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Change of Structure in the Solid State.

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Besides the changes which occur when a metal or alloy passes from the liquid to the solid state, there are those which take place after solidification.

(1) Change of structure due to mechanical stress and the growth of crystals on annealing the metal or alloy thus strained. This subject has been carefully studied by Ewing and Rosenhain * and others.

(2) Due to change in composition in the solid—diffusion. Under this heading we have carburization † (cementation, case-hardening, etc.); decarburization ‡ (and change of

* Phil. Trans. Royal Society, 195, p. 279, and 193, p. 353.

† Arnold. *Journal I. and S. Inst.*, II, 1898, p. 185.

‡ Stead. *Proc. Cleveland Inst. Eng.*, Dec., 1895, p. 79.



FIG. 1.

$\times 35. V.$

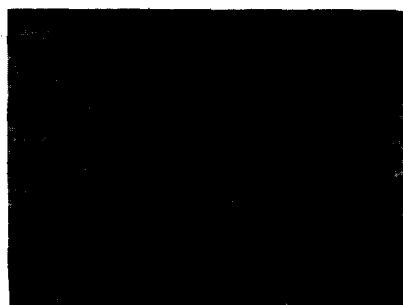


FIG. 2.

$\times 20. V.$



FIG. 3.

$\times 30. O.$



FIG. 4.

$\times 35. V.$

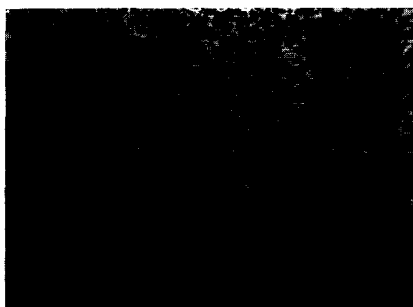


FIG. 5.

$\times 16. V.$

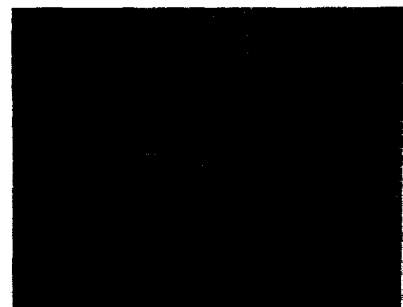


FIG. 6.

$\times 35. V.$



FIG. 7.

$\times 35. V.$



FIG. 8.

$\times 16. V.$



FIG. 9.

× 35. V.

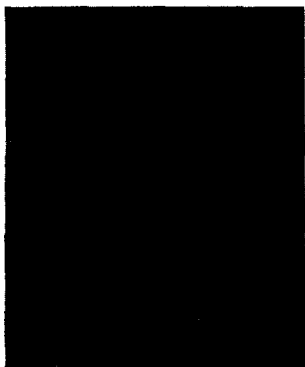


FIG. 10.

× 35. V.

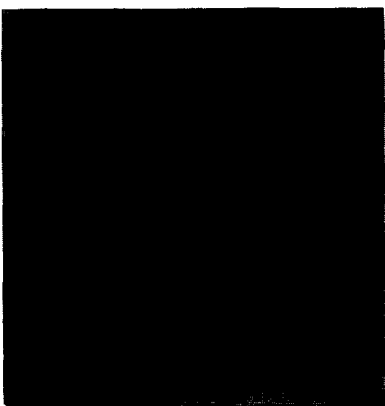


FIG. 11.

× 33 V.



FIG. 12.

× 33. V.

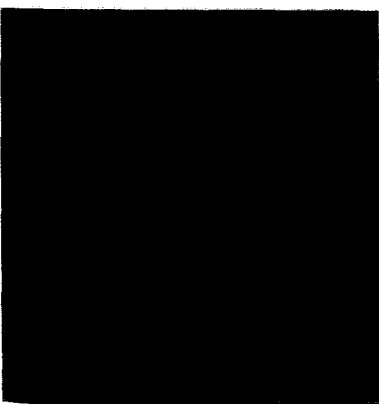


FIG. 13.

× 35. V.



FIG. 14.

× 35. V.

carbon from the combined to the free state, or from cementite to graphite, *e. g.*, malleable cast iron): passage of one metal into another, as gold into lead:* oxidation, as the formation of alloys of copper and oxide of copper in the solid.†

(3) Changes which occur in the solid with change of temperature, such as the change of pure iron from one state or allotropic modification into another‡ (α , β and γ). *The change of structure in the solid state* which occurs when certain alloys cool down from their point of solidification to the normal temperature. Such changes are found in the alloys of copper and aluminum, of copper and tin, of copper and antimony, of iron and steel, etc.

Copper and Aluminum.—In the alloys of copper and aluminum, Le Chatelier has found at least three compounds, viz.: Al_2Cu , AlCu and AlCu_3 .

From pure aluminum to Al_2Cu we have a simple series, whose freezing-point curve is composed of two inclined branches, intersecting at the eutectic alloy (about 32 per cent. Cu). As we pass from the aluminum end to the alloy with 31 per cent. Cu, we find dendrites and grains of aluminum set in an increasing eutectic or groundmass, which freezes at about 530°C .

Fig. 1, magnified 35 diameters, vertically illuminated, shows the alloy containing 23 per cent. Cu, in which part of a large dendrite of aluminum is seen surrounded by the eutectic. This eutectic is seen in places to be composed almost entirely of Al_2Cu , because, during solidification, its aluminum has migrated to and merged with that composing the grains and dendrites. As Stead has pointed out, this is of common occurrence in many eutectics. It is specially marked in the case of the copper-rich or silver-rich alloys of the copper-silver series.

From 32 per cent. Cu to Al_2Cu , we find this compound crystallizing out in decreasing amounts of the eutectic.

* Phil. Trans. Royal Society, 187 (1896), p. 383.

† Heyn. Inter. Ass. Test. Mat., 1901. (Hofman. T. A. I. M. E. 1903.)

‡ Osmond. "Annales des Mines," Jan., 1900. *Metallographist*, III, 181.

Fig. 3 $\times 30$ diameters oblique illumination shows the 45 per cent. alloy, and may be taken as a type. The structure of the whole series is well shown in a diffusion alloy, made by pouring molten aluminum onto the molten compound, Al_2Cu , and allowing the whole to slowly solidify. *Fig. 2* $\times 20 \vee$ represents the junction between the two. (The top of the alloy is on the left hand of the photomicrograph.) We see dendrites of aluminum growing down into the eutectic alloy, whilst crystals and dendrites of the compound Al_2Cu grow upwards.

When the copper in the alloy is increased above Al_2Cu , the second compound AlCu is found crystallizing out in a groundmass of the first. *Fig. 4* $\times 35 \vee$ shows this structure. The alloy contains 66 per cent. copper, 34 per cent. aluminum. With further increase in copper, the alloys are apparently homogeneous from 78 to above 83 per cent. Cu. Above this point to about 90 per cent. Cu, we find structures in the slowly cooled alloys due to a rearrangement in the solid. *Fig. 5* $\times 16 \vee$ is the alloy containing about 85 per cent. Cu, in which dark veins and irregular grains are surrounded by a lighter envelope. If the alloy be raised to a red heat and quenched, a change in structure occurs, and under a low power (33 diameters) the alloy is apparently homogeneous, though with a higher magnification it is seen to be composed of alternate light and dark bodies. On reheating to a red and slowly cooling, the original structure is restored. *Fig. 6* $\times 35 \vee$ shows the same alloy quenched, then reheated and slowly cooled. The structure of *Fig. 5* has been reproduced. As the copper is again increased, the dark constituent disappears, leaving the light body which, under high powers, is seen to possess a eutectic structure. With further additions of copper, bright grains and veins of AlCu_3 make their appearance. *Fig. 7* $\times 35 \vee$ shows the 89 per cent. Cu alloy and consists of bright AlCu_3 set in a darker groundmass with the eutectic structure. Again, the structure of the series can be well shown by a diffusion alloy between 80 and 90 per cent. copper. Such an alloy is seen in *Fig. 9* $\times 35 \vee$. (The top of the figure is on the left.) Dark dendrites, similar to those in *Fig. 5*, are seen to grow downwards,

whilst the bright AlCu_3 grows upwards. The central zone is composed of the alloy having the fine eutectic structure. Between this and the upper part of the alloy, a third constituent sometimes occurs, as long bright needles, etc., but as yet it has not been isolated. Now if the alloy shown in *Fig. 9* be reheated to a red and quenched, the whole mass becomes homogeneous and has the structure seen in *Fig. 10*. This structure closely resembles that of steel quenched from a very high temperature (martensite). On reheating and slowly cooling, the original structure is restored. Although the complete cooling curves for these alloys have not yet been published, there is no doubt that the alloys solidify as homogeneous solid solutions resembling martensite, and at a lower temperature rearrange themselves as shown in *Fig. 9*. The curve due to this rearrangement in the solid will therefore be similar to that of a simple series of alloys forming neither solid solutions nor isomorphous mixtures.

From 92 per cent. Cu onwards, we find the alloys consist of solid solutions (probably of AlCu_3 and Cu). *Fig. 8* $\times 16 \vee$ shows the alloy containing 97 per cent. Cu slowly cooled. The copper dendrites are seen to vary in composition from center to outside, and in this they resemble those at the copper end of the CuSn series. It may be, however, that we are not dealing with a compound AlCu_3 , but with a series of solid solutions whose maximum composition corresponds to AlCu_3 .

Copper and Tin.—The constitution of the alloys of copper and tin has been carefully worked out by Heycock and Neville.* *Fig. 33* is based on their curve. In a former paper† the structure of the series was shortly set forth, but several points were left open to discussion, because the exact meaning of many of the changes which take place in the solid were not known, my own investigations‡ only explaining some of them.

The curve *A B L C D E G H I K* marks the beginning of crystallization and above this freezing-point curve the alloys

* Bakerian Lecture. *Phil. Trans. R. S.*, Vol. CCII, A., pp. 1-69.

† *Jour. Frank. Inst.*, July-Sept., 1902.

‡ *Proc. Inst. Mech. Eng.* (London), Dec., 1901, pp. 1211-1272.

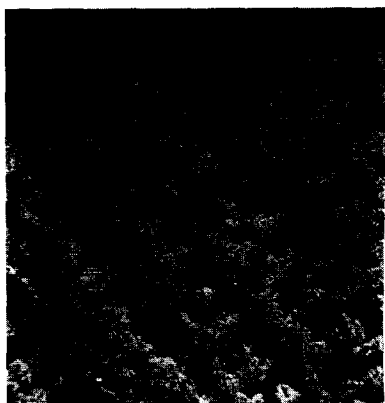


FIG. 15. $\times 55$. V.

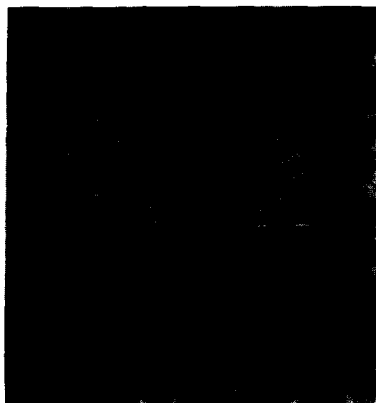


FIG. 16. $\times 35$. V.

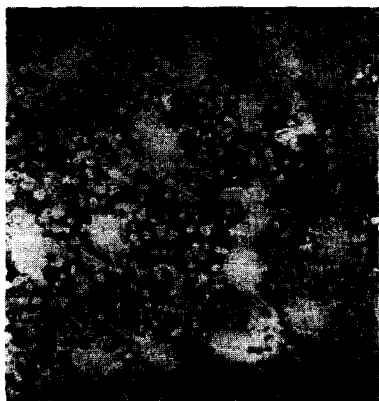


FIG. 17. $\times 33$. V.



FIG. 18. $\times 88$. V.

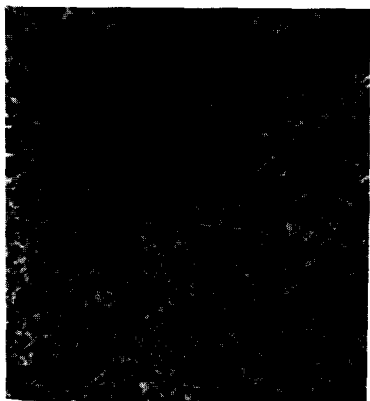


FIG. 19. $\times 120$.



FIG. 20. $\times 120$.

are in the liquid state. Professor Rooseboom calls a curve of this kind the "liquidus." Below the curve $Ab l c m d e f$. $E_2 E_3 H' H'' K'$ everything is solid, this being termed the "solidus." Between the two we have a mixture of the solid and liquid states, whose compositions are given by a horizontal line cutting the liquidus and solidus. The horizontal line marks the temperature at which these two phases (liquid and solid) are in equilibrium. Heycock and Neville divide the series into ten groups marked by the points B, L, C, D, E, F, G, H and I .

(1) The alloys occurring between A and B (100 to 91 per cent. Cu) consist of a uniform solid solution of up to 9 per cent. tin in copper (α) below Ab . Between the liquidus and solidus, they consist of crystals of α + α liquid richer in tin. In the moderately slowly cooled alloys, it is often found that the central parts of the dendrites of α etch differently from the outsides, due to their being richer in copper, and cooling not being slow enough to allow of perfect diffusion to produce uniform composition. Such a structure is seen in *Fig. 8*.

(2) The alloys from 91 to 77.5 per cent. copper or B to L on passing the liquidus begin to crystallize out dendrites of α ; but on reaching the temperature marked by the line $b l C$ they react with the mother liquor:

α (of composition b) + liquid (of composition C) = β (of composition l) until the whole of it is used up. The substance β is a solid solution containing from 22.5 to 27 per cent. tin. Below $b l$, or 790°C ., the whole mass is solid, and consists of dendrites of copper containing about 9 per cent. tin in solid solution (α_b) surrounded by a solid solution of composition 77.5 per cent. Cu, 22.5 per cent. Sn (β_1). As the temperature falls from 790°C . ($b l$) to 500°C . ($b' C'$) the dendrites of α continue to grow at the expense of the solid solution β , whose composition is reduced from 77.5 to 74.5 per cent. Cu. On $b' C'$ the residual β breaks up into minute α and Cu_4Sn (δ). In other words, at the temperature $b' C'$ (500°C .) the remaining solid solution β is transformed into the eutectoid of copper (containing tin in solid solution) and the compound Cu_4Sn , which is the structure found at the normal temperatures.

(3) The alloys from 77·5 per cent. to 74·5 per cent. copper, or *L* to *C*, on reaching the liquidus begin to separate dendrites and grains of α , but the whole of this is changed into β containing *l* per cent. of copper on reaching the temperature marked by *l C*. The dendrites, etc., of this solid solution β continue to grow, their composition and that of the liquid being given by the solidus *l c* and the liquidus *C D* as before, until the whole is a solid solution below *l c*. On reaching the temperature of the curve *l C'*, however, the solid solution β becomes saturated with α , which crystallizes out as in the alloys under (2). Then when the temperature marked by the line *b' C'* is reached, the remaining β is resolved into the eutectoid of α and δ or copper (with tin in solid solution) and Cu_4Sn .

(4) The alloys from 74·5 per cent. to 68·2 per cent. copper comprise the series from *C* to *D*, or from the eutectoid to the compound Cu_4Sn . On reaching the liquidus *C D* they separate out the solid solution β , but when less than *c* per cent. copper is present they are changed into the solid solution γ on reaching the temperature *c m D*. Below the solidus the whole mass is a solid solution, until the temperature of the curve *D'X* is reached, when the compound Cu_4Sn or δ separates out as veins and irregular grains or rosettes. The compound continues to separate out until the temperature *X D₂* is reached, when the remaining solid solution splits up into the eutectoid of $\alpha + \delta$ as before.

As Heycock and Neville have pointed out,* the surfaces of these alloys are covered with large dendrites due to the initial crystallization. If the surface is polished, it is at once seen that they have re-arranged themselves, and are now built up of the compound Cu_4Sn and the eutectoid. *Fig. 15* $\times 55 \vee$ shows such a polished surface in the alloy containing 73 per cent. copper, in which the composite nature of the primary crystallization is seen. *Fig. 16* $\times 35 \vee$ shows the same alloy quenched at the solidification point, and shows the dark dendrites of the solid solution β set in the lighter groundmass richer in tin. *Fig. 17* $\times 33 \vee$

* *Proc. Royal Society*, Vol. XCVI.

shows the same alloy slowly cooled to 650° C. and quenched. The alloy is not homogeneous throughout, but parts have been resolved into a light and dark constituent. It may be that we have a partial separation of the compound Cu_4Sn due to the quenching being too slow. *Fig. 18* $\times 88 \vee$ shows the very slowly cooled alloy in which the bright Cu_4Sn has separated out of the solid solution as veins and rosettes, whilst under a higher power the darker groundmass is seen to be composed of the eutectoid.

(5) The alloys from 68.2 per cent. to 61.6 per cent. copper, or from *D* to *E*, pass from the compound Cu_4Sn to the compound Cu_3Sn . On reaching the curve *DE*, dendrites of the solid solution γ crystallize out until the whole mass is solid. When the temperature reaches the curve *E'D'*, the compound Cu_3Sn separates out (η) until at the temperature *D'E''* the residual γ has the composition of 68.2 per cent. Cu, when it is transformed into δ , or the compound Cu_4Sn . *Fig. 12* $\times 33 \vee$ shows the alloy containing 66 per cent. Cu 34 per cent. Sn quenched just before solidification, and is composed of cells of the solid solution γ . *Fig. 13* $\times 35 \vee$ shows the same alloy quenched on the solidus, and is composed of almost uniform γ . *Fig. 14* $\times 35 \vee$ shows the alloy quenched between the solidus and *E'D'*. All trace of the cell-like structure has gone, and we have large grains of γ , with a curious linear structure (seen also in *Fig. 13*), due perhaps to the difficulty in preventing the beginning of the change on *D'E'* or to the nature of γ itself. *Fig. 11* $\times 33 \vee$ shows the alloy slowly cooled, and consists of dark bands of Cu_3Sn or η surrounded by the lighter SnCu_4 or δ . The compound η separated out on reaching the temperature of the curve *D'E*, whilst the residual solid solution γ changed over into the bright Cu_4Sn on reaching *D'E''*.

(6) The alloys between 61.6 per cent. and 59 per cent. copper, or *E* to *F*, are very remarkable. To quote Heycock and Neville: "These go through the same stages of γ + liquid, then homogeneous γ , then $\gamma + \eta$; but when the temperature of the line *fG* is reached, the residual γ breaks up into η and liquid of the composition *G*. Thus these alloys present the somewhat rare phenomenon of the partial melt-

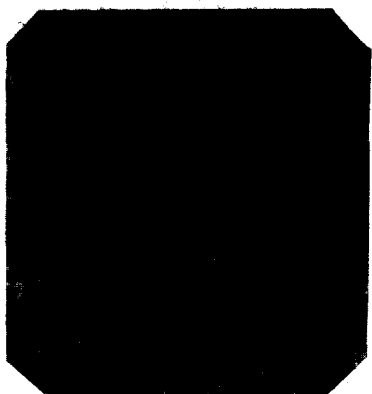


FIG. 21.

× 120.

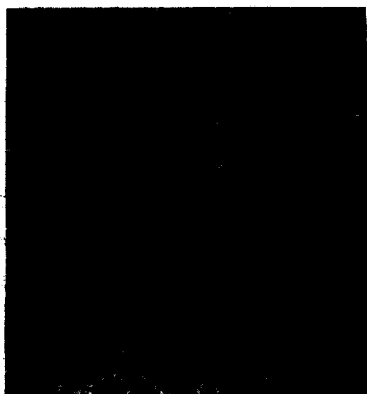


FIG. 22.

× 33. V.

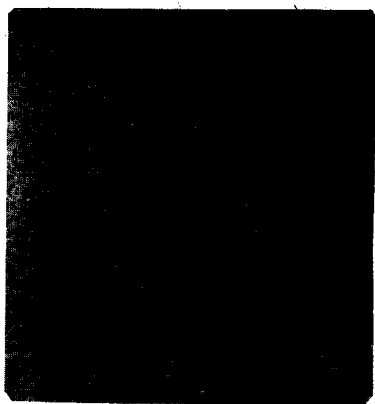


FIG. 23.

× 33. V.

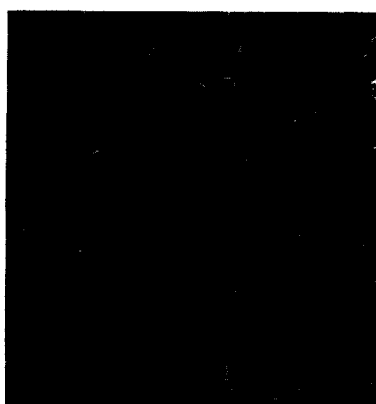


FIG. 24.

× 33. V.

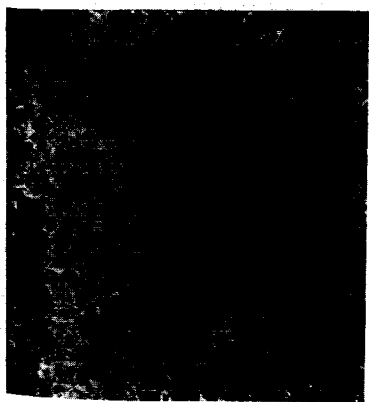


FIG. 25.

× 33. V.

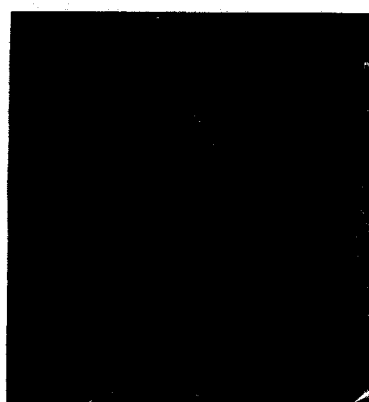


FIG. 26.

× 33. V.

ing of a solid brought about by cooling it. The transformation $\gamma_f = \eta_{E'} + \text{liquid}_G$, or as we may safely write it, $\gamma_f = \text{Cu}_3\text{Sn} + \text{liquid}_G$, is the transformation which causes the angle at G in the liquidus."

(7) The alloys between 59 per cent. and 42.5 per cent. copper, or F to G , act as the above, and when cooled below the temperature $E_2 G$ (630°C.) continue to separate out Cu_3Sn and thus enrich the liquid portion of the alloy in tin, whilst below the temperature $E_3 H$, or 400°C. , they behave as the next series.

(8) The alloys from 42.5 per cent. to 7 per cent. copper begin to separate out the compound Cu_3Sn on reaching the liquidus G to H , and the liquid alloy is enriched in tin until it has the composition H . At this temperature $E_3 H$ (400°C.) the compound Cu_3Sn is no longer in equilibrium with the remaining liquid, but reacts with it, and we get the compound H (approximately CuSn) formed. The reaction does not go far enough to produce complete equilibrium by changing the whole of the liquid on the left of H' and the whole of the CuSn or H on the right of H' , because the crystals of the compound Cu_3Sn soon become covered by an envelope of H , which prevents further action except by diffusion. Hence a third phase is found in each case, which is enclosed by a bracket to denote it ought not to exist if the change had been complete. By keeping the alloys for several days at a temperature just below $E_3 H$, Heycock and Neville have succeeded in establishing equilibrium and producing two phases. As the temperature passes the line $E_4 I K'$, the liquid, which has the composition I (about 1 per cent. copper), due to further separation of the solid H , as in the next group, solidifies as the eutectic of tin and H .

(9) Between H and I , or 7 per cent. to 1 per cent. copper, the solid H (approximately CuSn) separates out on passing the liquidus and enriches the mother-liquid in tin until, at the temperature $M I$, it has the composition of about 1 per cent. Cu , when it solidifies as the eutectic as before.

Lastly, the alloys containing 1 to 0 per cent. copper separate out grains and dendrites of tin on reaching the liquidus $I K$, whilst at the temperature $I K'$ the remaining liquid (1 per cent. Cu) solidifies as the eutectic of tin and CuSn .

The above is a short account of the changes which occur during and after solidification in the alloys of copper and tin. The Bakerian Lecture by Heycock and Neville, "On the Constitution of the Copper-Tin Series of Alloys," is by far the best piece of work upon this subject, and is illustrated by over 100 beautiful photomicrographs which will well repay the reader.

Iron and Carbon.—The alloys of iron and carbon, due to their great importance, have been studied more than any other series. Their constitution is represented by the diagram in *Fig. 34*, which is based upon that of Professor Rooseboom.*

The freezing-point curve or liquidus is represented by $A B D$, whilst below the solidus $A a B C$ everything is solid. The branch $A B$ marks the commencement of solidification. Dendrites of martensite separate out and contain a maximum of about 2 per cent. carbon in solid solution. In alloys containing more than 2 per cent. carbon the martensite-graphite eutectic makes its appearance. The horizontal line $a B C$ marks the evolution of heat due to its solidification. The branch $B D$ corresponds to the separation of free graphite. Hence we find from 0 to 2 per cent. carbon the alloys solidify as dendrites of martensite; from 2 to 4·3 per cent. carbon or a to B , the alloys solidify as dendrites of martensite set in the groundmass or eutectic of graphite and martensite. Alloys having the composition B solidify as the eutectic and contain neither free martensite nor free graphite, whilst above B or 4·3 per cent. carbon we have free graphite (as kish) and the eutectic.

As the temperature falls from $a B C$ to $E F H$, or about $1,000^{\circ}\text{C}$., the martensite becomes supersaturated with graphite, which separates out along the line $a E$, reducing the total carbon in solid solution to about 1·8 per cent. At the temperature $E F H$ a transformation occurs. The martensite is no longer in equilibrium with graphite but reacts with it. Martensite (1·8 per cent. C) + Graphite = Cementite (Fe_3C).

* *Zeits. f. Phys. Chem.*, XXXIV, 1900, p. 437.

This reaction is very slow and in ordinary cooling only goes a short way, and hence we find graphite below $E F H$ due to lag.

As the temperature falls below $1,000^{\circ}\text{C.}$, the martensite becomes supersaturated with carbon, which separates out as cementite (Fe_3C) along the curve $E S$ until at the temperature S , or just under 700°C. , recalescence occurs and the residual martensite, containing about 0.8 per cent. carbon, is transformed into the eutectoid pearlite, consisting of alternate laminae of cementite and ferrite (or pure iron).

In the case of white irons, solidification commences, as before, by the separation of dendrites of martensite, but the mother-liquid solidifies as a eutectic of martensite and cementite, on the line $E' B' F'$. This must take place because martensite and graphite are not in equilibrium, and the difference between this and gray irons is probably due to the difference in the amount of silicon, manganese and other impurities present. On further cooling the martensite is transformed in the solid as before.

Coming next to the series containing 0 to 1.8 per cent. carbon. Above the temperatures marked by the curve $G O S E$ they exist as the solid solution martensite, but as the temperature falls transformations occur.

In the case of alloys containing up to S or 0.8 per cent. carbon, as the temperature reaches the curve $G O S$ the martensite becomes supersaturated with ferrite, which separates out and enriches the martensite in carbon until it contains S or 0.8 per cent. at just under 700°C. At this point recalescence occurs and the residual martensite is transformed to the eutectoid pearlite. Hence within the area $G O S P$ we have ferrite and martensite, whilst below $P S$ we have ferrite and pearlite. The steel containing S or 0.8 per cent. carbon exists as martensite until the temperature S is reached, when it is transformed into pearlite as before. The alloys containing 0.8 to 1.8 per cent. carbon become supersaturated with cementite, which separates out along the curve $E S$ and reduces the carbon in solid solution to S or 0.8 per cent. at just under 700°C. , when the residual martensite is transformed to pearlite as before. Hence, between

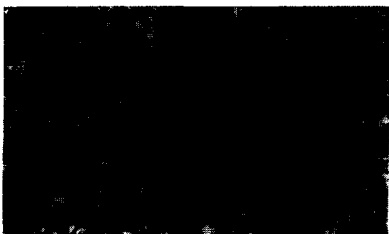


FIG. 27.

× 120.

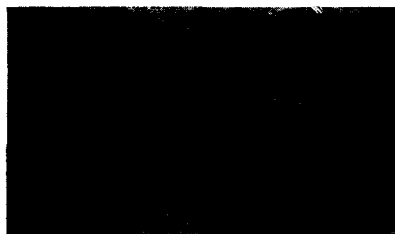


FIG. 28.

× 120.

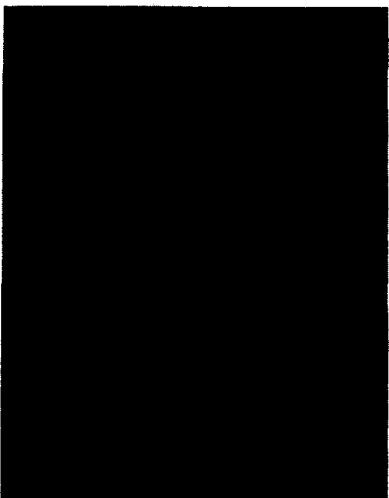


FIG. 29.

× 120.

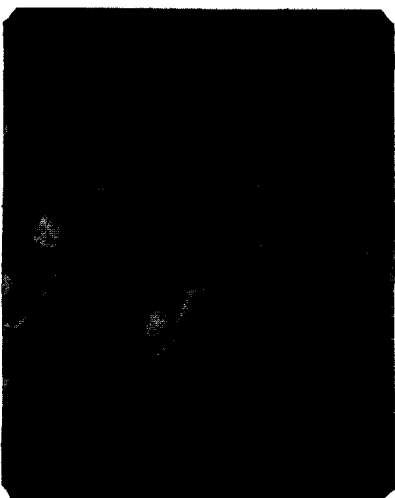


FIG. 30.

× 33.

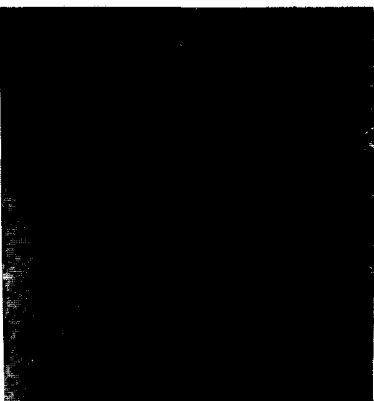


FIG. 31.

× 33. V.

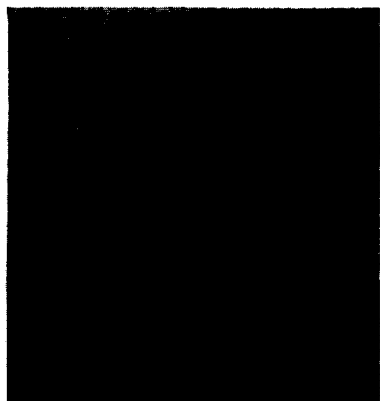


FIG. 32.

× 33. V.

the temperatures ES and PSK , we have cementite and martensite, whilst below the temperature SK we have cementite and pearlite.

Another change occurs with fall of temperature. Iron has three allotropic modifications, viz., α , β and γ . The γ form exists above the temperature $GO S$, the β form within the area $GO M$, whilst the α modification occurs below $MO S$. The evolution of heat MO is due to the transformation of β into α iron with the regain of magnetism.

These changes in the solid are of the utmost importance, because upon them depend hardening, refining and the like. Sauveur,* in a paper on "The Relation between the Structure of Steel and its Thermal and Mechanical Treatment," gives a very clear account of the changes which occur. Stead† has shown the effects of heating bars of from 0.013 to 1.14 per cent. carbon to various temperatures, whilst Arnold‡ has done much work along the same line.

The following will give some idea of the great changes which occur with heat and mechanical treatment. A steel containing 0.50 per cent. carbon and 0.98 per cent. manganese gave two critical points on heating. Ac_1 at about 700° to 710° C. very marked, and $Ac_{2,3}$ at about 745° to 750° C. very slight. On cooling, $Ar_{2,3}$ was slight at about 700° C., whilst Ar_1 , the recalescence point, was very strong at 660° C. The effect of slowly heating to given temperatures and cooling in air and quenching in water was determined by physical tests and by microstructure. The material was $\frac{7}{16}$ inch square.

* *Journal Iron and Steel Institute*, II, 1899, p. 195. (Also see *T. A. I. M. E.*, 1896.)

† *Journal Iron and Steel Institute*, I, 1898.

‡ *Jour. Iron and Steel Institute*.

The following table gives the results of physical tests :

Bar heated to Degrees C.	COOLED IN AIR.				QUENCHED IN WATER.			
	Elastic L., lbs. per sq. in.	Maximum Load, lbs. per sq. in.	Elongation in 8 inches.	Reduction of Area.	Elastic L., lbs. per sq. in.	Maximum Load, lbs. per sq. in.	Elongation in 8 inches.	Reduction of Area.
659	72,500	102,900	15·6	55·7	67,000	107,150	15·2	50·2
682	67,100	104,100	17·5	50·8	64,000	107,400	15·6	55·3
700	62,500	101,250	17·6	53·1	63,000	127,800	—	8·5
702	62,400	100,400	14·3	55·8	61,250	133,500	—	2·2
718	63,700	102,300	17·4	54·3	—	188,900	—	—
733	65,600	108,400	17·4	52	71,100	203,100	—	—
746	75,200	112,000	16·25	51·5	—	135,050	—	0·3
766	74,600	112,600	16·5	42·8	60,900	103,800	—	0·1
775	74,600	112,200	—	50·6	—	104,000	—	0·1
819	73,600	115,950	15	48·4	—	60,100	—	—
843	73,100	117,100	15·6	46	—	39,000	—	0·4
902	71,400	115,000	11·87	41	—	80,500	—	—
966	69,700	114,800	13·6	42·7	—	72,300	—	0·5
1030	67,600	110,300	14	38·4	—	45,750	—	—
1086	66,400	108,800	12·1	29·3	—	61,950	—	0·2
1151	66,100	109,950	8·1	34·4	—	61,300	—	—
1212	64,900	108,400	11·25	32·2	—	70,200	—	0·2
1268	66,900	112,800	8·1	12·7	—	54,900	—	—
1339	65,400	113,900	5·5	7·6	—	56,800	—	—
1390	60,700	98,200	3·4	5·4	—	61,800	—	0·6
Original	70,550	113,400	13·9	46·4				

Steel Cooled in Air.—From the above it will be seen that re-heating to the lower critical point lowers the elastic limit and maximum load uniformly, whilst from this point to the upper point AC_2 , there is an improvement until we return to almost what we started with. The best elastic limit occurs just at this point, whilst the greatest maximum load occurs about 840° C. The elongation shows a marked improvement to a little below the upper critical point, after

which there is a regular falling off until at $1,390^{\circ}\text{C.}$ the steel is very much overheated. The reduction of A_{ka} is greatest at A_{c_1} , and falls off with higher temperatures until reduced to $5\frac{1}{2}$ per cent. at $1,390^{\circ}\text{C.}$

On examining the microstructure, the original steel, shown in *Fig. 19* $\times 120$, consists of medium-sized grains of dark pearlite surrounded by veins of ferrite. Above 700°C. these grains are reduced in size until we get the finest structure at 733°C. or just below $A_{\text{c}_{2-3}}$. This is shown in *Fig. 27* $\times 120$, which is the bar heated to 733°C. and slowly cooled in air. With increase in temperature, we get an increase in the size of structure. *Fig. 21* $\times 120$ shows the bar heated 819°C. , and the structure is much larger than that of the original steel. There is a better separation of the ferrite, the pearlite being less unsegregated. *Fig. 22* $\times 33 \vee$ shows the bar heated to 966°C. , whilst *Fig. 23* $\times 33 \vee$ is the bar heated to $1,086^{\circ}\text{C.}$ with a proportionate growth of grain. The photograph is taken at the edge of the section to show the very distinct decarburization of the outer layer. *Fig. 24* $\times 33 \vee$ shows the steel heated to $1,151^{\circ}\text{C.}$, and *Fig. 25* $\times 33 \vee$ is that heated to $1,212^{\circ}\text{C.}$, the photograph being again taken from the edge to show decarburization. The structure has become very coarse indeed. *Fig. 26* $\times 33 \vee$ shows the steel heated to $1,339^{\circ}\text{C.}$ The crystals have grown to an enormous size, whilst in the center of the largest a new structure is seen, which may be a relic of the old martensite which was not completely transformed on passing A_{r_1} . We have evidently reached the point where we get great overheating.

In considering the changes which have taken place on re-heating, we know that the *pearlite* will give the finest structure when the steel has been heated to just above A_{c_1} , or when it has been transformed to martensite. Heating above this point will cause a growth of structure, the higher the temperature the coarser the structure. The *ferrite* begins to diminish in size above A_{c_1} , because the martensite commences to dissolve it. This will continue until the whole of it has disappeared, when the change $A_{\text{c}_{2-3}}$ is complete. Now, the *whole steel* will have the finest

Temperature Centigrade.

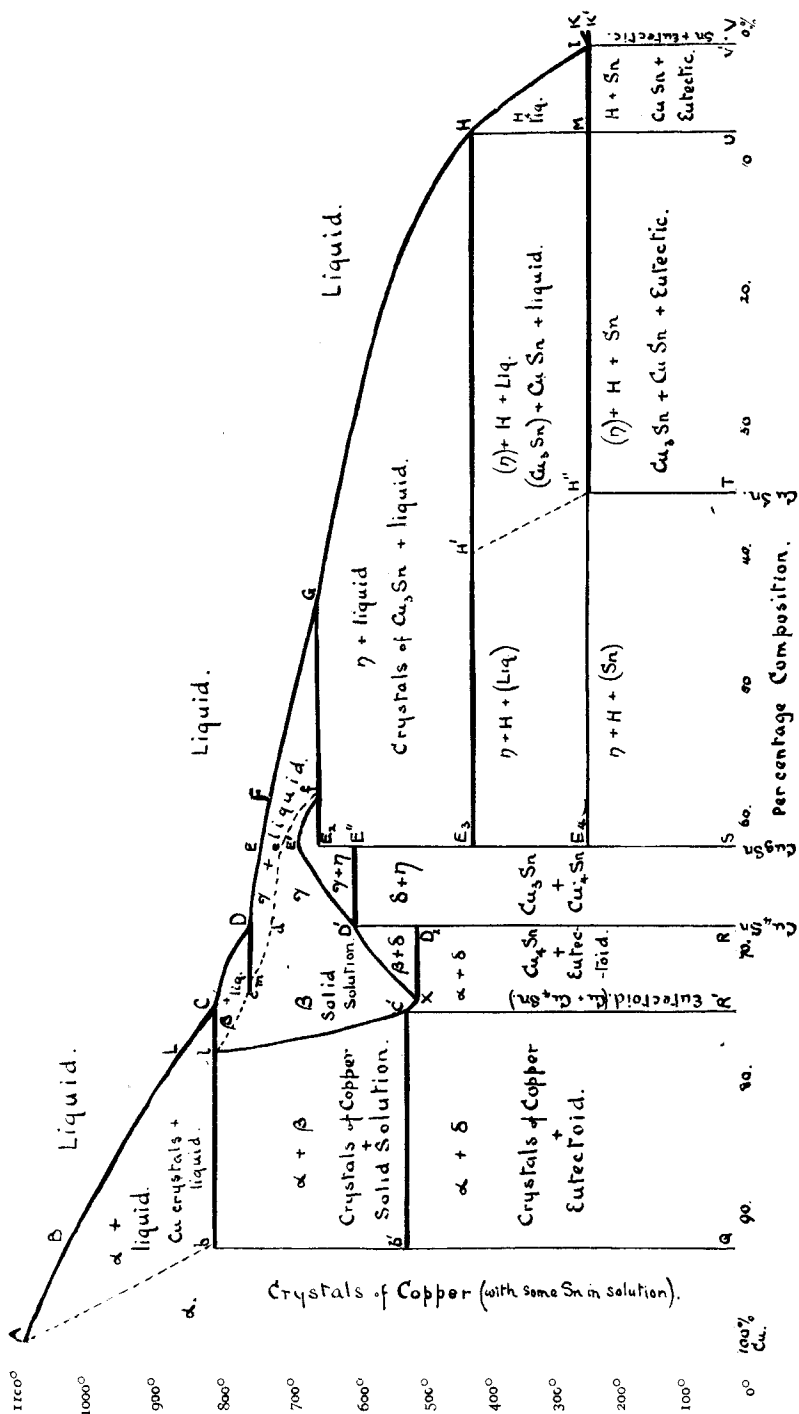


FIG. 33.—Equilibrium curve: γ -copper-tin series.

structure where these two changes balance, which is apparently just below Ac_{2-3} . Thus we find the steel heated to 733° C. has the finest structure, and in *Fig. 27* this is shown.

Steel Quenched in Water at about 15° C.—On looking at the physical properties of the quenched bars, we see that at the lower critical point Ac_1 hardening takes place and the reduction of area falls to 8.5 per cent. The maximum load runs up at this point also, and reaches a maximum at 733° C. of almost twice the original. Heating to above this point causes a rapid falling off. (The great difficulty experienced with the hardened bars to get them quenched straight, constant breaking in the grips of the testing machine, etc., accounts for the poor results in the table.)

Under the microscope, we see no marked effect from quenching below the lower critical point. The bar quenched from 700° C. (Ac_1) showed a great change. The ground-mass is no longer pearlite, but is now hard martensite. Hence the falling off in the reduction of area. *Fig. 20* \times 120 shows the steel quenched from 733° C. It has the highest maximum load and also the finest structure. The ferrite has been nearly all absorbed. Under high powers two constituents are seen: the one is hard and but lightly attacked by the etching fluid (2 per cent. nitric acid, 1.4 specific gravity in alcohol), whilst the other is turned black. These two are martensite and probably the transition form troostite.

Bars quenched from above Ac_{2-3} consist entirely of martensite. The size and shape of the martensite grains (which, of course, increase with the temperature to which the bars have been heated) can be seen on grinding down a fractured surface. *Fig. 28* \times 120 shows such a surface from the steel quenched from 900° C., in which the course of fracture is seen between the grains of martensite. *Fig. 29* \times 120 shows a section of the bar quenched from $1,212^{\circ}$ C. The structure of the martensite is now coarse enough to be seen with this magnification, and is characterized by a series of light and dark bands in three directions usually, forming triangular markings. Lastly, in *Fig. 30* \times 33, we have a polished fracture of the bar heated to $1,390^{\circ}$ C. and quenched. The

martensite crystals have grown to an enormous size, and in section are bounded by more or less straight lines. The overheating has evidently been very great.

Heat Refining.—Supposing we have a quantity of the above steel, which has cooled down slowly from $1,390^{\circ}\text{C}.$, it is very much overheated, and it is required to refine it, to what temperature must we re-heat it to obtain the best results? The answer can be seen from the table of heat treatment and the microstructure of the bars cooled in air. We shall find that re-heating to that point where the changes due to Ac_1 and Ac_{2-3} just balance, will give the best results, for here we have the finest structure as before.

Mechanical Refining.—If, on the other hand, we have our steel at a high heat, it is cooling in the furnace from $1,390^{\circ}\text{C}.$, and we wish to know at what temperature we have to roll it, or rather finish rolling it, to obtain the best results; if rolling be sufficient to break up the structure produced by the high temperature $1,390^{\circ}\text{C}.$, then the final structure will depend on the growth of grain in cooling from the finishing temperature to Ar_1 .

In a series of experiments, in which the bars were heated to $1,390^{\circ}\text{C}.$, slowly cooled to certain temperatures and rolled, the reduction in area was 30 per cent. in two passes. The results are given in the following table:

Bar rolled at — Degrees C.	Elastic L., lbs. per. sq. in.	Maximum Load, lbs. per sq. in.	Elongation in 8 inches.	Reduction of Area.
963	86,050	126,800	9.6	28.0
939	85,800	127,300	10.25	27.0
837	84,400	128,400	10.25	29.3
809	84,700	126,000	10.75	33.1
781	87,700	126,500	10.0	33.3
752	95,100	130,000	8.0	39.0
724	89,400	124,200	9.4	41.3
695	94,700	129,100	9.75	29.6
667	98,050	130,200	8.75	27.3
Not rolled.	60,700	98,200	3.4	5.4
Original.	70,550	113,400	13.9	46.4

On examining the results of physical tests it is seen that the elastic limit shows a great increase throughout. The maximum load has also passed that of the original and is greatest at the lowest rolling temperature. The elongation has been raised from 3.4 per cent. in the bars cooled in air from $1,390^{\circ}\text{C.}$ to an average of 9.5 per cent., and is very fair when compared with that of the original steel, viz., 13.9 per cent. The reduction of area shows the more marked varia-

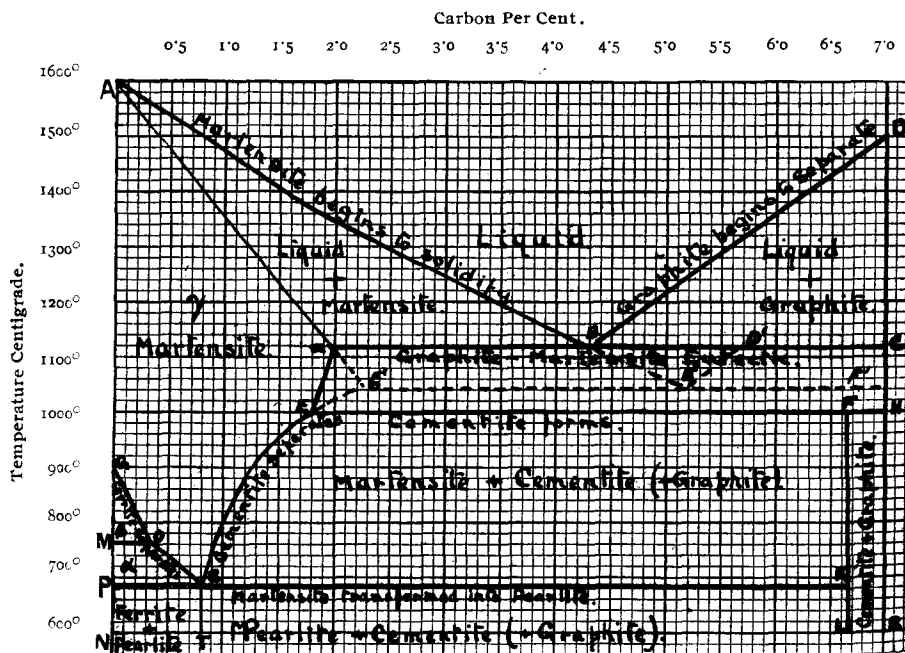


FIG. 34.—Equilibrium curve: iron carbon series.

tion. The bars heated to $1,390^{\circ}$ and rolled at 752° and 724°C. , respectively, show the best reduction—39 and 41.3 per cent. This is good, when compared with the unrolled bars and with the original with 5.4 and 46.4 per cent., respectively.

On examining the microstructure we find that the lower the rolling temperature the finer the grain, down to the bar rolled at 724°C. , below which there is apparently a slight increase in size. In each case there has been more or less decarburization of the outside layer. In the bar rolled at

the highest temperature we have the largest grain, but this is very small when compared with that of the overheated bar. The ferrite has separated out as thin veins round the grains of pearlite, and also in them as irregular patches. With the lowering of the rolling temperature, we find little difference in the ferrite except that the veins are smaller because they follow the grain, and there is less free ferrite within the grain itself. On reaching the bar rolled at 724° C., a marked change is noticed. The ferrite veins round the outside of the specimen begin to thicken very much. This is seen in *Fig. 31* $\times 33 \vee$, which shows the corner of this bar. The decarburized layer is seen on the top and left, whilst just within this zone a thickening of the ferrite is seen. This shows that the outer layer had reached the upper critical temperature before work had ceased. This is the steel which has been most refined. Below this we find that the thickening of the ferrite veins occurs right through the steel, or rolling was finished whilst the whole was below Ar_{2-3} . The bar rolled at 667° C., the lowest temperature, is shown in *Fig. 32* $\times 33 \vee$. The coarsening of the ferrite walls is seen throughout the section. The top is near the edge and we have decarburization as before, but here we probably have the traces of cold rolling, for under high powers the ferrite has separated out as flattened forms and the pearlite is often abnormally coarse.

Although no rule can be drawn from one series of experiments, it is evident that, with the methods used, the best finishing temperature is such that the bars leave the rolls as near Ar_{2-3} as possible. The bars would of course have to be drawn from the furnace at a slightly higher temperature, to allow for cooling in the rolls. Making an allowance of say 40° , the rolling temperature would be about 740° C. This agrees with the experimental results shown in the table, for the two bars rolled at 752° and 724° C., respectively, gave the best results. The reason why the bar rolled at 667° C. does not show more traces of cold-rolling is because of the great evolution of heat at the recalescence point.

From the above examples are seen the great changes which occur, not only in iron and steel, but also in other

alloys, and cause a more or less complete rearrangement of structure. As the physical properties vary with the structure, great stress must be laid upon these changes in the solid, and our study of the effects of heat treatment must accompany that of microstructure, because the two go hand-in-hand and help to interpret each other.

THE EMPTY CAR HAUL.

The bane of railroad operation is the empty car haul, and to its reduction the best efforts of the transportation department are being constantly put forth. It is realized that the movement cost of each ton is the same whether it is embodied in the car itself or in its contents, and when it is considered that from 30 to 40 per cent. of the total tonnage moved by railroads consists of empty car haul, the importance of the question is easily understood. In view, therefore, of the magnitude of the subject and the part that it plays in operating expenses, it seems a little strange that a car of general utility, that is to say, one which could be used for two or more special commodities, has not yet been evolved. A number of attempts have been made to provide a car which would answer for both live stock and merchandise, but that appears to be impossible in the nature of things. A car suitable for joint use in coal and live stock traffic, or in coal and merchandise traffic, would seem to be more nearly possible, and we understand efforts are now being made in both of these directions. There is certainly enough to be gained by the production of a successful car of this character to warrant the devotion of the time and energy for its production.—*Railway Age*.

PHOTOLINOL.

Some interesting demonstrations have been carried out in London with a new photographic art material called "photolinol." This fabric is composed of linen, which is thoroughly permeated with the photograph, producing a high translucency. One very picturesque effect obtained by this means is that the picture, when colored and viewed with a reflected light, bears a very strong resemblance to an oil-painting, the lines of the weaving of the linen appearing similar to the canvas in a painting. Photolinol is waterproof and indestructible, while the photograph does not fade in the sun, as it appears to be woven into the material. By its aid much greater enlargements than are now possible can be made with ease. The fabric can be made to any size, some of the enlargements shown being 10 feet square. It is applicable to an extensive variety of purposes. As it is transparent, it can be adapted to lamp shades and other ramifications of photographic art for which transparencies are now employed. Novel results can be obtained with it, for the picture appears with equal distinctness on either side by either reflected or transmitted light. The process is a secret one, but its commercial utility and value are already asserted, since it can be employed for curtains, screens or theatrical scenery. For the latter it is peculiarly adapted, and is both cheaper and more durable than hand-painted scenery.—*Scientific American*.