RECENT ADVANCES IN SCIENTIFIC STEEL METALLURGY.[1]

To render clear the exact nature of certain modern scientific advances in steel metallurgy it is necessary briefly to consider what is known of the past history of steel, more particularly with reference to cutting implements, whether for the purposes of peace or war. That steel (or, to be more accurate, probably steely-wrought iron) was known to the ancients, say, 3000 years ago, seems to be proved by a passage translated by Pope from the ninth book of Homer's "Odyssey":—

> "And as when armourers temper in the ford
> The keen-edged pole-axe, or the shining sword,
> The red-hot metal hisses in the lake
> So in his eyeballs hissed the plunging stake."

As has been truly remarked by Roscoe and Schorlemmer, the above description can be applied only to steel—that is to say, to iron containing a very considerable percentage of carbon.

So far as definite records are concerned, the story of early British steel metallurgy is wrapped in profound obscurity, and its history can be only indirectly surmised from collateral historical evidence. About A.D. 60 a great British army under the command of Queen Boadicea stormed the Roman camp at Colchester and annihilated the Ninth Legion. She then marched on St. Albans and London, and in both places put the garrisons and the Roman colonists to the sword, the stake, or the cross. Tacitus, the Roman historian, records that the losses of the Romans and their allies in these battles reached the startling total of 70,000 people. In the subsequent campaign, which ended in the defeat and death of the heroic British Queen, the same historian states that the British lost 80,000 persons.

It is evident, therefore, that Boadicea must have commanded at least 100,000 British troops, or she could never have undertaken such extensive and formidable military operations. It is also clear that these troops were armed with swords and spears, to say nothing of the scythes attached to the axles of their war chariots. There is no reason to suppose that these weapons were not of native manufacture. They would partly be made of bronze and partly of steely-iron, since the country had been for a century occupied by Roman soldiers and artisans. It is therefore almost certain that in the first century the manufacture of steely-iron weapons and implements would be on a fairly large scale, and would doubtless mainly be concentrated in iron ore and charcoal-producing districts, such as Sussex and the Forest of Dean.

In connection with Sheffield—now the greatest British steel centre—the earliest written record refers to the twelfth century, and states that in 1160 the monks of Kirkstead Abbey had somewhat extensive works at Kimberworth, near Sheffield, manufacturing wrought-, and, no doubt, steely-irons. In 1386 Chaucer, in "The Reve's Tale," in describing a miller of the time of Edward III., wrote, "A Shefeld thywtel bare he in his hose." Since 1386 Sheffield steel in the form of table knives has been in almost everybody's mouth. In 1590 Peter Bales, "The Writing Schoolmaster," recommends Sheffield razors and penknives for the cutting of quill pens. It is obvious that for this purpose fine steel carrying a perfect cutting edge is necessary, and was being made at Sheffield prior to 1590. Hunter states that in 1615 Sheffield workmen could make armour only fit for the common man-at-arms. The armour for knights was imported from Spain and Italy. Scott, in "Ivanhoe," embodies this fact in his description of the siege of "Torquilstone":—

"Thrice did Locksley bend his shaft against De Bracy, and thrice did his arrow bound back from the Knight's armour of proof. 'Curse on thy Spanish steel coat,' said Locksley. 'Had English smith forged it, these arrows had gone through an as if it had been silk or sendal.'"

The opening scene in "Ivanhoe" was near Woodhouse (five miles east of Sheffield), where, until quite recently, wrought-iron was manufactured at the Rotherwood Iron Works.

In 1760 Horace Walpole, writing to George Montague, remarks: "I passed through Sheffield, which is one of the foulest towns in England in the most charming situation. There are two-and-twenty thousand inhabitants making knives and scissors. They remit eleven thousand pounds a week to London. One man there has discovered the art of plating copper with silver. I bought a pair of candlesticks for two guineas, that are quite pretty."

Antiquarians express the opinion that the remarkable concentration of the cutting-steel industry round Sheffield was due to the juxtaposition of coal and iron ore in the district. This reason, however, is quite unconvincing to metallurgists; first, because charcoal and not coal was used, and, secondly, because the local ore produces an iron high in phosphorus, from which it is practically impossible to make cutting implements of fine steel. There is little doubt that the main factor which originally determined the location of the chief British steel industry at Sheffield was the unique situation of the town in a hollow near the confluence of four rivulets into the Don. Along these streams, running down the valleys of the Sheaf, the Porter, the Rivelin, and the Locksley, the old Sheffield steel-workers could, by the construction of numerous dams, get water-power for their forging hammers and grinding wheels at a small cost, and waterwheels worked by some of these dams are still in operation along these valleys, that of the Don itself actuating tilt-hammers and grindstones.[2] The latter are made from the carboniferous sandstones of the district. There is proof positive that the basis metal, consisting of nearly pure iron, from which the best Sheffield cutting steels are still made, was being imported into the town in the sixteenth century from abroad.

Among entries in the accounts of the Sheffield Church burgesses for the year 1557 is the following:—

"Paid to Robert More for one stone and quarter of Danske Yron XXIId. Paid to ye same Robt. for X lib of Spanysche Yron XV."

In modern money the cost of this raw material works out to at least 60*l.* per ton, or 3*l.* per cwt.[3] The Danish (Danske) iron was probably Swedish, just as at present much of the Danish butter imported comes from Swedish dairies.

In connection with the early importation of pure Swedish or Spanish iron for a basis metal, it is significant that in 1442 Sheffield obtained a Royal warrant to construct towpaths to make the River Don navigable. This river runs into the Humber at Goole, and there is little doubt that so early as the fifteenth century Sheffield steel-makers were endeavouring to replace the costly packhorse transit of foreign raw

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[1] Discourse delivered before the Royal Institution on Friday, January 24, by Prof. J. O. Arnold, F.R.S.

[2] There is evidence in old documents that the name Sheffield may be a corruption of "Escafeld," meaning "the field of waters."

[3] Prof. Thorold Rogers in his Oxford lectures, 1888–9, stated that about 1685, using a multiplier of 2, the value in modern money of English wrought-iron was about 73*l.* per ton. The Sheffield record, however, proves beyond doubt that in 1557, *or more than a century and a quarter earlier*, the imported and superior Spanish and Swedish irons were commanding in Sheffield, retail, not more than 14*l.* per ton, which, using a multiplier of 4.5, is equivalent in present money to 63*l.* per ton.

materials by cheaper water carriage from the Humber.

It is next of interest to consider how, during the fourteenth, fifteenth, sixteenth, seventeenth, and half the eighteenth centuries, Sheffield made all its fine steel. It seems almost certain that the nearly pure imported Swedish or Spanish irons were carburised "in the dry way," by cementation in charcoal at a yellow heat. The highly ductile bar iron and the blistered and brittle steel resulting from its cementation-carburisation were described. The blister bar was then made into what for perhaps two hundred and fifty years has been known as "shear steel."

(The method of producing from blister bar both single and double shear steel was then described.) The origin of the name "shear steel" was due to the fact that British cloth-workers insisted on having this fine quality of steel for their cloth-cutting shears, and this material is still branded with rude representations of clothiers' shears. One pair of shears signifies single shear and two pairs double shear steel. The chemical composition of this steel, which is the purest made, is as follows:—Carbon 1·00 per cent; silicon, 0·03 per cent.; manganese, 0·07 per cent.; sulphur, 0·01 per cent.; phosphorus, 0·015 per cent. With its high reputation built up during centuries this material has naturally had its name branded on inferior kinds of steel. Indeed, bars of steel up to 6 in. in diameter have been sold as "shear steel" at 18*s.* per cwt., the price of the raw material from which shear steel is manufactured. Probably a bar 1½ in. in diameter marks the advisable limit of size for genuine shear steel, and its average market price is about 45*s.* per cwt.

The year 1740 marked for Sheffield, and indeed for the world, the beginning of an epoch of great metallurgical importance. Benjamin Huntsman, a well-known clockmaker of Doncaster, found that shear steel, on account of its sometimes varying temper and of its weld-lines, often presented uneven hardness and exasperating flaws when made into clock springs. He consequently determined to make a steel even in texture and free from weld flaws. He experimented successfully, and worked out a method for the production of sound steel ingots by the fluid or crucible process, and so founded in Sheffield an industry, destined to become world-wide, which soon extended the fame of Sheffield steel throughout the civilised world.

(A composition typical of crucible cast-steel was then given. It is less pure than shear steel, but sounder, being free from weld-lines. It is said that the famous American, General Sherman, when asked to "spare the good Indians," replied that the only good Indians he had ever met were dead Indians. Be this as it may, it is certain that no steel can be good unless it is properly "killed," or, in other words, "dead melted."

Fig. 1 shows two crucible steel ingots of identical composition and weight when poured in a "lively" and in a "killed" condition. Ignoring the "pipe," or central contraction cavity, the killed steel is quite solid, whilst the unkilled metal is riddled from end to end with gas cavities or "blowholes," containing, under pressure, hydrogen, carbonic oxide, and nitrogen gases, evolved in the plastic steel during solidification, and thus rendering the ingot commercially worthless. The sound and hence apparently much smaller ingot has been "killed" by the presence of a trace (say 0·01 per cent.) of metallic aluminium. The scientific explanation of this, the most remarkable phenomenon in the whole range of steel metallurgy, may be found in text-books or in reports of metallurgical lectures, but the present lecturer must confess that he is no nearer a convincing solution of this problem than when he began his researches twenty-five years ago.

It is next necessary to correlate the chemical and micrographic analyses of the plain carbon steel upon which the world depended for its cutting implements from the time of Homer to 1870.

The structure of pure Swedish iron is usually contaminated with a little slag. Ignoring this, the mass consists of white allotrimorphic crystals of iron with optically black boundaries.

In a micrograph of nearly pure iron containing about 0·4 per cent. of carbon, almost half the mass consists of the dark-etching compound constituent pearlite.

The structure of nearly pure iron containing 0·89 per cent. of carbon consists entirely of pearlite, a mechanical mixture of 87 per cent. of iron with 13 per cent. of normal carbide of iron, Fe_3C. The mass abrasion hardness of normal pearlite is about 4·5—that is, between fluorspar and apatite on Moh's mineral scale.

We have next to consider the phenomena known as the hardening and tempering of steel.

Figs. 2 and 3 show very clearly the beginning, the progression and end of the hardening of steel—that is to say, the transformation (during a thermal amplitude of perhaps 3° C.) of the compound constituent pearlite $(21Fe+Fe_3C)$ to the micrographically amorphous constituent hardenite, which corresponds to the empirical figures $Fe_{24}C$, in which the carbide of iron, owing to the quenching, is trapped in some molecular association with the whole of the iron. The constituent hardenite has a hardness of 7 on Mohr's mineral scale—that is to say, it is as hard as quartz, flint, or rock crystal.

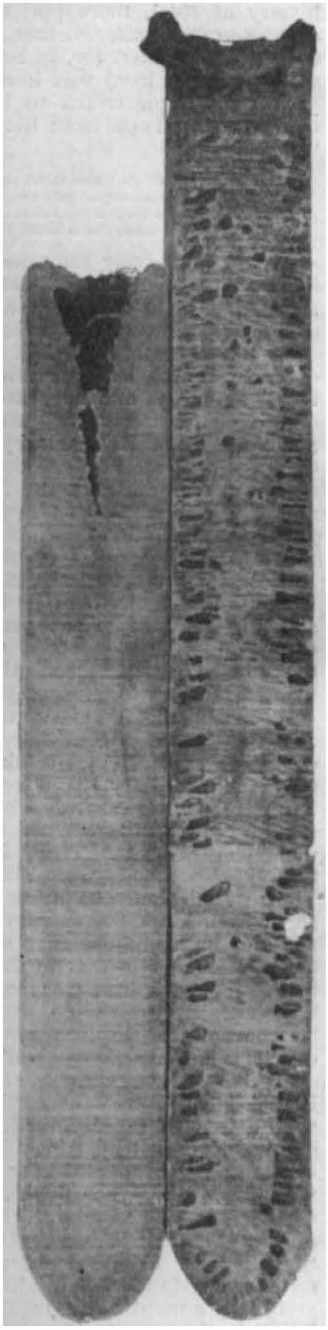


FIG. 1.

It is a little difficult to realise how much the thermal capability of the mineral pearlite (with a hardness of 4·5) to transform itself into the igneous rock hardenite (with a hardness of 7) has contributed to the advance of civilisation and to the material well-being of the human race. But unfortunately it was found that hardenite was thermally very unstable, and that its cutting powers were greatly limited by the fact that the heat of friction in turning operations caused the hardenite to revert largely to relatively soft pearlite at a blue heat, say, 300° C. This property naturally limited the operations of engineers as to speed, as to traverse, and as to depth of cut, and consequently as to the cost and rate of output of all the engines and appliances necessary to our modern civilisation.

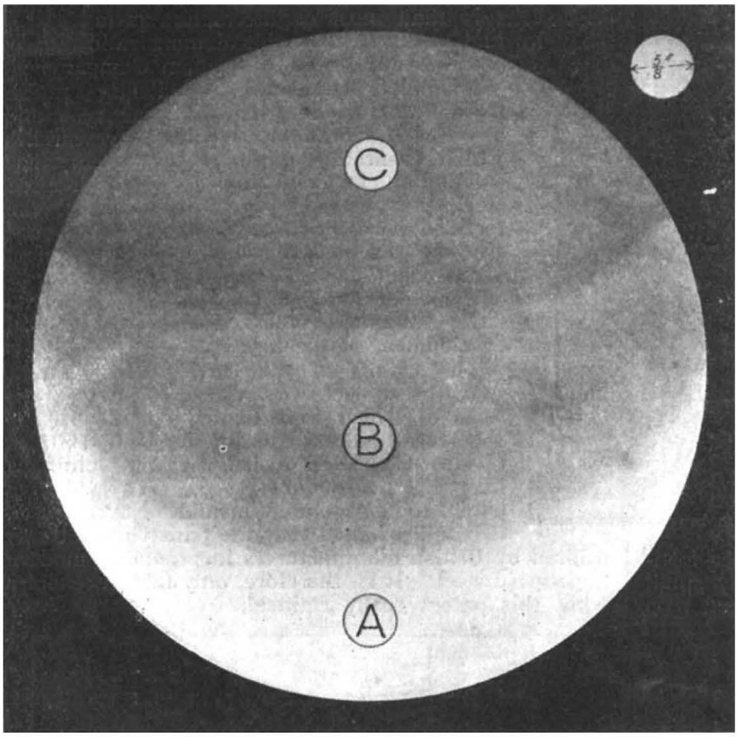
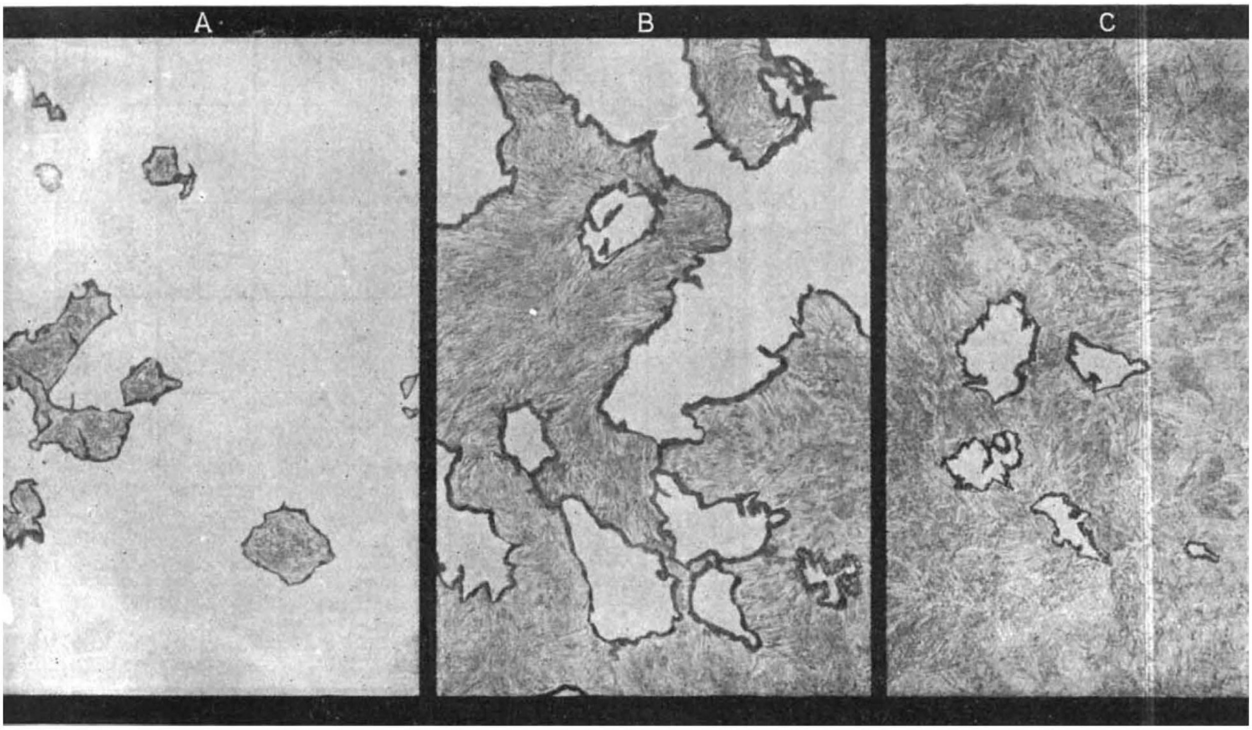


FIG. 2.—Carbon 0·89 per cent. The edge A was quartz-hard, stripping file teeth. The edge C was quite soft to the file. Etched $\frac{5}{8}$ in. diameter disc. Magnified about 12 diameters after differential heating and rapid quenching. For high-power magnification see Fig. 3.

(A tempering diagram was then explained in which the black areas show the evolution of the latent heat of hardening, and consequently the transformation of the quartz-like hardenite to soft pearlite. This change at about 250° C. acquires a marked increase in velocity which reaches a maximum at about 300° C. Here the soft pearlite becomes the predominant partner, and the cutting power of the mass has practically vanished.)

About the year 1870 marked the first beginnings of an epoch in cutting-steel metallurgy, which may be called the tungsten-chrome era. Robert Forrester Mushet, at the Clyde Works, Sheffield, began to manufacture on a considerable scale his "self-hardening steel." Mushet had practically discovered that when carbon steel was alloyed with a large percentage of tungsten, it, when cooled from a yellow heat in a draught of air, was not only sufficiently hardened, but, owing to the fortifying action of the tungsten on the carbon, the hardenite was thermally considerably more stable than that of plain carbon steel.

It is probable that in Mushet's early steels the "letting-down" point



Transformation nearly completed. Temperature about 730° C.

Transformation half completed. Temperature about 729° C.

Transformation beginning. Temperature about 728° C.

FIG. 3.—Pale areas, hardenite. Laminated areas, normal pearlite. Dark borders, troostitic pearlite. Carbon 0·89 per cent. Magnified about 450 diameter

of the hardenite was raised to a temperature of perhaps 400° C., thus enabling engineers to take bigger cuts and work at higher speeds. Later, about 1880, Mushet still further fortified his hardenite by the addition of relatively small percentages of chromium, and between 1880 and 1900 self- or air-hardening steels were produced by many steel manufacturers in considerable variety.

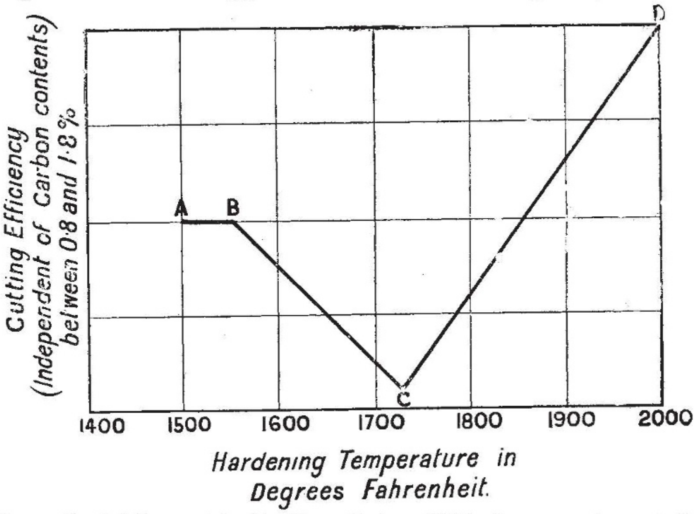


FIG. 4.—Physical diagram claimed by Messrs. Taylor and White for tungsten-chrome steels

In connection with cutting steels, a profound sensation was made throughout the steel world when, at the Paris Exhibition in 1900, the Bethlehem Steel Co. of America showed turning tools made under the alleged patent of Messrs. Taylor and White, cutting very mild steel at a speed which rendered the nose of the tool red-hot. It was obvious that in these tools the thermal stability of the hardenite had been raised to perhaps 600° C. The chemical compositions in the patent embodied nothing which had not been included in the Mushet type of steel for a period of about twenty years prior to the date of the American patent. In fact, what Taylor and White had really done was to show that this type of steel was capable of retaining its cutting edge at a much higher temperature than most engineers and metallurgists had realised. For this demonstration every credit is due to the Bethlehem Company.

Sheffield steel-makers, realising future possibilities, made from the year 1900 and onwards a series of experimental researches which eventually gave to engineers that astounding material known as high-speed steel, in which the thermal stability of the fortified hardenite was raised to about 700° C., and the striking difference in chemical composition between Mushet's and high-speed steels was shown; nevertheless, the latter are merely a progressive experimental development of the former.

The claims of the Taylor-White patent were the subject of a protracted lawsuit, the costs of which were about 50,000*l*. In the end, Mr. Justice Cross, of the United States Circuit Court, in a lengthy and luminous judgment, pronounced the Taylor-White patent to be absolutely invalid. Nevertheless, it is still claimed that the patent in suit was utilised by British manufacturers in producing modern high-speed steel. It is, therefore, only fair to consider what this patent really claimed.

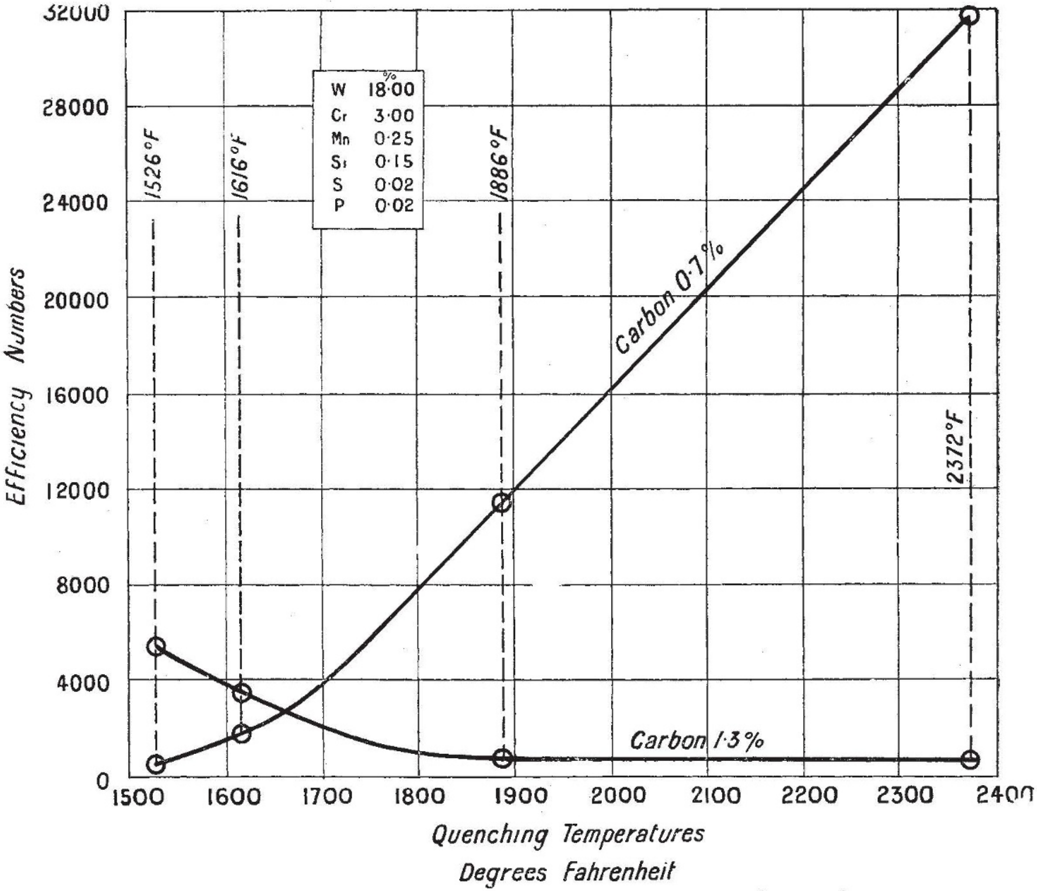


FIG. 5.—Physical curves obtained by Arnold and McWilliam for tungsten-chrome steels

Fig. 4 shows a physical curve of tungsten-chrome steels which the patentees claimed to have discovered. The coordinates are vertically the cutting efficiencies of tungsten-chrome steels with any carbon from 0·8 to 1·8 per cent. (the amount being a matter of indifference), and horizontally the hardening temperatures in degrees Fahrenheit. The short horizontal line "A–B" between 1500° and 1550° F. was alleged to be the range in which, prior to the patent, all tungsten-chrome air-hardening steel had been hardened. The falling line "B–C" between 1550° and 1725° F. was stated to be the breaking-down range discovered by the patentees, along which the cutting power of the steel steadily deteriorated. Then along the rising line "C–D," from 1725° to 2000° F (the maximum temperature specified in the patent), the quality of the steel improved as the temperature of hardening rose, until in the higher part of this range the turning tools had an efficiency never before achieved in the art, and in effect (to use the words of Coleridge's "Ancient Mariner") the patentees claimed:—

> We were the first that ever burst
> Into that silent sea.

My late colleague, Dr. A. McWilliam, and I were commissioned to investigate at Sheffield University the accuracy or otherwise of the curve specified in the patent. The results are embodied in Fig. 5. The coordinates are, horizontally hardening temperatures in degrees F., and vertically cutting efficiency numbers obtained by the approximate and relative formula $e = t \times s^2$, where e is an efficiency number, t the time endurance in minutes, and s the cutting speed, *caeteris paribus,* in feet per minute. It will be seen that with a steel containing about 17 per cent. of tungsten, 3 per cent. of chromium, and 1·3 per cent. of carbon, the maximum efficiency number of about 5000 is obtained at the lowest temperature, 830° C., after which the higher the hardening temperature the less the efficiency number, which at 1300° C. or 2400° F. has fallen to 500, or only twice the efficiency of plain carbon steel. In a similar steel, containing, however, only 0·7 per cent. of carbon, the efficiency number at 830° C. is only about 500, but the efficiency steadily rises with the hardening temperature, until at 1300° C. or 2400° F. it reaches the astounding number of about 32,000. In a word, there is no breaking-down range, and so far from the percentage of carbon being immaterial the cutting efficiency is actually a function of the carbon and hardening temperatures.

(*To be continued.*)

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

BIRMINGHAM.—The council, in accepting the resignation by Prof. J. H. Poynting of the office of dean of the faculty of science, has passed the following resolution:—"That this council deeply regret the illness which has deprived them of the greatly valued and long-continued services of their former colleague, Dr. Poynting, at their meetings, and earnestly trust that his health, now happily restored, may be preserved for many years."

Prof. Barling has resigned the chair of surgery on his election as Vice-Chancellor.

Dr. Alfred H. Carter has resigned the chair of medicine, and the following resolution has been passed by the council:—"That the council accepts with great regret the resignation of Dr. A. H. Carter of his appointment as professor of medicine in this University. It desires to thank him for his valuable services not only as teacher during the past twenty years, but also for the great assistance he rendered in promoting the union of the medical faculty of Queen's College with Mason College, a step which materially advanced medical education and the University idea in Birmingham."

CAMBRIDGE.—The following is a summary of benefactions received by the University during the year ended December 31, 1912:—

	£	*s.*	*d.*
Gonville and Caius College, towards the maintenance of the new buildings for physiology and experimental psychology	500	0	0
Dr. J. B. Hurry, St. John's College, for the endowment of a research studentship in physiology to be called the Michael Foster research studentship	1100	0	0
Anonymous, for the endowment of the Arthur Balfour professorship of genetics	20,000	0	0
Balfour Library Endowment Fund, subscribers to	2302	3	2
Col. W. Harding, for the endowment of a lectureship in zoology	1100	0	0
St. John's College, towards the equipment of the Solar Physics Laboratory on its installation at Cambridge ...	500	0	0
Anonymous, for the purpose of increasing the stipend of the director of the Fitzwilliam Museum	100	0	0
	£25,602	3	2

In addition, sums amounting to about 10,000*l.* have been presented to the University. These include 5000*l.* from Mr. Otto Beit, 1000*l.* from the Mercers' Company, 1000*l.* from Messrs. Rothschild and Son, and 200*l.* from Mr. Almeric Paget, M.P., for the new school of physiology.

The Vice-Chancellor gives notice that he has appointed Saturday, April 19, as the day for the election to the Plumian professorship of astronomy and experimental philosophy vacant by the death of Sir George Darwin. Candidates for the professorship are requested to send their names to the Vice-Chancellor on or before Friday, April 11.

The director of the Solar Physics Observatory has, with the consent of the Vice-Chancellor, appointed the following to be members of the staff of the Solar Physics Observatory:—F. J. M. Stratton, to be assistant director; C. T. R. Wilson, to be observer in meteorological physics; F. E. Baxandall, to be first senior observer; C. P. Butler, to be second senior observer; W. E. Rolston, to be first junior observer; W. Moss, to be second junior observer.

LEEDS.—Arrangements are being made for the establishment of a Yorkshire Summer School of Geography to be organised in alternate years by the Universities of Leeds and Sheffield. The course for 1913 will be held at Whitby, from August 4–25, under the auspices of the University of Leeds. The aims of the course are to provide instruction which shall equip students for attacking problems in the regional geography of any area, and to discuss and elucidate problems connected with the teaching of geography. The work of the school will include field work, laboratory work, and lectures on geological, meteorological, economic, and historical aspects of the geography of Yorkshire. The agricultural, mining, textile, and metallurgical industries will be dealt with, as well as questions connected with language and place-names. Further information will be available in June, on application to the secretary, Summer School of Geography, the University, Leeds.

In September next Prof. H. R. Procter will retire