VII. — *On the Hardness of Metals and Alloys.*

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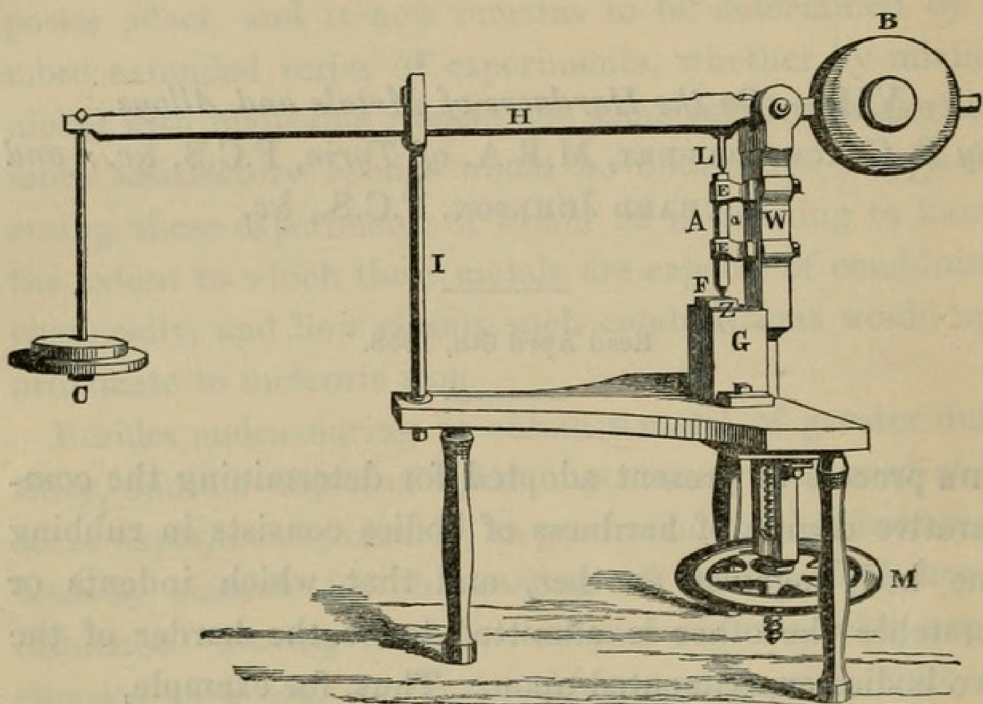
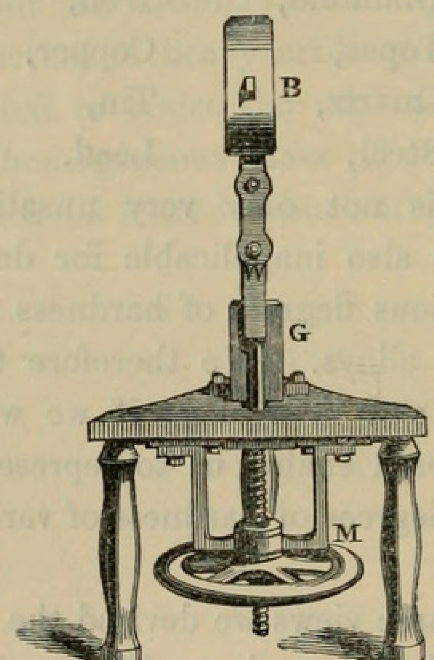
The process at present adopted for determining the comparative degree of hardness of bodies consists in rubbing one body against another, and that which indents or scratches the other is admitted to be the harder of the two bodies experimented upon. Thus, for example,

Diamond,	Iron,
Topaz,	Copper,
Quartz,	Tin,
Steel,	Lead.

This method is not only very unsatisfactory in its results, but it is also inapplicable for determining with precision the various degrees of hardness of the different metals and their alloys. We therefore thought that it would be useful and interesting if we were to adopt a process which would enable us to represent by numbers the comparative degrees of hardness of various metals and their alloys.

To carry out these views we devised the following apparatus and method of operating. The machine used is on the principle of a lever, with this important modification, that the piece of metal experimented upon can be relieved from the pressure of the weight employed without removing the weight from the end of the longer arm of the lever. The machine consists of a lever H with a counterpoise B and a plate C, on which the weights are gradually placed. The fulcrum L bears on a square bar of iron A,





passing through supports E. The bar A is graduated at *a*, and has at its end a conical steel point F, 7*mm.* or 0·275 of an inch long, 5*mm.* or 0·197 of an inch wide at the base, and 1·25*mm.* or 0·049 of an inch wide at the point which bears on the piece of metal Z to be experimented on, and this is supported on a solid piece of iron G. The support or point of resistance W is lowered or raised by the screw M, and when, therefore, this screw is turned the whole of the weight on the lever is borne by the support I and the screw M. When it is necessary, by turning the screw M, the weight on the lever is re-established on the bar, and experimented upon.

When we wished to determine the degree of hardness of a substance we placed it on the plate G, and rested the point F upon it, noticing the exact mark on *a* on the bar A, and then gradually added weights on the end of the lever C until the steel point F entered 3·5*mm.* or 0·128 of an inch during half an hour, and then read off the weight. A result was never accepted without at least two experiments were made, which corresponded so far as to present a difference of only a few pounds. The following table gives the relative degree of hardness of some of the more common metals. We specially confined our researches to this class, wishing the results to be practically useful to engineers and others who have to employ metals, and often require to know the comparative hardness of metals and alloys.

Names of Metals.	Weight employed.	Calculated Cast Iron = 1000.
	lbs.	
Staffordshire Cold Blast Cast Iron — Grey, No. 3	4800	1000
Steel	4600 ?	958 ?
Wrought Iron*	4550	948
Platinum	1800	375
Copper — pure	1445	301
Aluminium	1300	271
Silver — pure	1000	208
Zinc do.	880	183
Gold do.	800	167
Cadmium do.	520	108
Bismuth do.	250	52
Tin do.	130	27
Lead do.	75	16

* This wrought iron was made from the above-mentioned cast iron.

This table exhibits a curious fact, viz., the high degree of hardness of cast iron as compared with that of all other metals, and although we found alloys which possessed an extraordinary degree of hardness, still none were equal to cast iron.

The first series of alloys we shall give is that of copper and zinc.

Formulæ of Alloys and per centages.	Weight employed.	Obtained Cast Iron = 1000.	Calculated* Cast Iron = 1000.
	lbs.		
$Zn\,Cu_5$ {Cu 82·95, Zn 17 05}	2050	427·08	280·83
$Zn\,Cu_4$ {Cu 79·56, Zn 20·44}	2250	468·75	276·82
$Zn\,Cu_3$ {Cu 74·48, Zn 25·52}	2250	468·75	276·04
$Zn\,Cu_2$ {Cu 66·06, Zn 33·94}	2270	472·92	261·04
$Zn\,Cu$ {Cu 49·32, Zn 50·68}	2900	604·17	243·33
$Cu\,Zn_2$ {Cu 32·74, Zn 67·26}	Broke with 1500 lbs. without the point entering.		
$Cu\,Zn_3$ {Cu 24·64, Zn 75·36}	Broke with 1500 lbs. with an impression ½ *mm.* deep.		
$Cu\,Zn_4$ {Cu 19·57, Zn 80·43}	Entered a little more than the above; broke with 2000 lbs.		
$Cu\,Zn_5$ {Cu 16·30, Zn 83·70}	Entered 2 *mm.* with 1500 lbs.; broke with 1700 lbs.		

These results show that all the alloys containing an excess of copper are much harder than the metals composing them, and what is not less interesting, that the increased degree of hardness is due to the zinc, the softer metal of the two which compose these alloys. The quantity of this metal must, however, not exceed 50 per cent. of the alloy, or the alloy becomes so brittle that it breaks as the steel point penetrates. We believe that some of these alloys, with an excess of zinc, and which are not found in commerce owing to their white appearance, deserve the

* To calculate the hardness of an alloy we multiplied the per centage quantity of each metal by the respective hardness of that metal, added the two results together, and divided by 100. The quotient is the theoretical hardness.

attention of engineers. There is in this series an alloy to which we wish to draw special attention, viz., the alloy Cu Zn composed in 100 parts of

Copper	49·32
Zinc	50·68
	100·00

Although this alloy contains about 20 per cent. more zinc than any of the brasses of commerce, still it is, when carefully prepared, far richer in colour than the ordinary alloys of commerce. The only reason that we can give why it has not been introduced into the market is, that when the amount of zinc employed exceeds 33 per cent. the brass produced becomes so white that the manufacturers have deemed it advisable not to exceed that proportion. If, however, they had increased the quantity to exactly 50·68 per cent. and mixed the metals well, they would have obtained an alloy as rich in colour as if it had contained 90 per cent. of copper, and of a hardness three times as great as that given by calculation. In order to enable engineers to form an opinion as to the value of this cheap alloy we give them the degrees of hardness of several commercial brasses : —

Commercial Brasses.		Weight employed.	Cast Iron = 1000. Obtained.	Calculated.
		lbs.		
"Large Bearing"	Copper 82·05 *Tin 12·82 Zinc 5·13	2700	562	259
"Mud Plugs"	Copper 80 *Tin 10 Zinc 10	3600	750	262
"Yellow Brass"	Copper 64 Zinc 36	2500	520	258
"Pumps and Pipes"	Copper 80·0 *Tin 5·0 Zinc 7·5 Lead 7·5	1650	343	257

* These alloys all contain tin.

The alloy Cu Zn possesses another remarkable property, viz., the facility with which it is capable of crystallising in prisms half an inch in length, of extreme flexibility. There is no doubt that this alloy is a definite chemical compound, and not a mixture of metals, as alloys are generally considered to be. Our researches on the conductibility of heat by alloys, which we have recently presented to the Royal Society, leave no doubt that many alloys are definite chemical compounds.

On Bronze Alloys.

Formulæ of Alloys and per centages.		Weight employed.	Obtained Cast Iron = 1000.	Calculated Cast Iron = 1000.
		lbs.		
$Cu\ Sn_5$	Cu 9·73, Sn 90·27	400	83·33	51·67
$Cu\ Sn_4$	Cu 11·86, Sn 88.14	460	95·81	59·56
$Cu\ Sn_3$	Cu 15·21, Sn 84·79	500	104·17	68·75
$Cu\ Sn_2$	Cu 21·21, Sn 78·79	650	135·42	84·79
$Cu\ Sn$	Cu 34·98, Sn 65·02	At 700 lbs. the point entered one half and the alloy broke.		
$Sn\ Cu_2$	Cu 48·17, Sn 51·83	At 800 lbs. the alloy broke without the point entering.		
$Sn\ Cu_3$	Cu 61·79, Sn 38·21	At 800 lbs. the alloy broke into small pieces (blue alloy).		
$Sn\ Cu_4$	Cu 68·27, Sn 31·73	1300 lbs. divided the alloy into 2 pieces without the point having entered 1*mm.*		
$Sn\ Cu_5$	Cu 72·90, Sn 27·10	The same as the preceding.		
$Sn\ Cu_{10}$	Cu 84·32, Sn 15.68	4400	916·66	257·08
$Sn\ Cu_{15}$	Cu 88·97, Sn 11·03	3710	772·92	270·83
$Sn\ Cu_{20}$	Cu 91·49, Sn 8·51	3070	639·58	277·70
$Sn\ Cu_{25}$	Cu 93·17, Sn 6·83	2890	602·08	279·16

The results obtained from this series of alloys lead to several conclusions deserving our notice. First, the marked softness of all the alloys containing an excess of tin; secondly, the extraordinary fact that an increased quantity of so malleable a metal as copper should so suddenly render the alloy brittle, for the

Alloy Cu Sn_2

or

Copper ...... 21·21 } is not brittle,
Tin .... 78·79 }

whilst the alloy Cu Sn

or

Copper ...... 34·98 } is brittle.
Tin .... 65·02 }

Therefore the addition of 14 per cent of copper renders a bronze alloy brittle. This curious fact is observed in all the alloys with excess of copper, Sn Cu_2, Sn Cu_3, Sn Cu_4, Sn Cu_5, until we arrive at one containing a great excess of copper, viz., the alloy Sn Cu_{10}, consisting of copper 84·68 and tin 15·32, when the brittleness ceases; but strange to say this alloy, which contains four-fifths of its weight of copper, is notwithstanding nearly as hard as iron. This remarkable influence of copper in the bronze alloys is also visible in those composed of

Sn Cu_{15}, containing 88·97 of copper.
Sn Cu_{20}, " 91·49 "
Sn Cu_{25}, " 93·17 "

Copper acquires such an increased degree of hardness by being alloyed with tin or zinc that we thought it interesting to ascertain if alloys composed of these two metals would also have a greater degree of hardness than that indicated by theory; we accordingly had a series of alloys prepared in equivalent quantities, and these are the results arrived at:

Formulæ of Alloys and per centages of each.	Weight employed.	Obtained Cast Iron = 1000.	Calculated Cast Iron = 1000.
	lbs.		
$Zn\ Sn_2$ {Zn 21·65, Sn 78·35}	300	64·50	60·83
$Zn\ Sn$ {Zn 35·60, Sn 64·40}	330	68·75	82·70
$Sn\ Zn_2$ {Sn 47·49, Zn 52·51}	400	83·33	110·00
$Sn\ Zn_3$ {Sn 37·57, Zn 62·43}	450	93·70	124·58
$Sn\ Zn_4$ {Sn 31·14, Zn 68·86}	505	105·20	131·22
$Sn\ Zn_5$ {Sn 26·57, Zn 73·43}	600	125·00	142·08
$Sn\ Zn_{10}$ {Sn 15·32, Zn 84·68}	580	120·83	158·33

These results show that these metals exert no action on each other, as the numbers indicating the degrees of hardness of their alloys are rather less than those required by theory. Our researches on the conductibility of heat by the three above series of alloys throw, we believe, some light on the great difference which the alloys of bronze present as compared with those of tin and zinc; for we have stated above that the latter conduct heat as a mixture of metals would do, and not as the former series, which conduct heat as definite chemical compounds.

We shall conclude by giving the degrees of hardness of two other series of alloys, viz., those composed of lead and antimony, and lead and tin. In the series of lead and tin we find that tin also increases the hardness of lead, but not in the same degree as it does that of copper.

Lead and Antimony.

Formulæ of Alloys and per centages.	Weight employed.	
	lbs.	
$PbSb_5$ {Pb 24·31, Sb 75·69}	....	Entered 2·5*mm.* with 800 lbs.; then broke.
$PbSb_4$ {Pb 28·64, Sb 71·36}	....	Entered 2·7*mm.* with 800 lbs.; broke with 900 lbs.
$PbSb_3$ {Pb 34·86, Sb 65·14}	875	
$PbSb_2$ {Pb 44·53, Sb 55·47}	....	Entered 2·5*mm.* with 500 lbs.; broke with 600 lbs.
$PbSb$ {Pb 61·61, Sb 38·39}	500	
$SbPb_2$ {Pb 76·32, Sb 23·68}	385	
$SbPb_3$ {Pb 82·80, Sb 17·20}	310	
$SbPb_4$ {Pb 86·52, Sb 13·48}	300	
$SbPb_5$ {Pb 88·92, Sb 11·08}	295	

Lead and Tin.

Formulæ of Alloys and per centages.	Weight employed.	Obtained Cast Iron = 1000.	Calculated Cast Iron = 1000.
	lbs.		
$PbSn_5$ {Pb 26·03, Sn 73·97}	200	41·67	23·96
$PbSn_4$ {Pb 30·57, Sn 69·43}	105	40·62	23·58
$PbSn_3$ {Pb 36·99, Sn 63·01}	160	32·33	22·83
$PbSn_2$ {Pb 46·82, Sn 53·18}	125	26·04	20·09
$PbSn$ {Pb 63·78, Sn 36·22}	100	20·83	19·77
$SnPb_2$ {Pb 77·89, Sn 22·11}	125	26·04	18·12
$SnPb_3$ {Pb 84·09, Sn 15·91}	135	28·12	17·23
$SnPb_4$ {Pb 87·57, Sn 12·43}	125	26·04	17·08
$SnPb_5$ {Pb 89·80, Sn 10·20}	110	22·92	16·77

We have great pleasure in thanking here Mr. Siméon Stoikowitsch, F.C.S., for his valuable assistance during these long researches.