# Columbium-Boron High-Tensile Steel

**T. V. Cherian**

BORON is seldom used as an alloying element in low carbon steels, although it is recognised to be a potent and cheap alloy to replace sizable quantities of costly elements normally used in hardenable steels, to bolster the depth of hardening. Pearlitic steels of commerce encompass a wide range in composition and properties. Amongst these an economically superior class, is the high tensile steels, that are characterised by good strength, high yield-tensile ratio and adequate ductility. In composition, they are of the low carbon low alloy grade, conducive to easy frabrication, which is a highly desirable quality. These features, particularly, the high mechanical properties in the as rolled or normalised condition, is responsible for their special recognition and commercial popularity. The invention of molybdenum-boron steel[1], more popularly known as fortiweld, was a notable addition to this class and metallurgically it is a significant advancement as it extended the scope of boron alloying to non martensitically hardenable steels. However attempts to develop a general class of boron-bearing high-tensile steel by replacement of molybdenum with a series of common alloying elements were met with rather discouraging results. Based on these observations and the thermal behaviour of the steel, it was advocated that fortiweld alloy combination is a unique entity and its superior strength is the outcome of certain delayed phase transformations. Yet, a critical study of the ageing characteristics, mass effect, and response to heat-treatment of the steel gave certain indications that are common to a precipitation hardening phenomenon. If so, substitution of molybdenum by a chemically similar element appeared to be a logical possibility and in view of similarity in structure and other physico-chemical traits, the element columbium was selected for the purpose.

## Experimental data

A series of 15 lb experimental melts containing the desired alloys in requisite amounts were made in high-frequency furnace using low-carbon steel base material. Ferro-alloys of columbium and boron were of 50% and 17·5% element contents respectively. Prior to boron addition, deoxidation of the melt with aluminium at the rate of 0·75 to 1·0 lb per ton gave a boron efficiency not less than 50%. Ingots cast from these melts were forged into 1 inch diameter bar or 3/8 × 1·1/4 inch flat and standard 0·505″ or 2″ gauge flat test samples were prepared from forged, normalised-stress relieved materials. The melts are grouped into five series with respect to alloy combination and their particulars of composition given in Table I include only the soluble part of boron analysis. The mechanical properties of these steels are given in Table II with the particulars of heat-treatment. Essentially all the series contain Cb and B except the comparison series. However, each series may be treated separately in view of the slight differences in composition.

*I. Columbium-boron series*: Eight steels, M-1—M-8, comprising this series show that a columbium containing boron treated low-carbon steel has exceptional strength properties in the as-forged or normalised condition. That extremely low quantities of these alloys are sufficient to impart a pronounced increase to the strength of a low-carbon steel is evident from a comparison of steel M-1 and Steel M-23. The yield stress of the former is 72,600 p.s.i. whereas that of the latter is only 42,500 p.s.i. and so an increase of 70% in yield-stress is solely attributable to 0·06% columbium and 0·003% boron. That it is the columbium-boron combination and not the individual alloy that is responsible for the enhanced property is borne out by columbium-alloyed steel M-21 and boron-alloyed steel M-22. The mechanical properties, in relation to columbium weight percentage for the series is shown in Fig. 1 for the as-forged condition and that after a normalising treatment, in Fig. 2. The plots are self explanatory, the more dominant features are the rapid increase in strength at the low alloy range and the effectiveness of the alloy even at a very low percentage. The yield-tensile ratio of these steels is not less than 85% in the as-forged, whereas after normalising it approaches 95%. Even with the high yield-tensile ratio, the elongation and reduction in area are equally satisfactory indicating adequate ductility. These high physicals that are attainable with these low-alloy combinations in presence of extremely low carbon makes this steel a unique addition to the family of high-tensile steels.

In the above plots, steels M-4 and M-7 were

---

Mr. T. V. Cherian, Assistant Superintendent of Research, Research and Control Laboratory, Tata Iron and Steel Co. Ltd., Jamshedpur.

## TABLE I

*Composition of experimental steels*

| Steel designation | ANALYSIS % | | | | | | |
|---|---|---|---|---|---|---|---|
| | C. | Mn. | Si. | Cb. | B. | V. | Other elements |
| I. **Columbium-Boron series.** | | | | | | | |
| Steel M-1 | 0.06 | 0.42 | 0.18 | 0.06 | 0.003 | - | - |
| - M-2 | 0.07 | 0.39 | 0.20 | 0.08 | 0.003 | - | - |
| - M-3 | 0.06 | 0.41 | 0.28 | 0.16 | 0.005 | - | - |
| - M-4 | 0.06 | 0.25 | 0.17 | 0.22 | 0.005 | - | - |
| - M-5 | 0.06 | 0.38 | 0.27 | 0.24 | 0.007 | - | - |
| - M-6 | 0.08 | 0.59 | 0.35 | 0.26 | 0.004 | - | - |
| - M-7 | 0.07 | 0.21 | 0.26 | 0.27 | 0.0034 | - | - |
| - M-8 | 0.08 | 0.40 | 0.32 | 0.41 | 0.009 | - | - |
| II. **Columbium-Boron-Vanadium series.** | | | | | | | |
| Steel M-9 | 0.09 | 0.35 | 0.17 | 0.014 | 0.003 | 0.06 | - |
| - M-10 | 0.08 | 0.40 | 0.21 | 0.014 | 0.002 | 0.06 | - |
| - M-11 | 0.06 | 0.36 | 0.16 | 0.019 | 0.002 | 0.06 | - |
| - M-12 | 0.05 | 0.37 | 0.15 | 0.038 | 0.003 | 0.05 | - |
| - M-13 | 0.05 | 0.61 | 0.38 | 0.07 | 0.006 | 0.06 | - |
| - M-14 | 0.05 | 0.51 | 0.24 | 0.35 | 0.007 | 0.06 | - |
| III. **Columbium-Boron-Vanadium Low Silicon series.** | | | | | | | |
| Steel M-15 | 0.03 | 0.36 | 0.05 | 0.05 | 0.004 | 0.04 | - |
| - M-16 | 0.04 | 0.47 | 0.02 | 0.064 | 0.0025 | 0.05 | - |
| - M-17 | 0.04 | 0.40 | 0.02 | 0.08 | 0.0025 | 0.05 | - |
| - M-18 | 0.05 | 0.34 | 0.09 | 0.13 | 0.003 | 0.05 | - |
| IV. **Columbium-Boron-Vanadium-Molybdenum series.** | | | | | | | |
| Steel M-19 | 0.06 | 0.45 | 0.24 | 0.03 | 0.004 | 0.05 | Mo-0.14 |
| - M-20 | 0.04 | 0.55 | 0.07 | 0.03 | 0.003 | 0.04 | Mo-0.20 |
| . **Comparison series.** | | | | | | | |
| Steel M-21 | 0.09 | 0.45 | 0.25 | 0.44 | - | - | Al-0.12 |
| - M-22 | 0.10 | 0.48 | 0.29 | - | 0.0025 | - | Al-0.44 |
| - M-23 | 0.08 | 0.46 | 0.17 | - | - | - | - |
| - M-24 | 0.10 | 0.44 | 0.25 | - | 0.002 | - | Zr-0.30 |
| - M-25 | 0.06 | 0.24 | 0.47 | - | 0.003 | - | Ti-0.12 |
| - M-26 | 0.09 | 0.46 | 0.17 | - | - | 0.065 | Al-0.06 |

Note:

(1) All steels contained P less than 0.03 % and S less than 0.04 %.

(2) All boron treated steels contained Al as a deoxidiser.

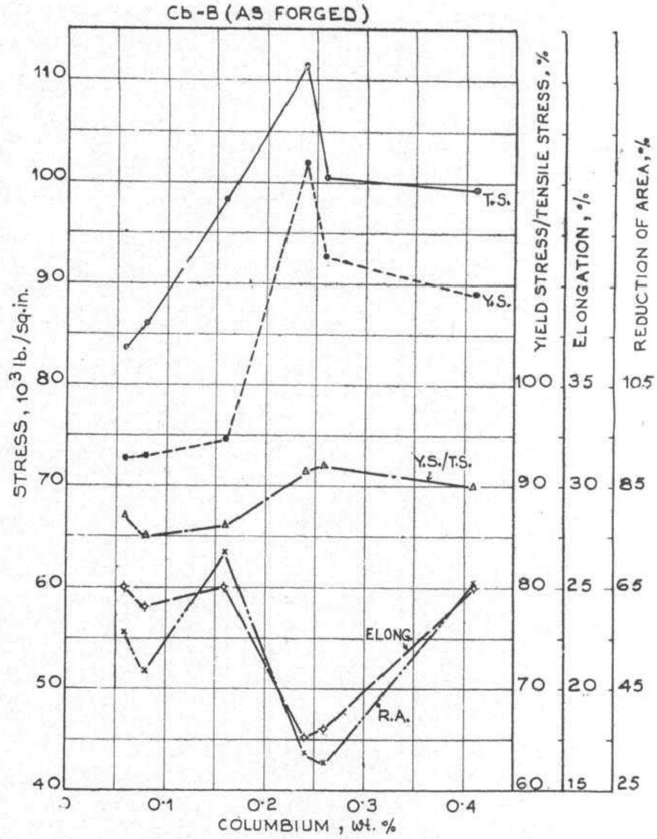

Fig. 1.

Relation between alloy content and mechanical properties.

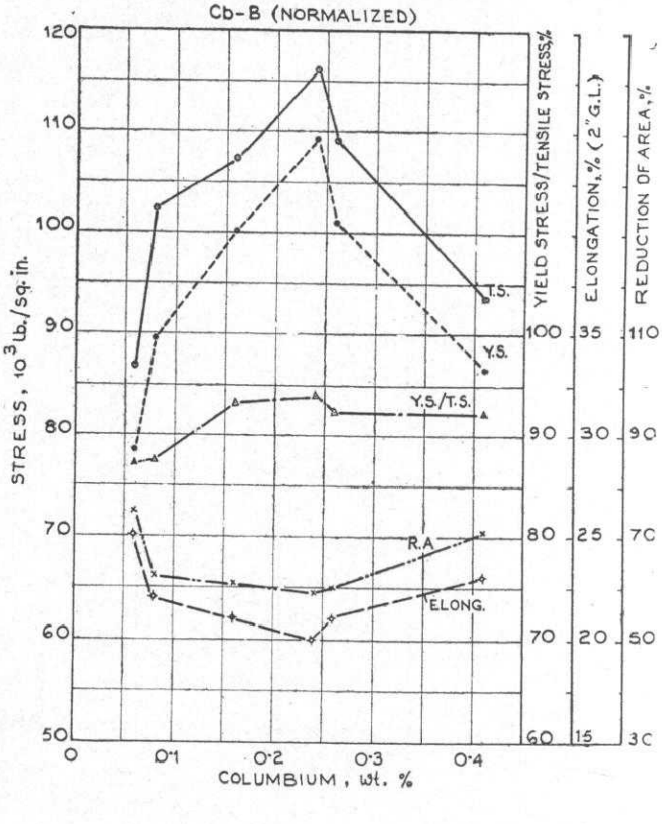

Fig. 2.

Relation between alloy content and mechanical properties.

## TABLE II

*Heat-treatment and mechanical properties of experimental steels.*

| Steel Designation. | Cb % | Heat-treatment | | Mechanical properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Normalizing Temp. °C. | Stress relieving Temp. °C. | Yield stress p. s. i. 0·2% off set | Tensile stress p. s. i. | Elong. (2" Ga-L) % | Reduction of Area % | Yield tensile ratio |
| I.Cb-B-Series. | | | | | | | | |
| Steel M-1 | 0.06 | As forged | None | 72,600 | 83,600 | 25 | 56.1 | 0.87 |
| " | " | 1200 | 540 | 78,500 | 86,800 | 23 | 75.5 | 0.905 |
| " M-2 | 0.08 | As forged | None | 72,900 | 86,000 | 24 | 48.3 | 0.85 |
| | " | 1200 | 540 | 89,500 | 102,300 | 22 | 62 | 0.875 |
| Steel M-3 | 0.16 | As forged | None | 84,400 | 98,200 | 25 | 72.8 | 0.86 |
| | " | 1200 | 540 | 100,000 | 107,200 | 21 | 60.6 | 0.932 |
| Steel M-4 | 0.22 | As forged | None | 41,800 | 58,900 | 33 | 67.4 | 0.71 |
| | " | 980 | " | 51,800 | 67,700 | 30 | 69.9 | 0.765 |
| | " | 1040 | " | 59,300 | 75,400 | 26.5 | 70.5 | 0.787 |
| | " | 1090 | " | 67,700 | 83,300 | 26 | 65.7 | 0.815 |
| Steel M-5 | 0.24 | As forged | None | 102,000 | 111,450 | 17.5 | 32.3 | 0.915 |
| | " | 1090 | 540 | 86,600 | 93,500 | 25 | 70.7 | 0.93 |
| | " | 1200 | 540 | 109,000 | 116,000 | 20 | 58.5 | 0.942 |
| Steel M-6 | 0.26 | As forged | None | 92,600 | 100,500 | 18 | 30.6 | 0.92 |
| | " | 1200 | None | 103,500 | 114,800 | Broken outside | G.L. | 0.90 |
| | " | 1200 | 400 | 98,000 | 108,800 | 20 | 61 | 0.90 |
| | " | 1200 | 540 | 101,000 | 109,000 | 21 | 60 | 0.927 |
| Steel M-7 | 0.27 | As forged | None | 58,900 | 77,200 | 23 | 58.6 | 0.762 |
| | " | 925 | None | 42,500 | 60,800 | 36.5 | 73.0 | 0.70 |
| | " | 925 | 540 | 40,500 | 60,000 | 36.5 | 73.5 | 0.675 |
| | " | 1090 | None | 77,000 | 93,300 | 20 | 55.2 | 0.825 |
| Steel M-8 | 0.41 | As forged | None | 89,100 | 99,400 | 25 | 66.3 | 0.90 |
| | " | 1090 | None | 83,800 | 94,300 | 20 | 51.5 | 0.898 |
| | " | 1090 | 540 | 86,500 | 93,600 | 23 | 71.0 | 0.925 |
| II.Cb-B-V-Series. | | | | | | | | |
| Steel M-9 | 0.014 | As forged | None | 55,400 | 69,300 | 29 | 66.5 | 0.80 |
| | " | 925 | None | 50,200 | 62,000 | 36 | 79.0 | 0.81 |
| | " | 1150 | 540 | 67,500 | 74,200 | 23 | 73.5 | 0.91 |
| | " | 1200 | 540 | 73,500 | 81,000 | 21 | 72.0 | 0.91 |
| Steel M-10 | 0.014 | As forged | None | 53,500 | 67,300 | 24 | 59.0 | 0.796 |
| | " | 1150 | 540 | 77,500 | 83,500 | 19 | 63.0 | 0.93 |
| | " | 1200 | 540 | 74,000 | 81,000 | 23 | 72.0 | 0.915 |
| Steel M-11 | 0.019 | As forged | None | 66,000 | 76,700 | 27 | 61.0 | 0.86 |
| | " | 1200 | 540 | 75,000 | 82,500 | 23 | 72.0 | 0.915 |
| Steel M-12 | 0.038 | As forged | None | 67,500 | 76,600 | 27 | 66.0 | 0.88 |
| Steel M-13 | 0.07 | As forged | None | 84,000 | 91,500 | 25 | 69.0 | 0.923 |
| Steel M-14 | 0.35 | As forged | None | 94,000 | 105,700 | 24 | 63.0 | 0.89 |
| | " | 1200 | 540 | 114,000 | 121,000 | 19 | 51.0 | 0.945 |
| III.Cb-B-V-Low Si.series | | | | | | | | |
| Steel M-15 | 0.05 | As forged | None | 84,500 | 92,500 | 27 | 67.5 | 0.915 |
| | " | 1040 | None | 62,600 | 71,500 | 30 | 73.6 | 0.877 |
| | " | 1090 | None | 76,400 | 84,700 | 28 | 72.4 | 0.905 |
| | " | 1150 | None | 78,500 | 82,500 | 19 | 49.5 | 0.95 |
| Steel M-16 | 0.064 | As forged | None | 66,000 | 71,700 | 25 | - | 0.92 |
| | " | 1090 | None | 68,400 | 72,200 | 25 | - | 0.95 |
| Steel M-17 | 0.08 | As forged | None | 62,900 | 69,400 | 26 | - | 0.907 |
| | " | 1090 | None | 74,700 | 82,000 | 24 | - | 0.912 |
| Steel M-18 | 0.13 | As forged | None | 82,500 | 95,000 | 25 | 69.3 | 0.87 |
| | " | 1040 | None | 63,800 | 75,500 | 30 | 75.5 | 0.845 |
| | " | 1090 | None | 77,000 | 85,000 | 27 | 73.0 | 0.905 |
| | " | 1150 | None | 86,000 | 93,200 | 26 | 68.0 | 0.922 |
| IV.Cb-B-V-Mo-series | | | | | | | | |
| Steel M-19 | 0.03 | As forged | None | 71,000 | 86,000 | 24 | 69.0 | 0.825 |
| | " | 1150 | 540 | 78,500 | 83,500 | 20 | 71.0 | 0.945 |
| | " | 1200 | 540 | 88,600 | 90,300 | 20 | 68.5 | 0.98 |
| Steel M-20 | 0.03 | As forged | None | 81,000 | 85,700 | 22 | 68.9 | 0.945 |
| | " | 1150 | 540 | 79,500 | 85,250 | 22 | 76.5 | 0.932 |
| | " | 1200 | 540 | 84,000 | 86,600 | 20 | 68.4 | 0.97 |
| V.Comparison series | | | | | | | | |
| Steel M-21 | 0.44 | As forged | None | 50,700 | 64,500 | 35 | 77.5 | 0.785 |
| | " | 1150 | 540 | 56,300 | 69,700 | 32 | 79.4 | 0.81 |
| Steel M-22 | Nil | As forged | None | 45,000 | 59,200 | 37 | 70.5 | 0.76 |
| | " | 1150 | 540 | 50,000 | 64,000 | 34 | 71.0 | 0.78 |
| Steel M-23 | Nil | As forged | None | 42,500 | 59,000 | 38 | 71.5 | 0.72 |
| | " | 1150 | 540 | 48,000 | 62,000 | 38 | 67.6 | 0.77 |
| Steel M-24 | Nil | As forged | None | 39,000 | 58,100 | 38 | 72.5 | 0.67 |
| | Nil | 1150 | 540 | 56,500 | 65,200 | 25 | 74.5 | 0.866 |
| | Nil | 1200 | 540 | 48,300 | 60,600 | 30 | 70 | 0.80 |
| Steel M-25 | Nil | As forged | None | 52,300 | 62,000 | 31 | 70.9 | 0.84 |
| | " | 1150 | 540 | 50,900 | 61,600 | 27 | 70.9 | 0.82 |
| | " | 1200 | 540 | 45,450 | 59,900 | 34 | 71.0 | 0.75 |
| Steel M-26 | Nil | As forged | None | 45,500 | 59,600 | 38 | 70.5 | 0.76 |
| | " | 1150 | 540 | 48,000 | 62,600 | 38 | 69.6 | 0.765 |

not included as they showed abrupt decrease in strength, departing from the general trend. Even though the data is insufficient to assess accurately the specific roles of the base alloys, these steels show that there is a minimum amount of manganese required to develop the high strength character. The dependence of yield-stress to this alloy content is quite clear from the plots given in Fig. 3. It is to be inferred that a manganese content below 0·35% irrespective of columbium has a deleterious action on the strength properties.

*II. Columbium-boron-vanadium series*: It is apparent from Table II that high temperatures were required to develop the optimum properties of the steel in a normalising treatment. Even though columbium is a grain refiner, the abnormally high temperature induced considerable grain coarsening when this alloy content was extremely low. But steels of the low-alloy range are the most significant type, considering the remarkable increase in the strength properties. Hence to retain the fine grained structure vanadium to the extent of 0·05% was used as an additional alloy. This amount of element resisted grain coarsening even up to a 1,200°C normalising treatment, yet, that it does not contribute markedly to the strength properties is evident from a comparison of steel M–26 and the plain carbon steel M–23. All the steels of the series except steel M–14 contain very low columbium and the mechanical properties in relation to the alloy content are shown in Fig. 4. Steels M–9 and M–10 are of interest in revealing the boron requirement. Both steels contain 0·014% columbium whereas the boron content is 0·003% and 0·002% respectively. After a normalising treatment at 1,200°C, the steels are almost identical in strength and so it is evident that a boron content of 0·002% is enough to develop the high strength character.

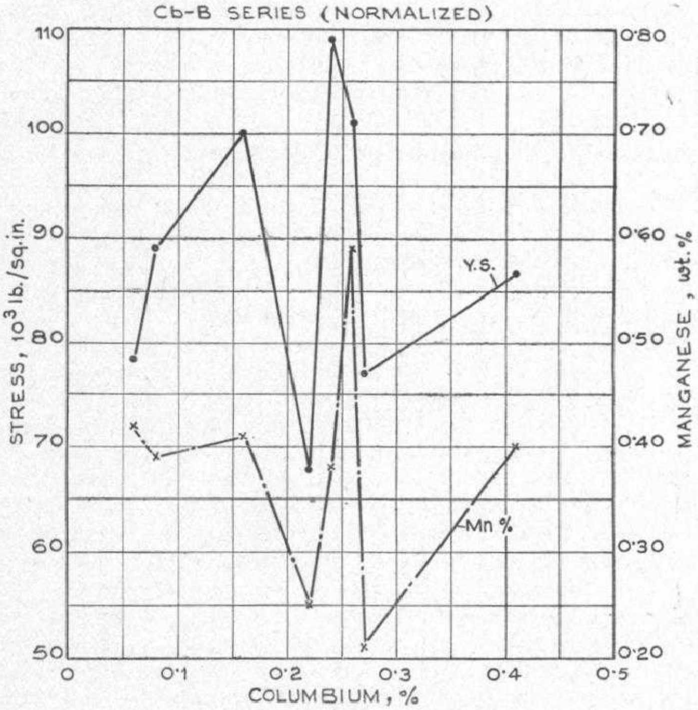

Fig. 3.

Effect of manganese variation on yield stress.

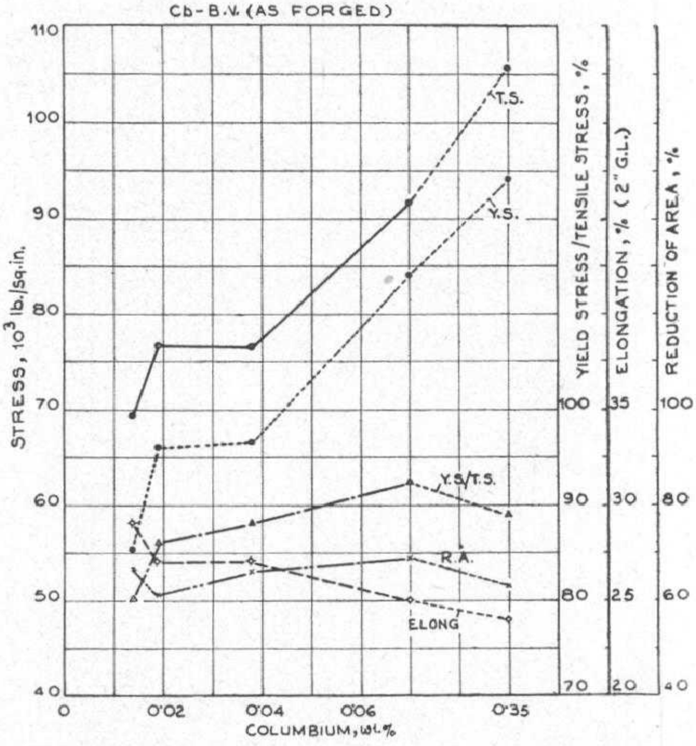

Fig. 4.

Relation between alloy content and mechanical properties.

*III. Columbium-boron-low-silicon series.* The series show that the superior strength character can be retained with a low silicon content in the range customarily present in a semi-killed steel (Fig. 5, 6). Deoxidation of the melt with 1·5 lbs. of aluminium per ton and 0·05% vanadium gave satisfactory boron efficiency. However, extremely low silicon appears to be not so satisfactory from the mechanical strength point of view as is evidenced by steels M–16 and M–17 containing only 0·02% of the element. In general the steels are of slightly inferior strength to that of steels of the proceeding series having the element in the range normally present in a fully killed steel. The outstanding feature of the series is the high strength manifested with extremely low alloy content. This may be exemplified by steel M–15 that has an alloy content not exceeding 0·6% including the base alloys. The mechanical properties of the steel in the as-forged condition are of the order of 84,500 p.s.i. yield strength at 0·2% offset, 9·5% yield-tensile ratio, 2·% elongation and 67·5% reduction in area. This extraordinary combination of properties is a unique feature hitherto unknown among lean alloy low carbon steels.

*IV. Columbium-boron-vanadium-molybdenum series.* The high tensile properties of "fortiweld" begin to manifest only when the molybdenum content exceeds 0·2%, whereas columbium even at 0·014% is extremely powerful in imparting this property. If the actions of these alloys are identical in all respects, they can be expected to reinforce each other. Thus it was thought that small amounts of molybdenum could enhance the strength properties of a low columbium-boron bearing steel. But steels M–19 and M–20 of the series fail to show any outstanding contribution due to the addition of molybdenum. Steel M–20 is of a confirmatory nature that a low silicon content is sufficient to give the high physicals.

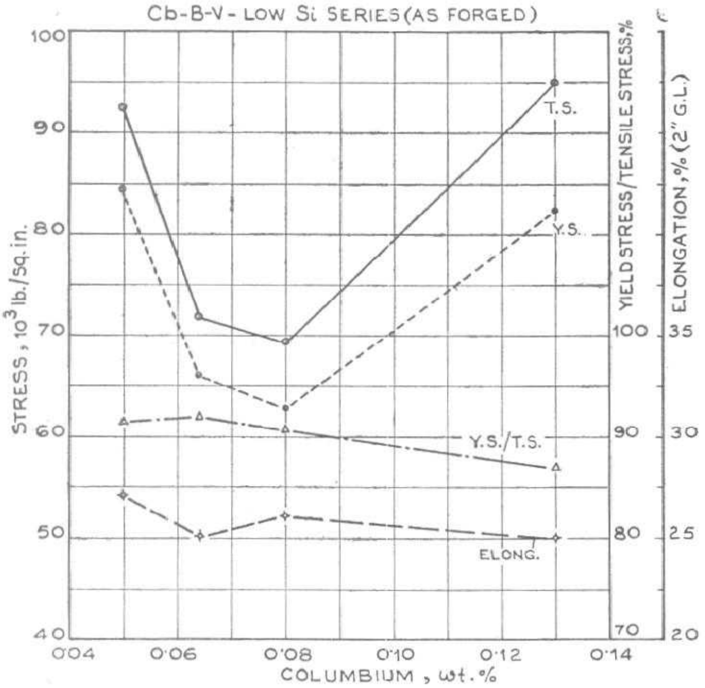

Fig. 5.

Relation between alloy content and mechanical properties.

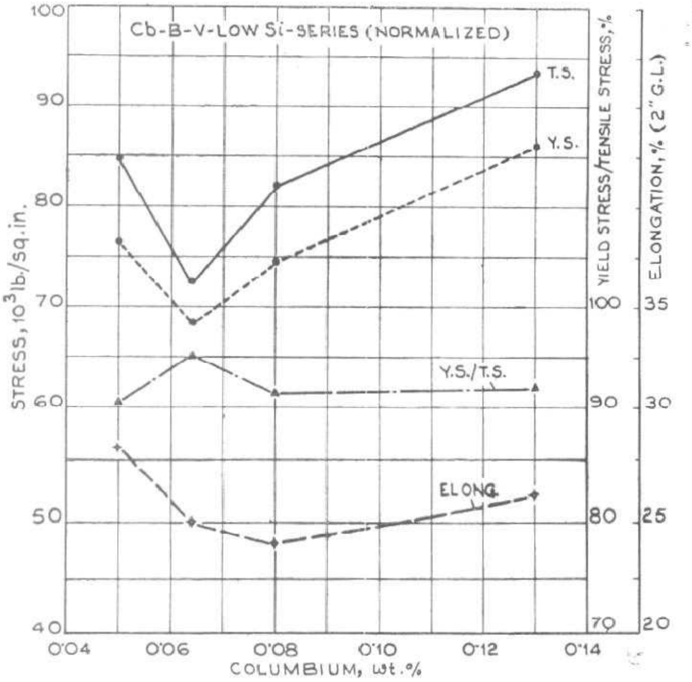

Fig. 6.

Relation between alloy content and mechanical properties,

*V. Comparison series.* The object of this series was to show the specificity of Cb-B combination in relation to individual alloying. In this respect mention has been already made of steels M–21, M–22, M–23 and M–26. Steels M–22, M–24 and M–25 bring out the fact that elements like aluminium, zirconium, and titanium in comparable amounts are incapable of duplicating the quintessence of columbium. In presenting the data emphasis was given to columbium principally due to the fact that the strength of the steel varies according to this alloy content. The role of boron in developing the strength properties is equally important and may be recognised from the as-forged properties of steels M–5 and M–21 given below.

| Steel | C | Mn | Si | Cb | B | Y.S. (p.s.i.) | T.S. (p.s.i.) |
|---|---|---|---|---|---|---|---|
| M–5 | 0·06 | 0·38 | 0·27 | 0·24 | 0·007 | 102,000 | 111,450 |
| M–21 | 0·09 | 0·45 | 0·25 | 0·44 | — | 50,700 | 64,500 |

Comparatively, steel M-21 is of higher alloy content, yet the yield stress is less than half that of steel M-5. This phenomenal increase of more than 100% in yield stress by the mere presence of 0·007% B indicates the enormous potency of the element in the specific combination.

## Response to normalising treatment

Columbium-boron steels exhibit good mechanical properties in the as-forged condition (Table II). Since all the steels of the series contain carbon less than 0·10% the customary normalising temperature would be about 925°C. However, a normalising treatment at this temperature was found to give a softening effect to the steel, whereas higher temperatures rapidly improved the strength. The relation between yield stress and normalising temperature for a few compositions are shown in Fig. 7. It is evident that the steel should be normalised in the temperature range of 1,100°–12,00°C to bring out the high strength. Since decarburisation is of little consequence to the properties of the steel, the only detrimental feature is grain coarsening in a high temperature treatment, which is effectively counteracted by vanadium not exceeding 0·05% in the composition. The softening of the steel at the lower temperature range is accompanied by the considerable increase in ductility which is a favourable feature to the workability.

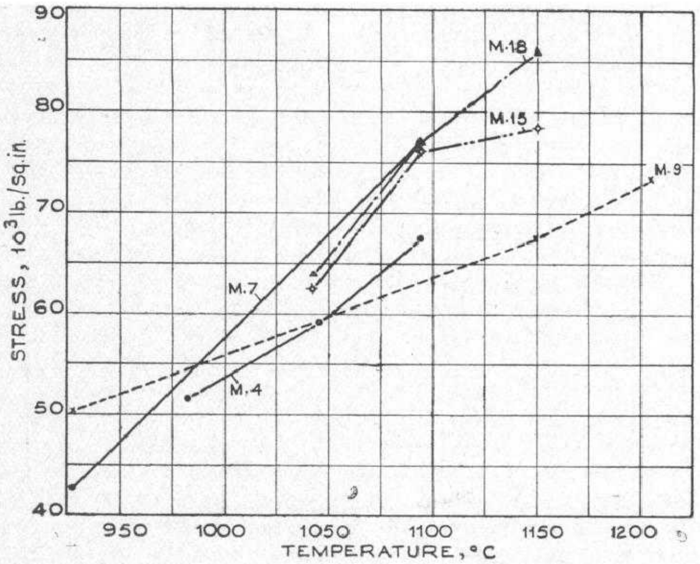

Fig. 7.
Effect of normalising temperature on yield stress of Cb-B-steel.

## Elevated temperature strength

Necessity of fairly high temperature in a normalising treatment and the resistance to softening shown even at 540°C stress relieving suggest that the steel would have superior elevated temperature properties. Results of tests presented in Fig. 8 show that the yield tensile properties are least affected up to a temperature of about 375°C. Randomly selected steels tested at about 540°C were equally satisfactory in the sense that the loss in strength for short time exposures was extremely meagre. It may be noted that lower temperature tests were conducted with longer exposures of about three hours at the test temperature, whereas at 540°C this could not be done due to lack of proper facilities.

## Low temperature impact resistance

A low temperature of transition from ductile to brittle fracture is a desirable property of engineering steels and becomes critically important for usage under wide fluctuations of temperature. Laboratory method that is commonly adopted to evaluate this property is impact testing. Using Charpy Key-Hole specimens, energy absorption values at different temperatures were determined for steels M–13 and M–19 in the as-forged condition. Results of tests are shown graphically in Fig. 9. Based on the criterion of 20 ft. lb energy absorption these steels show a transition temperature of—35°C and—65°C respectively. That these steels differ appreciably in their boron content could be an important factor in their observed difference to low temperature impact resistance.

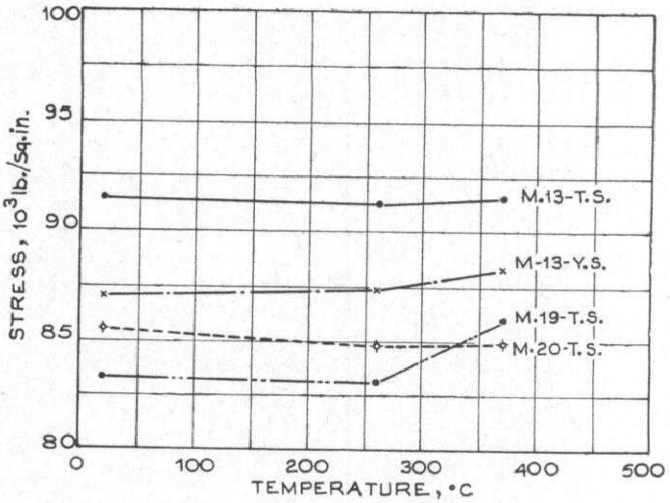

Fig. 8.
Elevated temperature strength of Cb-B steel.

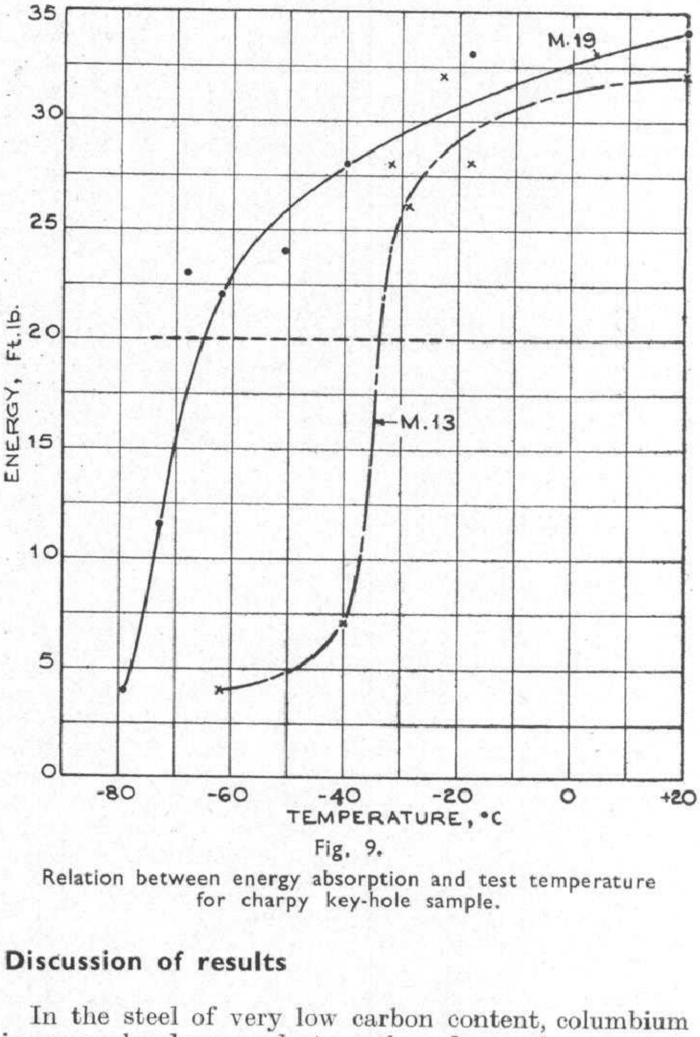

Fig. 9.
Relation between energy absorption and test temperature for charpy key-hole sample.

## Discussion of results

In the steel of very low carbon content, columbium increases hardness and strength and retards recrystallization[2] by entering into solid solution in the ferrite.

In hardenable steels, it is reported[3] that the element decreases hardenability. But the effect of columbium[4] on critical cooling rates depends on whether it exists as undissolved carbide or is dissolved in the austenite at the austenitising temperature. When present as undissolved it accelerates transformation by nucleation effects, whereas in solid solution it inhibits transformation. Since high temperatures are required for carbide dissolution, the element would decrease hardenability at normal hardening temperatures. Even though columbium is not recognised to be a common alloy, it is often used as a minor constituent in a number of steels. The reason for its use is based on certain poignant traits of the element, which are the strong carbide forming tendency, limited solubility in alpha iron and the affinity to form stable intermetallic compounds. The element's role as a stabiliser in stainless chrome-nickel[5,6] or in reducing the air hardening tendency[7] of plain-chromium corrosion-resistant steel is attributable to stable carbide formation. For complete carbon inactivation the minimum amount of element required is about eight times the carbon content. This carbide precipitation in ferritic steels enhances hardness and strength. But the action of the element in columbium-boron steel as one of carbide formation has to be discredited, because columbium alone (steel M-21) is found to be ineffective in imparting the superior strength. Further, a very small amount of the element (0·014% Cb in steels M-9 and M-10) in the presence of boron is sufficient to manifest the high tensile character wherein the possible amount of carbide formation of molecular formula Cb-C or $Cb_2C_4$[8] would be extremely negligible. The property of the element in decreasing temper-brittleness[9] which bears direct correlation to transition temperature[10,11] is advocated to the stability of carbide. In other words the element is said to decrease super saturation of austenite with carbon. However, the observed low transition temperature of Cb-B steel, an indication of low susceptibility to temper-brittleness can hardly be explained by any carbide formation. Likewise the formation of any stable ternary phase of iron-columbium-carbon[8] is equally inadequate to explain the properties of the steel.

The iron rich end of the iron-columbium diagram[12] (Fig. 10) shows that the solid solubility of the element increases from about 0·5% to 1·0% in the temperature range of 600°C to 900°C. The development of a number of Cb bearing iron alloys that are susceptible to precipitation hardening[13,14] is based on this solubility feature. These alloys are found to be specially suited to high temperature use, since the precipitate formed, an intermetallic compound of composition $Fe_3Cb_2$, is stable having a melting point of 1,660°C and is critically dispersed in alpha iron. In Cb-B steel, such precipitation is not justifiable for reasons similar to those cited in the case of carbide formation. Another source of intermetallic compound formation arises from the extreme affinity of boron to form a boride. Columbiumboride[15] of formula $CbB_2$ is very stable. It is close packed in structure and has high hardness and melting point in addition to well developed metallic properties. A critical dispersion of this phase in alpha iron is apparently a possible explanation to the observed high strength. However, the properties of the steel are almost independent of the boron content when present above a certain minimum limit which appears to be about 0·002% (steels M-9 and M-10). In these steels the columbium content is extremely low and stoichiometrically a boride precipitation should have given an accountable difference in the physical properties, which is not the case. Hence a boride precipitation in Cb-B steel is equally unjustifiable. On the contrary the behaviour of boron is more in agreement with the known hardenability effect wherein the factor reaches a maximum at about 0·001%. Since the exact magnitude of this factor decreases with increasing carbon content, the hardenability effect of boron should be maximum in a very low carbon steel. It is evident from the above review of features that the high strength properties of Cb-B steel cannot be accredited to any precipitation hardening phenomenon. However, a precipitation reaction of the secondary order is not at all a remote possibility, and therefore should not be totally ignored.

In the absence of a precipitation reaction, it is to be inferred that the effect of alloying elements in Cb-B steel is one of solid solution. It has already been mentioned that the behaviour of boron is in agreement with this inference. Further, the extreme similarity of this steel with Mo-B steel is in affirmation of the above conclusion. In Mo-B steel[16, 17] the alloys induce a delay in transformation such that a bainitic structure is obtained under

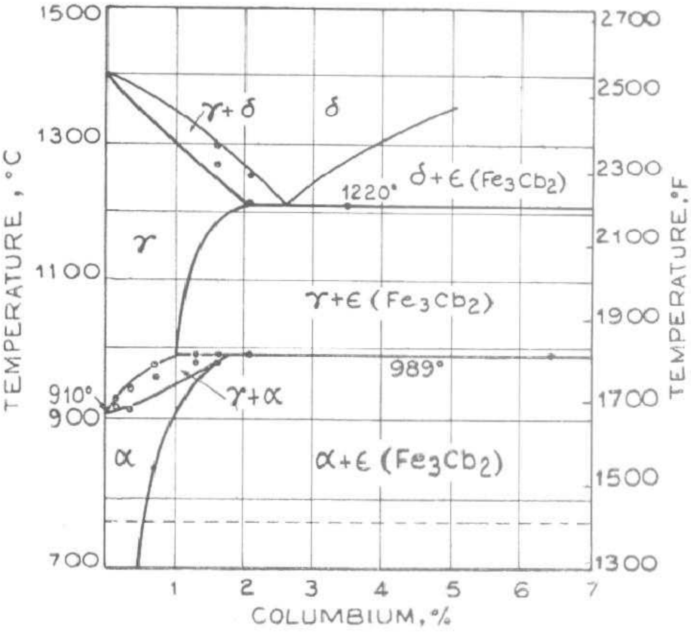

Fig. 10.
The iron-rich end of the iron-columbium diagram.

air cooling. And so in the replacement of molybdenum by columbium, the latter exerts the same influence of enhancing bainitic hardenability in presence of boron. But the element columbium differs markedly in exercising this function compared to molybdenum. In Mo-B composition the steel is insensitive to bainitic hardening unless the Mo content exceeds 0·20%, whereas columbium even at 0·014% is found to be effective in transforming the steel to that of a high tensile category. For Mo-B steel the maximum tensile value is about 90,000 p.s.i. and is achieved not below 0·5% Mo content, but columbium substituted steel gives equivalent strength at an alloy content not exceeding 0·07% Cb. For example, steel M-13 containing 0·07% Cb gives a tensile value of 91,500 p.s.i. in the as-forged condition and steel M-2 containing 0·08% Cb after a normalising treatment at 1,200°C gives a tensile strength of 102,300 p.s.i. Thus Cb-B is capable of duplicating the strength of fortiweld at less than one-seventh of the alloy content of the latter. Moreover, Cb-B steel is characterised by higher tensile strength than fortiweld. Steel M-5 (0·24% Cb) has a tensile strength of 111,450 p.s.i. in the as-forged condition and on normalising at 1,200°C this value is increased to 116,000 p.s.i. In case of steel M-6 (0·26% Cb) even though the as-forged strength is only 100,500 p.s.i. after a normalising treatment the strength is increased to 114,800 p.s.i. By comparison the alloy contents of these steels are in the range of 50% to that of molybdenum, yet the strength properties are increased at least by 25%. However, increasing columbium above 0·25% appears to have little effect in further improvement of the strength properties and so it is similar to Mo-B steel for which the limiting value of Mo is 0·5%. Another beneficial feature of Cb-B steel is the tendency to give a higher yield-tensile ratio. For Mo-B base this ratio is about 0·75 whereas for the former this value is invariably above 0·85 and a stress relieving treatment enhances this value even to 0·95. Since yield stress is the most important physical index of high tensile steels, the importance of this observation is self-evident. It should be noted that the high yield-tensile ratio is accompanied by equally good ductility. Theoretically, these properties indicate the possibility that the bainitic transformation of Cb-B occurs within a restricted range at such temperatures so as to induce a certain degree of self-tempering.

An undesirable feature of Cb-B steel is the necessity of a high temperature for the normalising treatment. This is a common trait of all columbium-alloyed steels, for the element in common with other elements that form alpha ferrite, raises the temperature of transformation. The reported[14] finding of the influence of heat-treating temperatures on the hardness of plain columbium alloyed iron is that the maximum hardness is attained between 1,100°C and 1,200°C with a steep rise from 900°C. This observation is quite in agreement with the behaviour of Cb-B steel. Also the creep strength is said to be maximum for the alloy if austenitised just below the delta transformation. Even though no proper explanation is advanced to this high temperature requirement of columbium bearing steel, it may be conjectured that it could be related to the extreme affinity of the element to form iron intermetallics and carbides of high thermal stability. However, the softening of the steel at about 925°C is reasonably clear from the carbon-free iron-columbium diagram shown in Fig. 10. About 1% of columbium raises the $Ac_3$ temperature from 910°C to 989°C. The widening of the alpha-gamma loop even at low percentage of the element shows that even in a lean alloy, retention of ferrite is likely to occur below a temperature of 989°C. Since the effect of the element arises from solid solution in austenite and subsequent bainitic transformation, ferrite retention would cause decrease in strength. And so the austenitising temperature of the steel should be above 989°C to assure complete transformation while any temperature below this limit would be conducive to a softening reaction.

It is evident from the composition and properties of the steel that elevated temperature strength has to be related to the phase structure. In Mo-B steel the bainitic structure is resistant to softening even up to 600°C[17]. Since Cb alloying is established to be superior to Mo in imparting high temperature strength to steels, in general, the bainitic stability of Cb-B steel should not be inferior to that of Mo-B steel. The observations made on the steel are in favour of this conclusion. Unlike Mo-B steel, this steel opens up a new field of investigation, namely, the precipitation of iron-columbide in a bainitic matrix. Such a steel can be expected to have better strength than the plain bainitic or ferritic precipitation hardened steel with equally good or better creep resistance. The low transition temperature of the steel is indicative of fairly good low temperature properties. The observed −35°C for steel M-13, is in the presence of 0·006% B which is far in excess of the minimum of 0·002% required. It is known that steels are susceptible to embrittlement when there is a high boron content. Therefore Cb-B steel with a lower boron content should have better low-temperature impact resitance and in fact steel M-19 containing 0·004% B gives a transition temperature of −65°C, which incidentally contains 0·14% Mo. However, the transition temperature of Mo-B steel is normally in the neighbourhood of −20°C, therefore the contribution of Mo in lowering the transition temperature of steel M-19 is to be considered insignificant. This tendency of columbium bearing bainitic steel to give lower transition temperature is to be attributed to its better grain refining ability.

## Conclusion

Among bainitic low carbon steels or lean alloy high tensile steels, Cb-B steel has exceptional mechanical properties to be recognised as a unique addition to this class. The main limitation of this steel is the non-availability of columbium in large quantities, since it is a rare element. However, economically the steel works out to be superior to Mo-B steel, for the alloy requirement is not more than one-seventh of Mo to give strength of the latter. Also a fiftiweld steel can be easily produced with Cb-B which is an unsurpassed achievement among lean-alloy low carbon steels. Even though no data have been presented regarding the weldability, it should be mentioned that the few tests conducted showed that the steel is as good as Mo-B steel in this respect. In general it must be admitted that a more detailed and thorough investigation is needed to elucidate the finer characteristics of the steel.

## Acknowledgement

The author wishes to acknowledge that the steel was developed by him in the laboratories of Kaiser Steel Corporation, Fontana, U.S.A. and the patent right has already been given in favour of the Corporation.

## References

1 W. E. Bargett and L. Reeve : J. Iron Steel Inst., 1949, Vol. 163. pp. 277–294.

2 Shteinberg, M. M : Stal, Vol. 7, 1947, pp. 1107–110.

3 Kramer, I. R., R. H. Hafner, and S. L. Toleman : Trans. Am. Inst. Mining Met. Engrs., Vol. 158, 1944, pp. 138–156.

4 Peter, W. and M. New : Kaiser-Welhelm-Institut Fur Eisenforschung, Clausthal-Nellerfeld, Report No. 64 May 1945, p. 15 (Brutcher Translation 2021).

5 Becket, F. M. and R. Franks : Trans. Am. Inst. Mining Met. Engrs., Vol. 113, 1934, pp. 143-162.

6 German Patent No. 667, 630 July 1938.

7 Tofaute W : Z. Ver. deut Ing., Vol. 81, 1937, pp. 1117–1122.

8 Eggers, H. and W. Peter : Mitt. Kaiser-Welhelm-Inst. Eisenforsch. Vol. 20, 1938, pp. 199–203.

9 Kishkm, S. T : Iron Age, Oct. 1. 1942, pp. 150–167.

10 G. Vidal : Rev. Met., Vol. 42, 1945, pp. 149–155.

11 L. D. Jaffe and D. C. Buffum : Trans. Amer. Soc. Metals, Vol. 42, 1950, pp. 604–614.

12 Genders, R. and R. Harrison : J. Iron and Steel Inst., Vol. 140, 1939, pp. 29P–37P.

13 Parker, E. R : Trans. Am. Soc. Metals, Vol. 28, 1940, pp. 797–810.

14 Wever, F. and W. Peter : Arch Eisenhuttenw., Vol. 15, Feb. 1942, pp. 357–363.

15 John T. Norton and Others : J. Metal Trans. Vol. 185, Oct. 1949, pp. 749-751.

16 K. J. Irvine, F. B. Pickering, W. C. Heselwood and M. Atkins : J. Iron Steel Inst., 1957, Vol 186, pp. 54–67.

17 K. J. Irvine and F. B. Pickering, Ibid. 1957, Vol. 187, pp. 292-309.