled or normalized condition to replace and improve upon ordinary carbon steel. A convenient solution from our point of view, to any argument as to whether or not they are alloy steels, is to consider them in a separate category of their own, i.e. a category which satisfactorily bridges the gap between the plain carbon and the alloy steels.

The prime objective of the steel producer in introducing a weldable structural steel having a higher tensile strength than the normal commodity, is to provide an improved and more profitable product having such potential economic advantages that, through its adoption, lighter weight or stronger and more durable structures may be built thereby rendering many existing designs obsolete and subject to replacement. This benefits the producer of the steel (increased demand for a higher priced and more profitable product), the fabricator (increased replacement market) and the owner or operator of the improved structures (lighter weight or longer service life and lower operating and maintenance costs). With an ever improving standard of living and higher wages the advantages of steels which last longer, limit maintenance and thus economize in costly labour, become more and more worthwhile.

Until the middle 1930's riveting or bolting was the universal method used for construction, but since that time welding as a method of fabrication has developed rapidly. The early British high-tensile structural steels which obtained their strength from carbon and manganese contents higher than in the ordinary plain carbon steel gave trouble when welding was attempted and had to be modified, particularly by reducing the level of carbon to make them at all amenable. Even so precautions, to avoid cracking, had to be taken in the welding operation on these steels, the tensile levels of which had already been lowered by the modifications to analysis. It was this increase in the use of welding as a method of fabrication which brought about a change in the approach to the qualities of steel suitable for high-tensile structural purposes and resulted in the types used in America. These in general are relatively low-carbon steels containing small percentages of a number of alloying elements which exhibit a very high ratio of yield point to maximum stress. The extremely good weldability of the low-carbon ½ per cent molybdenum-boron composition, to a degree which is probably unique among steels with similar tensile properties, is its second outstanding feature.

The third main advantage claimed for modern low-alloy high-tensile structural steels is that they have better corrosion resistance than the plain carbon steels they replace. In this new steel the ½ per cent molybdenum content gives it better corrosion resistance than the plain carbon steels, but in the standard grade no attempt is made to improve on this by small additions of such metals as copper or chromium normally used for such purposes.

Composition and Properties

Now having described the position occupied by this new steel more precise details about its composition and properties will be considered. It has been produced in electric arc, electric high-frequency and open-hearth furnaces as well as in a Tropenas converter. However, bulk production for structural steel products is normally carried out in the basic open-hearth furnace when the steel is made to the following composition:

	Per cent
Carbon	0·15 max.
Manganese	0·60 max.
Silicon	0·40 max.
Molybdenum	0·40-0·55
Boron (soluble)	0·0015-0·0035
Sulphur	0·05 max.
Phosphorus	0·05 max.

This steel in the form of plates and sections up to at least 1½ in. in thickness in the as-rolled condition gives mechanical properties as follows:

Maximum stress	37 tons per sq. in. minimum
Yield point	29 tons per sq. in. minimum
Elongation on 2 in.	20 per cent minimum

Typical compositions and mechanical test results were given by Bardgett and Reeve[4] and these are reproduced in Table 1.

TABLE 1 — MECHANICAL PROPERTIES OF ½ PER CENT Mo-B STEEL CHANNELS AND PLATES IN THE AS-ROLLED CONDITION

Cast No.	C	Mn	Si	S	P	Mo	Boron Sol.	Boron Insol.
Composition								
45837	0·09	0·42	0·23	0·026	0·016	0·50	0·0026	0·0007
45966	0·09	0·42	0·20	0·025	0·020	0·46	0·0022	0·0009
48781	0·12	0·57	0·17	0·028	0·036	0·46	0·0025	0·0009

Mechanical Properties (As-Rolled) (All stress figures in tons/sq. in.)

(*a*) *Rolled Steel Channels, B.S.C.* 104, 6 *in.* × 3 *in.* × 12·41 *lb./ft.*

Cast No.	Ingot	Tensile Strength	Proof Stress 0·30%	Elongation % on 2 in.	Elongation % on 8 in.	Redn. of Area, %	Izod Impact, ft.-lb.
45837	A	41·0	33·6	32·0	15·0	56·0	82
	F	41·2	32·2	30·0	15·0	53·0	86
	L	39·8	33·6	28·0	13·5	52·0	63
45966	A	38·5	32·8	28·0	13·0	54·0	86
	F	39·6	32·0	30·0	13·5	57·5	81
	L	37·9	32·8	32·0	16·0	58·0	82
48781	A	41·2	—	27·0	13·0	—	97
	B	41·0	—	28·0	14·0	—	78

(*b*) *Plates*

Thickness, in.	Direction	Tensile Strength	Yield Stress	Proof Stress 0·30%	*Elongation % on 2 in.	*Elongation % on 8 in.	Redn. of Area, %	Izod Impact, ft.-lb.
0·243	L	40·7	31·9	—	26·0	12·5	54·0	54†
0·490	L	39·3	30·0	28·1	—	17·0	—	98
0·740	L	41·0	30·6	28·2	40·0	17·0	54·0	85
0·985	L	40·6	32·3	31·8	35·0	16·0	—	49
1·500	L	40·4	32·5	31·4	—	15·0	—	45

*Measured on British Standard Test Piece A. †Hounsfield Miniature Impact Test.

Production

So far as steel-making is concerned quite a lot has appeared in the American press on the methods of making boron additions to steel to ensure an adequate recovery in the desired condition, i.e. as soluble boron. In general the same procedure is necessary for this molybdenum-boron steel. For success a rigid procedure for the final deoxidation in conjunction with the boron addition is essential. The steel-making practice which has been found to be successful comprises melting charges containing molybdenum-bearing scrap, working the heat to a low carbon level before tapping it at a relatively high temperature, and leaving the finishing additions to be made to the ladle. In the ladle, additions to adjust the carbon content, if required, are first made followed by the normal ferro-silicon addition. Next aluminium at the rate of 4-6 lb. per ton is added with any ferro-molybdenum necessary for final adjustment of this alloy content if it has not already been made in the furnace.

Finally, the ordinary silico-manganese addition is made simultaneously with the additions of ferro-boron and ferro-titanium. The ferro-titanium (40 per cent) addition is designed to give a 0·015 per cent residual titanium content in the steel and sometimes this addition is split, a small proportion of it going in at the same time as the aluminium, while the bulk accompanies the ferro-boron and silico-manganese. The ferro-boron (12·6 per cent) addition is calculated to give under ideal conditions 0·0055 per cent boron in the finished steel, but as the yield in practice is only of the order of 50 per cent, the desired final result is achieved. In this particular steel only ferro-boron is used for the boron addition since most of the proprietary alloys for this purpose contain large quantities of other deoxidants where the quantity of titanium in particular would result in a higher content than the desired 0·015 per cent in the finished steel.

The resultant boron content of the steel amounts to less than 1 oz. per ton so that in view of its very marked effect upon the mechanical properties it is necessary to be assured that it distributes itself uniformly and thereby results in a product with consistent properties. A single cast of steel was rolled into six different plate thicknesses and an analysis for boron carried out on each section with the following results:

Plate Thickness in.	*Boron per cent*	
	Soluble	*Insoluble*
$\frac{1}{8}$	0·0035	0·0001
$\frac{1}{4}$	0·0032	0·0002
$\frac{1}{2}$	0·0032	0·0002
$\frac{3}{4}$	0·0033	0·0002
1	0·0033	0·0002
$1\frac{1}{2}$	0·0034	0·0001

The familiar practice of charging ingots direct to the soakers after stripping is the one usually followed with this steel, although for special purposes the ingots may be allowed to go cold and the surface dressed before rolling. No special procedures are necessary during the rolling operation apart, perhaps, from the necessity to ensure that the product is allowed to cool freely in air so as to develop fully its properties. If it becomes necessary to carry out heat treatment, this should consist either of normalizing within the range 930°-980°C. or subcritical heating. When normalizing it is important to ensure that the material receives a true normalizing treatment, that is to say, it is allowed to cool freely in air.

If in production the steel is to be reheated for any purpose, the temperature range between 650° and 900°C. should be avoided. The influence on the steel's properties of reheating temperatures between 300° and 950°C. is shown in Fig. 2. It will be noted that up to temperatures of at least 650°C. for 1 hr. there is little effect on the mechanical properties. Heating for several hours at 650°C. will result in a slow fall in the ultimate tensile strength, though the yield point is little affected. It will be noted from the curves that appreciable softening occurs at 700°C. and is very marked at 850°C. The properties are fully restored, however, on

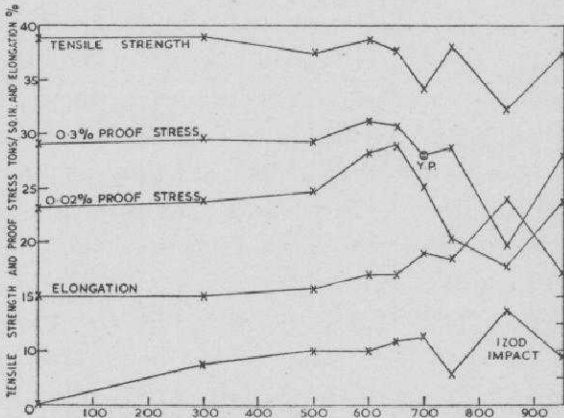

FIG. 2 — EFFECT OF REHEATING ON THE MECHANICAL PROPERTIES OF $\frac{1}{2}$ PER CENT Mo-B STEEL, AS-ROLLED

reheating to the normalizing temperature of 950°C.

Although in this paper attention has been directed principally to the production and use of this steel in the form of plates and sections, it can be, and is, produced in all other normal forms of supply, such as blooms, billets, bars, tube, sheet, strip, wire and castings.

In general high-tensile low-alloy steels require more care and attention during manufacture than plain carbon steels. The fact that quantities of alloy are present means that the raw materials are more costly. In some situations the rate of production of these steels might be lower, while rejections can be higher. Production departments like to produce those steels which are easy to make and on which production records can be made. This attitude must be borne in mind when introducing new qualities, and the production department's point of view given as much consideration as practicable by avoidance of unreasonable demands for samples and special lots.

Fabrication

Any structural high-tensile steel must be capable of withstanding the fairly drastic mechanical forming operations, such as shearing, punching, hot and cold-bending or pressing, which are used in fabricating shops. With the steel in question quite a number of these operations are essentially the same as in the case of mild steel and the other high-tensile structural steels. Apart from the somewhat greater forces required, there is little of special nature to be emphasized about the operations of shearing, punching, drilling and bending. The shearing limit is about 1 in. thickness above which gas-cutting becomes necessary.

This steel tends to work-harden more readily than mild steel so that in practice it is found advisable, for heavy plates, to make allowances for stresses at double those for mild steel. The radius of bends in all high tensile steels should be as generous as possible; and it is suggested that this should not be less than three times the plate thickness. Bending at sheared edges, particularly in the case of plates $\frac{3}{8}$ in. thick and heavier, is prone to lead to the development of serious cracks from the small ones inevitably present at such edges. Gas-cut edges are more satisfactory particularly if slight bevelling of the edges with a wheel is used while machined edges are the ideal especially on heavy plate. It is known that gas-cutting demands certain precautions with all steels, but so far little experience is available on the use of this process with the molybdenum-boron quality.

Welding

It is the welding aspect of the molybdenum-boron steel with particular reference to its freedom from hard zone cracking which is of outstanding interest and to which we especially wish to direct your attention. Our previous remarks on fabrication have dealt principally with mechanical processes, but welding being a metallurgical one has been deliberately separated from that section. Welding can be satisfactorily carried out by any of the recognized processes, gas welding, metallic arc welding, argon arc welding, or resistance welding.

The problems encountered with structural steels will be more easily understood if we bear in mind that the fusion process involves a small-scale steel-making operation in which temperatures in the plate immediately adjacent to the weld go up to 1500°C. for a period of a few seconds to be followed immediately by a violent quenching action owing to the rapid conduction of heat into the adjacent cold steel. The material adjacent to the weld will, therefore, harden to an extent as great as would occur in the water-quenching of the steel. Superimposed upon this hardening are the shrinkage stresses which in the neighbourhood of the weld will attain the yield point of the steel. In addition, according to the latest theories hydrogen diffuses from the weld metal into this heat-affected zone and may attain very high pressures. Experience has shown that cracking in this zone can be controlled by (a) steel composition, (b) type of electrodes and (c) welding technique. Within certain limits variations in the last two items will have similar effects on all weldable steels with the steel composition being the critical one in promoting weldability. With the low-carbon ½ per cent molybdenum-boron composition, the danger of hard zone cracking, even in thick sections welded under highly restrained conditions, is virtually absent. An extreme example of this excellent weldability is shown in the following test in which this steel was deliberately welded at very low temperatures to increase the severity of the test.

A miniature Reeve test consisting of an upper plate of this steel 2 × 2 × ½ in. thick was fastened to a lower plate 3 × 3 × 1½ in. thick analysing 0·12 per cent carbon and 1·43 per cent manganese. After anchor welding in the usual way with 4G. electrodes the test assembly was cooled to −76°C. in 'Cardice' and the test weld deposited with a 10G. 'Ironex' electrode. After standing in air for 60 hr. three sections were taken through the test weld and examined for cracks by microscopical examination and magnetic etching. No cracks were observed and the maximum hardness reported was 366 HD/10. If circumstances should by chance arise where it is considered that stress-relieving after welding is desirable, the temperature should preferably be kept nearer 600°C. than 650°C. to avoid the range of softening temperatures already explained. Even at this lower temperature a drop in tensile strength of between 1 and 2 tons is possible.

Theoretical Considerations

The value of the molybdenum-boron composition for structural steel purposes was discovered during an investigation designed to improve the properties of ½ per cent molybdenum steam pipe material. This led to a considerable amount of work exploring and developing its various features, and of course in trying to find an explanation for the unique properties of the steel.

The statement that the properties of a steel are primarily a function of its microstructure should not be accepted, even as generally true, without a recognition that the individual component phases, comprising that microstructure, can vary within limits, not only in composition but also in properties. Thus the high-tensile low-alloy steels of the American field owe their superior mechanical properties over the plain carbon steels not so much to change in microstructures as to the strengthening effects of the alloys in solid solution in the ferrite. The low-carbon ½ per cent molybdenum composition in contrast depends for its higher tensile properties on lower temperature transformation products. When ½ per cent molybdenum steel without boron is normalized in, say, 1 in. diameter bar, transformation from austenite occurs on cooling over a temperature range typically 840°-740°C. and the resultant microstructure consists of polygonal ferrite and sorbitic bainite as shown in Fig. 3. In the case of a similar steel with boron the transformation occurs at a lower temperature typically 700°-600°C. and the microstructure consists of small-grained ferrite with finely dispersed areas of acicular bainite and a little weak martensite illustrated in Fig. 4. This difference can be seen by a study of the relevant isothermal transformation diagrams (Figs. 5 and 6). Just how so small an addition as 0·003 per cent of soluble boron can cause so marked a change in the structure and properties becomes easy to understand when one realizes that boron is simply indulging in its normal behaviour of retarding the rate of transformation in the steel. However, instead of causing martensite to be formed more readily at slower rates of cooling, as in conventional hardenability concepts, the boron in the normalized ½ per cent molybdenum steel is simply allowing a low

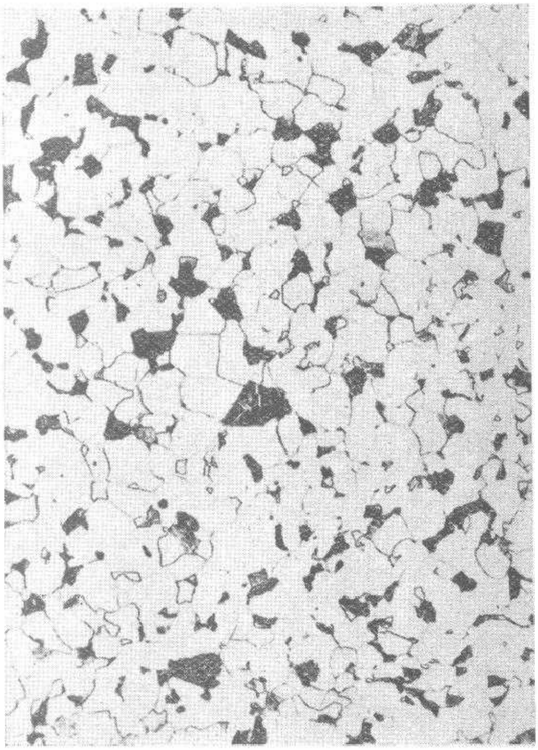

FIG. 3 — MICROSTRUCTURE OF ½ PER CENT Mo STEEL

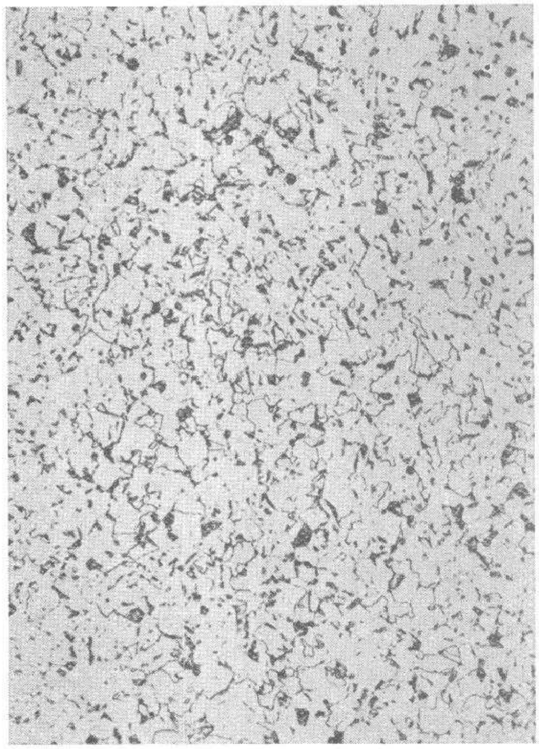

FIG. 4 — MICROSTRUCTURE OF ½ PER CENT Mo STEEL WITH BORON

carbon bainite to form on air-cooling, i.e. the steel is 'air-hardening' to form a low carbon bainitic structure.

The ½ per cent molybdenum content is essential in bringing about a favourable position of the upper part of the 'S' curve for air-cooling conditions. The mechanism by which so small a boron addition achieves the result it does, is one of retardation or inhibition of the formation of polygonal ferrite, which is invariably nucleated at the austenite grain boundaries. The result is that bainite is formed on air-cooling. The reason why only 0·003 per cent boron is necessary is that the boron segregates very markedly to the prior austenite grain boundaries, thereby causing their ability to nucleate for polygonal ferrite to be lost. It will be appreciated that if the boron concentrates just where its effect is most needed, as it does, very small quantities are required to promote an increase in the steel's hardenability. The way in which boron destroys the nucleating tendency of the austenitic grain boundaries for ferrite formation is as yet not completely understood, but may be connected with the diffusion of carbon near the grain boundaries or with thermodynamical considerations.

Transformation of a steel, even in part to martensite the most highly stressed and the most brittle of microconstituents, is the usual cause of cracking in the material and the crack sensitivity of martensite increases with its carbon content. Thus the low carbon content of the ½ per cent molybdenum-boron composition is most beneficial in welding applications. Further, it has been shown by fundamental research by the British Welding Research Association that a relationship exists between the severity of hard zone cracking as measured by the Reeve test, and

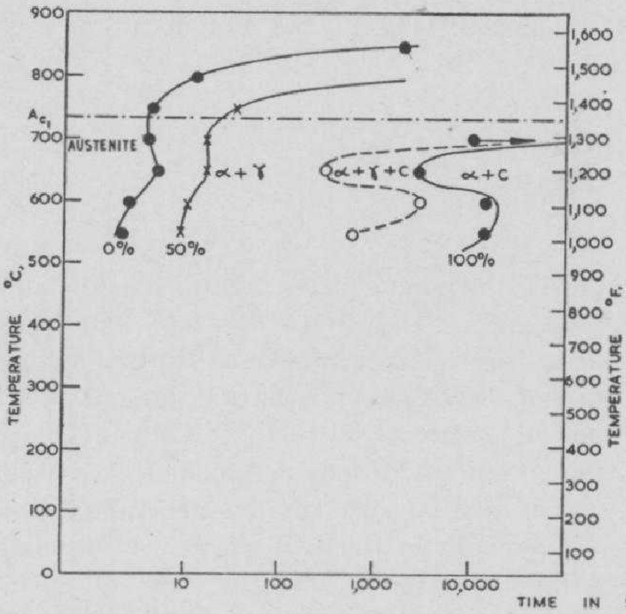

FIG. 5 — ISOTHERMAL TRANSFORMATION CURVE FOR ½ PER CENT MO STEEL

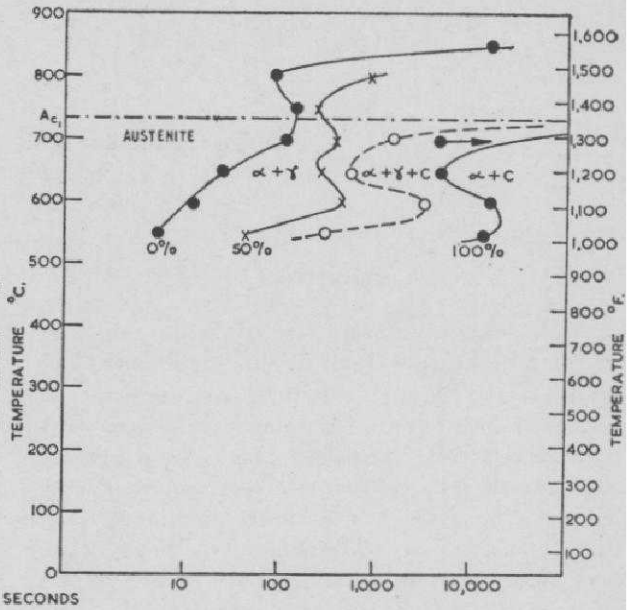

FIG. 6 — ISOTHERMAL TRANSFORMATION CURVE FOR ½ PER CENT MO STEEL WITH BORON

a critical end of transformation temperature, which temperatures have been measured in a special rapid-action dilatometer designed by Dr. Cottrell[5]. If the steel continues transforming below this temperature, hard zone cracking is likely to occur. This critical end of transformation temperature is about 290°C. for welds made with rutile-coated electrodes. In the case of the low-carbon ½ per cent molybdenum-boron composition the end of transformation temperature in the rapid-dilation test was found to be between 425° and 430°C. for a rate of cooling corresponding to conditions in a large weld. This is well above the critical temperature of 290°C. and indeed the highest end of transformation temperature of any of the high-tensile steels examined in this investigation. To this was attributed the exceptional freedom from cracking in the heat-affected zone of this steel with such high tensile properties.

In conclusion mention should be made of one further attractive feature of this steel, which has so far been omitted because its application more correctly belongs to the field of the more generally recognized alloy steels. In this field it is well known that molybdenum is useful in improving the high temperature properties of steel and the ½ per cent molybdenum composition is a standard one among creep-resisting steels. The addition of boron in no way detracts from this improvement in creep properties and consequently the steel has found quite wide application in the form of flat products and rings for jet and turbine aircraft engine construction. Here advantage is taken of the steel's high tensile room temperature properties, its creep resistance at elevated temperatures, and its weldability, in many of the structural and sheathing components of these engines.

References

1. *Indian Patent* 37,903. Registered Trade Name " Fortiweld ".
2. BARDGETT, W. E. & REEVE, L., " Mechanical Properties of Low Carbon Low Alloy Steels containing Boron ", *J.I.S.I.* (November 1949), 277-294.
3. REEVE, L., " Weldability of High Tensile Structural Steels ", *Trans. Inst. of Welding*, **16**(6) (Dec. 1953), 154.
4. BARDGETT, W. E. & REEVE, L., " High Strength Weldable Steel ", *Iron & Steel* (Oct.-Nov. 1954).
5. COTTRELL, C. L. M., *J.I.S.I.*, **174** (1953), 17-24.