Theoretical and Experimental Researches on Electric Resistance Welding.

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Chapter I. THEORETICAL INVESTIGATIONS.

§ 1. INTRODUCTION.

In the electric resistance welding process the metals to be welded are brought into intimate contact by being held closely together by metal clamps in butt welding or by electrodes in spot and seam welding, and the contact surfaces are pressed together by springs or levers giving a constant mechanical pressure even after the completion of the process. The metal clamps or electrodes are connected to the secondary terminals of the welding transformer and the heavy current flows through the contact surface and also the parts of the metals to be welded, near the surface. The resistance at the contact surface produces heat and raises the temperature in its immediate neighborhood, thus increasing the electric resistivity of the metal and the heat produced in the metal itself increases rapidly and the temperature rises with acceleration and soon reaches the welding temperature. Heat is also produced at the contact belween the metal to be welded and the metal clamps or electrodes, which offers a comparatively large resistance in the circuit, but this heat is easily carried away by the clamps or electrodes.

Thus the principle underlying the various kinds of electric resistance welding, namely butt, spot, seam or line and even percussion weldings is quite the same for all of them, so that the results of investigation on one or two of them can immediately be applied without any considerable alterations to the others.

In this paper the principle of resistance welding is developed theoretically and experimentally with regard to butt welding and also to percussion welding, which can be regarded as a special kind of resistance welding.

§ 2. WELDING TEMPERATURE.

In resistance welding, as has been mentioned before, the heat is generated at the contact surface and afterwards also in the metal itself, and the temperature begins to rise. When the temperature rises, the electric resistivity of the metal increases and the rate of generation of heat in the metal increases proportionally, thus accelerating the rise of temperature. The heat generated in the heighborhood of the point of contact is partly conducted away through the metal and also lost from the surface in the form of radiation and convection. The time interval, in which the process is completed, is generally short and the temperature rises and falls rapidly, and the maximum temperature in the metal near the point of contact is high, so that the microstructure and accordingly the mechanical properties of the metal more or less undergo a change.

Percussion welding may be regarded as one case of butt welding, in which the time interval becomes very small, indeed even smaller than one hundredth of a second, and in this case the manner of the division of the heat generated at the point of contact into both metals and the temperature distribution determine the weldability of a pair of different kinds of metals and also the quality of the weld.

Let us now try to find, from these points of view, a mathematical solution of the problem of the temperature distribution and variation along the bar or wire to be welded taking into consideration all the important factors, that is, the heat generated at the point of contact and also in the metal due to the electric resistance which increases with the temperature, the conduction of heat through the metal and the transmission into the air.

Let us assume that the two metallic bars to be welded are of the same material and cross section and that the conduction of heat takes place only in the axial direction.

We use the following symbols:

x distance in *cm* from the contact surface.

t time in seconds.

θ temperature in degrees Centigrade at any distance x and time t.

S cross sectional area of the bar in square *cm*.

K conductivity of heat.

σ specific gravity.

C specific heat.

H emissivity from the surface of the bar.

p peripheral length of the cross section of the bar in *cm.*

I welding current in amp.

ρ electric resistivity of the metal in ohms per cubic *cm.*

We consider the elementary volume bounded by the two planes x and $x+dx$, then the rate of gain of heat of this volume in calories per second is

$$\left(KS\frac{\partial^2\theta}{\partial x^2}-H\theta p+0.24\frac{I^2\rho}{S}\right)dx,$$

and this must be equal to

$$SC\sigma dx\frac{\partial\theta}{\partial t},$$

hence we get the following equation :—

$$\frac{\partial\theta}{\partial t}=\frac{K}{C\sigma}\frac{\partial^2\theta}{\partial x^2}-\frac{Hp}{C\sigma S}\theta+0.24\frac{I^2\rho}{C\sigma S^2} \quad \text{.....................(1)}$$

In this equation the electric resistivity ρ is not constant but depends upon the temperature θ. If ρ_0 denote the resistivity at 0°C, then we can put

$$\rho=\rho_0(1+\alpha\theta)$$

and eq. (1) becomes

$$\frac{\partial\theta}{\partial t}=\frac{K}{C\sigma}\frac{\partial^2\theta}{\partial x^2}-\left(\frac{Hp}{C\sigma S}-0.24\frac{I^2\rho_0\alpha}{C\sigma S^2}\right)\theta+0.24\frac{I^2\rho_0}{C\sigma S^2} \quad \text{......(2)}$$

The welding current I is assumed to be constant during the welding time T_0 and becomes zero as soon as the process is completed, hence

$$I=\text{constant, for } 0<t<T_0$$

$$I=0 \quad \text{, for} \quad t>T_0$$

and we put

$$
\left.\begin{aligned}
\varkappa &= \frac{K}{C\sigma} \\
\lambda_1 &= \frac{Hp}{C\sigma S} - 0.24\frac{I^2\rho_0 a}{C\sigma S^2} \\
\lambda_2 &= \frac{Hp}{C\sigma S} \\
a &= 0.24\frac{I^2\rho_0}{C\sigma S^2}
\end{aligned}\right\} \quad \cdots\cdots(3)
$$

Then the equation becomes

$$\frac{\partial\theta}{\partial t} = \varkappa\frac{\partial^2\theta}{\partial x^2} - \lambda_1\theta + a, \text{ for } 0 < t < T_0 \quad \cdots\cdots(4)$$

and

$$\frac{\partial\theta}{\partial t} = \varkappa\frac{\partial^2\theta}{\partial x^2} - \lambda_2\theta, \qquad \text{for } t > T_0 \quad \cdots\cdots(5)$$

In the solution of the equation we assume that the bars to be welded are infinitely long. This assumption is fairly true when we consider that the welding time is comparatively short and that the so-called welding temperature, that is, the temperature high enough to soften the metal or change the microstructure, occurs only in the neighborhood of the contact surface. Furthermore we assume that the flow of heat takes place parallel to the axis of the bars as already stated, as the heat loss from the outer surface is so small if compared with the generated heat that its effect upon the line of flow of heat can be neglected.

Now we proceed to solve equations (4) and (5). If we put

$$\theta = \theta' + \frac{a}{\lambda_1},$$

then eq. (4) becomes

$$\frac{\partial\theta'}{\partial t} = \varkappa\frac{\partial^2\theta'}{\partial x^2} - \lambda_1\theta'. \quad \cdots\cdots(6)$$

Next we put

$$\theta' = ue^{-\lambda_1 t} \quad \cdots\cdots(7)$$

then we get the equation

$$\frac{\partial u}{\partial t}=\varkappa\frac{\partial^2 u}{\partial x^2}\;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

The general solution of this differential equation, as is well known, is as follows:

$$u=\frac{1}{2\sqrt{\pi\varkappa t}}\int_{-\infty}^{+\infty}f(x')e^{-\frac{(x-x')^2}{4\varkappa t}}dx',\;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

where $u=f(x)$ for $t=0$.…………………………………………………(10)

Therefore we have

$$\theta'=\frac{e^{-\lambda_1 t}}{2\sqrt{\pi\varkappa t}}\int_{-\infty}^{+\infty}f(x')e^{-\frac{(x-x')^2}{4\varkappa t}}dx'+\frac{a}{\lambda_1}$$

Now, for $t=0$,

$$f(x')=u=\theta'=\theta-\frac{a}{\lambda_1}=f_0(x')-\frac{a}{\lambda_1},$$

hence we have

$$\theta=\frac{e^{-\lambda_1 t}}{2\sqrt{\pi\varkappa t}}\int_{-\infty}^{+\infty}\left(f_0(x')-\frac{a}{\lambda_1}\right)e^{-\frac{(x-x')^2}{4\varkappa t}}dx'+\frac{a}{\lambda_1}$$

$$=\frac{e^{-\lambda_1 t}}{2\sqrt{\pi\varkappa t}}\int_{-\infty}^{+\infty}f_0(x')e^{-\frac{(x-x')^2}{4\varkappa t}}dx'-\frac{e^{-\lambda_1 t}}{2\sqrt{\pi\varkappa t}}\int_{-\infty}^{+\infty}\frac{a}{\lambda_1}e^{-\frac{(x-x')^2}{4\varkappa t}}dx'$$

$$+\frac{a}{\lambda_1}$$

Putting

$$\frac{x-x'}{2\sqrt{\varkappa t}}=y,\text{ or }-\frac{1}{2\sqrt{\varkappa t}}dx'=dy,$$

$$\int_{-\infty}^{+\infty}e^{-\frac{(x-x')^2}{4\varkappa t}}dx'=2\sqrt{\varkappa t}\int_{-\infty}^{+\infty}e^{-y^2}dy=-2\sqrt{\varkappa t}.\sqrt{\pi},$$

thus we obtain the solution

$$\theta=\frac{e^{-\lambda_1 t}}{2\sqrt{\pi\varkappa t}}\int_{-\infty}^{+\infty}f_0(x')e^{-\frac{(x-x')^2}{4\varkappa t}}dx'+\frac{a}{\lambda_1}\left(1-e^{-\lambda_1 t}\right)\;\ldots\ldots\ldots(11)$$

As to equation (5), we can get the solution if we put $a = 0$ and λ_2 instead of λ_1, thus

$$\theta = \frac{e^{-\lambda_2 t}}{2\sqrt{\pi \kappa t}} \int_{-\infty}^{+\infty} f_0(x') e^{-\frac{(x-x')^2}{4\kappa t}} dx', \quad \text{.............................(12)}$$

where

$$\theta = f_0(x') \text{ for } t = T_0$$

Now let q denote the electric power in watts appearing at the contact surface $x = 0$ at the time T, then the heat quantity which appears during the elementary time interval from T to $T + dT$ is expressed by qdT and the temperature rise $d\theta$ at any time t due to this heat is given by

$$d\theta = \frac{e^{-\lambda_1(t-T)}}{2\sqrt{\pi \kappa(t-T)}} \int_{-\infty}^{+\infty} f_0(x') e^{-\frac{(x-x')^2}{4\kappa(t-T)}} dx'$$

$$+ \frac{a}{\lambda_1}\left\{1 - e^{-\lambda_1(t-T)}\right\} - \frac{a}{\lambda_1}\left\{1 - e^{-\lambda_1(t-T-dT)}\right\}.$$

But, when t tends to T, θ tends to $f_0(x')$ and is zero except in the immediate neighborhood of the plane $x = 0$. Hence we get

$$\int_{-\infty}^{+\infty} f_0(x') e^{-\frac{(x-x')^2}{4\kappa(t-T)}} dx' = \int_{-\varepsilon}^{+\varepsilon} f_0(x') e^{-\frac{x^2}{4\kappa(t-T)}} dx'$$

$$= \frac{0.24\, qdT}{C\sigma S} e^{-\frac{x^2}{4\kappa(t-T)}}$$

Therefore

$$d\theta = \frac{0.24\, qdT}{2C\sigma S\sqrt{\pi \kappa}} \cdot \frac{e^{-\frac{x^2}{4\kappa(t-T)} - \lambda_1(t-T)}}{\sqrt{t-T}} dT$$

$$+ a e^{-\lambda_1(t-T)} dT.$$

Integrating this from 0 to t we have

$$\theta = \frac{0.24}{2C\sigma S\sqrt{\pi \kappa}} \int_0^t \frac{q e^{-\frac{x^2}{4\kappa(t-T)} - \lambda_1(t-T)}}{\sqrt{t-T}} dT$$

$$+ \frac{a}{\lambda_1}\left(1 - e^{-\lambda_1 t}\right) \quad \text{...(13)}$$

Now q is the electric power appearing at the contact surface and is maximum at the beginning of the welding process but diminishes pretty rapidly owing to the melting of the contact surfaces and becomes very small when the process approaches its end.
Suppose q to be expressed by a function of T, thus

$$q = F(T),$$

and putting $t-T=t'$ we have

$$\theta = \frac{0.24}{2C\sigma S\sqrt{\pi\varkappa}}\int_0^t \frac{F(t-t')e^{-\frac{x^2}{4\varkappa t}-\lambda_1 t'}}{\sqrt{t'}}dt' + \frac{a}{\lambda_1}\left(1-e^{-\lambda_1 t'}\right).$$

If we put, for the sake of convenience, τ and t in place of t and t' respectively, then we have

$$\theta = \frac{0.24}{2C\sigma S\sqrt{\pi\varkappa}}\int_0^\tau \frac{F(\tau-t)e^{-\frac{x^2}{4\varkappa t}-\lambda_1 t}}{\sqrt{t}}dt$$

$$+\frac{a}{\lambda_1}\left(1-e^{-\lambda_1\tau}\right) \qquad (14)$$

This gives the temperature at any distance x and time τ during the welding process or for $\tau < T_0$. The function $F(\tau-t)$ is given by the product of the current and the voltage across the contact surface, these quantities being given by the oscillograms which shall be shown afterwards.

In order to solve this equation and find the temperature exactly we must know in the first place the form of the function $F(\tau-t)$ and then find the integration by means of the graphical method as we will explain in the following chapters.

If we can be satisfied with an approximate result, not so exact as that obtained by the above mentioned graphical method, we cause the function $F(\tau-t)$ to be expressed by an exponential function as follows:—

$$F(\tau-t) = q_0 e^{-\gamma(\tau-t)},$$

where q_0 is the initial value of the power q and the coefficient γ is to be found by proper means on the curve representing the function.

Then we get the following solution after several substitions and transformations,

$$\theta = \frac{0.24\, q_0 e^{-\gamma\tau}}{2C\sigma S\sqrt{\pi\chi}.k}\left[e^{2hk}\left\{\Phi\left(\frac{h}{\sqrt{\tau}}+k\sqrt{\tau}\right)-1\right\}\right.$$

$$\left.-e^{-2hk}\left\{\Phi\left(\frac{h}{\sqrt{\tau}}-k\sqrt{\tau}\right)-1\right\}\right]+\frac{a}{\lambda_1}\left(1-e^{-\lambda_1\tau}\right), \quad \text{...........(15)}$$

where

$$h = \frac{x}{2\sqrt{\chi}}, \quad k = \sqrt{\lambda_1 - \gamma}$$

and $\Phi(y) = \int_0^y e^{-z^2}dz$, the numerical values of which can be found in mathematical tables.

In the next place the temperature θ at any distance x and time t greater than T_0, namely after the process is completed and the welding current is cut out, can be found by applying the graphical method to eq. (12).

§ 3. THEORY OF PERCUSSION WELDING.

In this welding the stored energy of a condenser or an electro-magnet is utilized as the energy source and this is discharged through the contact surface, the heat being concentrated quite near the surface. Thus the duration of the welding current is very small and the process is completed almost instantaneously. Therefore we can regard this as a special case of butt welding, where the welding time T_0 may be assumed infinitely small.

In this case the heat generation in the metal itself due to the current and electric resistance is negligibly small, therefore we can put

$$a = 0$$

$$\lambda_1 = \frac{Hp}{C\sigma S} = \lambda$$

Now let Q denote the energy in joules which appears on the contact, then we have

$$\int_{-\infty}^{+\infty} f_0(x')dx' = \int_{-\varepsilon}^{+\varepsilon} f_0(x')dx' = \frac{0.24Q}{C\sigma S},$$

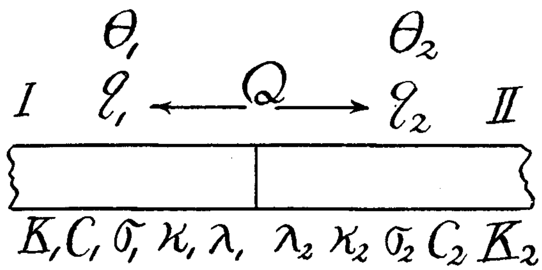
and hence

$$\theta = \frac{0.24\,Q}{2C\sigma S\sqrt{\pi k}} \cdot \frac{e^{-\frac{x^2}{4\kappa t}-\lambda t}}{\sqrt{t}} \quad \dots\dots\dots(16)$$

This gives the temperature at any distance x and time t when two wires of the same material and cross section are welded. But this is not the case when two wires of different kinds of material are welded together.

Fig. 1 shows two wires of the same cross section but of different

Fig. 1.



physical constants as the suffixes show. Let Q be divided and conducted into respective wires as q_1 and q_2 and their temperatures be denoted by θ_1 and θ_2 respectively, then we have

$$\left.\begin{aligned} \theta_1 &= \frac{0.24\,q_1}{C_1\sigma_1 S\sqrt{\pi\kappa_1}} \cdot \frac{e^{-\frac{x^2}{4\kappa_1 t}-\lambda_1 t}}{\sqrt{t}} \\ &\text{and} \\ \theta_2 &= \frac{0.24\,q_2}{C_2\sigma_2 S\sqrt{\pi\kappa_2}} \cdot \frac{e^{-\frac{x^2}{4\kappa_2 t}-\lambda_2 t}}{\sqrt{t}} \end{aligned}\right\} \quad \dots\dots\dots(17)$$

But these temperatures becomes equal as the distance x tends to zero, hence we have

$$\frac{0.24\,q_1}{C_1\sigma_1 S\sqrt{\pi\kappa_1}} \cdot \frac{e^{-\lambda_1 t}}{\sqrt{t}} = \frac{0.24\,q_2}{C_2\sigma_2 S\sqrt{\pi\kappa_2}} \cdot \frac{e^{-\lambda_2 t}}{\sqrt{t}}$$

or

$$\frac{q_1}{q_2} = \frac{C_1\sigma_1\sqrt{\kappa_1}}{C_2\sigma_2\sqrt{\kappa_2}} e^{(\lambda_1-\lambda_2)t} = \sqrt{\frac{C_1\sigma_1 K_1}{C_2\sigma_2 K_2}} e^{(\lambda_1-\lambda_2)t} \quad \dots\dots\dots(18)$$

Now the constant λ is usually small as the emissivity H is fairly small in the case of metals as will be shown numerically afterwards, say 0.002 for iron, and moreover the time t is also small; accordingly the exponent $(\lambda_1-\lambda_2)t$ is really very small and the above equation may be written

$$\frac{q_1}{q_2}=\frac{\sqrt{C_1\sigma_1K_1}}{\sqrt{C_2\sigma_2K_2}} \qquad \text{(19)}$$

This shows that the heat quantity which appears at the contact surface is divided and conducted into two wires in proportion to the square root of the product of specific heat, specific gravity and thermal conductivity.

As

$$\frac{q_1}{\sqrt{C_1\sigma_1K_1}}=\frac{q_2}{\sqrt{C_2\sigma_2K_2}}=\frac{Q}{\sqrt{C_1\sigma_1K_1}+\sqrt{C_2\sigma_2K_2}}$$

we have

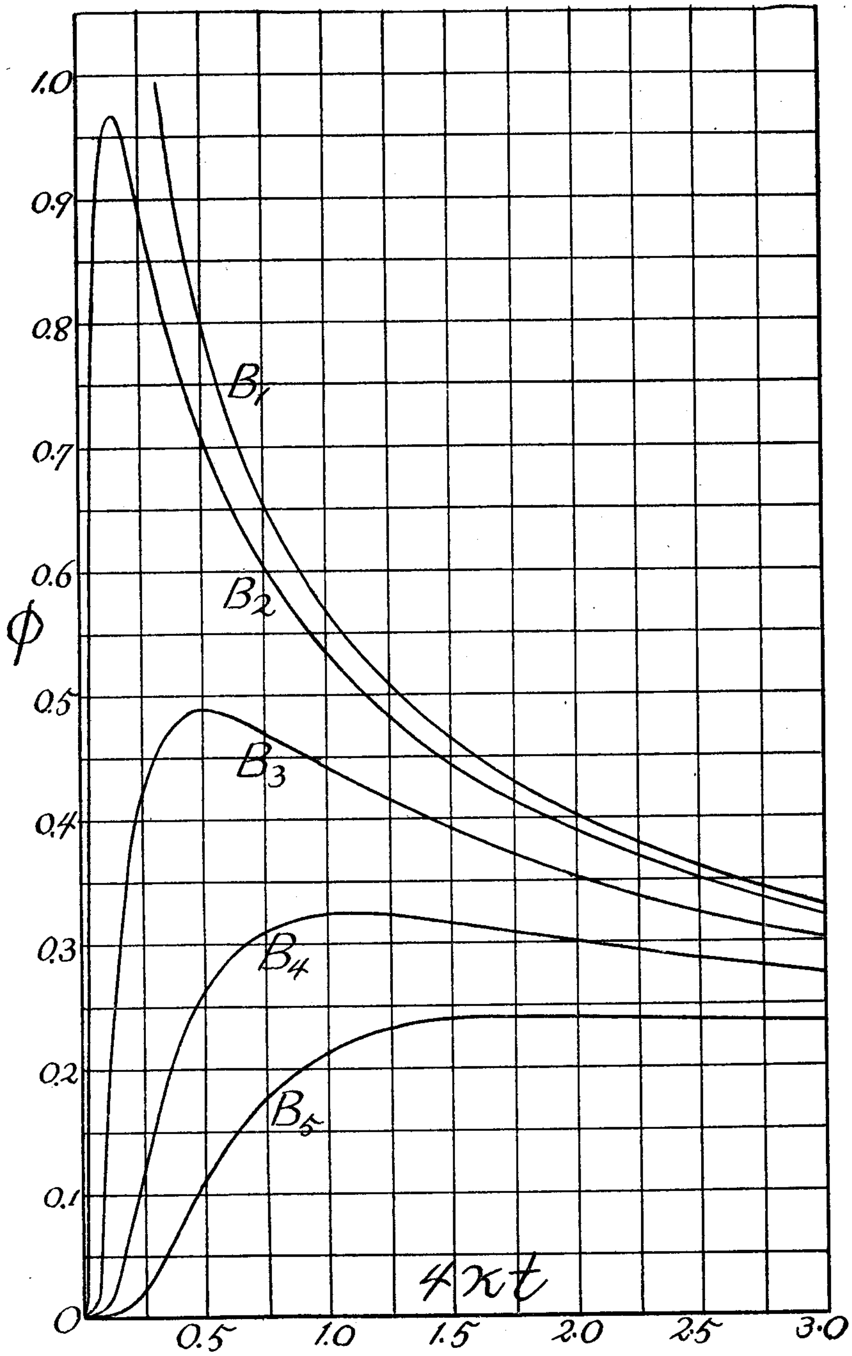
$$\left.\begin{aligned}\theta_1&=\frac{0.24\,Q}{(\sqrt{C_1\sigma_1K_1}+\sqrt{C_2\sigma_2K_2})S\sqrt{\pi}}\cdot\frac{e^{-\frac{x^2}{4\varkappa_1t}-\lambda_1t}}{\sqrt{t}}\\ \theta_2&=\frac{0.24\,Q}{(\sqrt{C_1\sigma_1K_1}+\sqrt{C_2\sigma_2K_2})S\sqrt{\pi}}\cdot\frac{e^{-\frac{x^2}{4\varkappa_2t}-\lambda_2t}}{\sqrt{t}}\end{aligned}\right\} \qquad \text{(20)}$$

If we neglect λ_1 and λ_2 we have

$$\left.\begin{aligned}\theta_1&=\frac{2\times0.24\sqrt{\varkappa_1}\,Q}{(\sqrt{C_1\sigma_1K_1}+\sqrt{C_2\sigma_2K_2})S}\cdot\frac{e^{-\frac{x^2}{4\varkappa_1t}}}{2\sqrt{\pi\varkappa_1t}}\\ \theta_2&=\frac{2\times0.24\sqrt{\varkappa_2}\,Q}{(\sqrt{C_1\sigma_1K_1}+\sqrt{C_2\sigma_2K_2})S}\cdot\frac{e^{-\frac{x^2}{4\varkappa_1t}}}{2\sqrt{\pi\varkappa_1t}}\end{aligned}\right\} \qquad \text{(21)}$$

In these equations the expression $\dfrac{e^{-\frac{x^2}{4\varkappa t}}}{2\sqrt{\pi\varkappa t}}$, which we denote with the symbol ϕ, is numerically calculated and shown graphically with curves in Carslaw's „The Conduction of Heat", 2nd Edition, p.155, as is shown heré in Fig. 2.

Fig. 2.



If we take t in the abscissa instead of $4xt$ in this diagram, the curves would shrink towards the ordinate axis inversely proportionally to the value of x, that is to say, the temperature at any point would reach its maximum value and again cool the more rapidly, the larger the value of x is. The maximum value of the temperature at any point is proportional to the value of $\sqrt{x}$ as is evident from eq. (21).

In Fig. 2 the curves B_1, B_2, B_3, B_4 and B_5 represent the values of ϕ for $x = 0, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$ and 1.0 cm respectively.

Although the welding time is made very small in this welding, the temperature at the contact surface rises very high and we can not therefore avoid more or less the unwelcome phenomena of the oxidization of metals such as aluminium or the vaporization and escaping away of a certain component in alloys such as zinc in brass, thus making the welded joint somewhat defective. In the case of welding a pair of different kinds of metals, the fused metals near the joint could sometimes form an alloy, the toughness or strength of which would exert an influence upon the welding ability of the pair.

These factors, which have not a small effect on the weldability, depend, however, largely on the chemical properties of metals and must be considered for individual cases of welding any combination of different metals.

In the following theory we are going to make clear how the metals behave under the influence of temperature distribution only from the physical point of view, namely, the melting and intermingling of both metals, forming thus a good joint. If this is not the case, although the metal on one side has softened or melted, that on the other side remains still in the solid state and the boundary between the two metals will show a sharp plane of demarkation, as would be the case if molten wax were dropped on a cold metallic surface.

If a good fusion be desired, the maximum temperatures at some small distance δ from the contact surface must be greater than the melting points of the respective metals. Now let θ_1 and θ_2 be the temperatures at the distance δ, then we have

$$\frac{\theta_1}{\theta_2} = e^{\frac{\delta^2(\varkappa_1-\varkappa_2)}{4\varkappa_1\varkappa_2 t}+(\lambda_2-\lambda_1)t}$$

As the value of $\varkappa$ is much larger than that of λ and moreover the time t is very small, we can neglect the term $(\lambda_2-\lambda_1)t$ and put

$$\frac{\theta_1}{\theta_2} = e^{\frac{\delta^2(\varkappa_1-\varkappa_2)}{4\varkappa_1\varkappa_2 t}} \qquad \text{.........................(22)}$$

Hence we have the following relation :—

$$\left.\begin{array}{l} \theta_1 \gtreqless \theta_2 \\ \text{according as} \\ \varkappa_1 \gtreqless \varkappa_2 \end{array}\right\} \qquad \text{.........................(23)}$$

As the temperatures θ_1 and θ_2 must be greater than and desirably proportional to the melting points of the respective metals, these melting points must consequently be in the same order of value as the quantities $\varkappa_1$ and $\varkappa_2$. If this condition be satisfied both metals melt simultaneously and intermingle together, thus forming a good joint.

In the following table the numerical values of C, σ, K, $\varkappa$, $\sqrt{C\sigma K}$ and melting points of various metals and alloys are shown.

Table 1.

Metals and alloys	C	σ	K	$\varkappa$	$\sqrt{C\sigma K}$	$\sqrt{C\sigma K}$ in %	Melting point
Aluminium	0.22	2.7	0.49	0.819	0.54	62	657
Cadmium	0.056	8.6	0.21	0.444	0.318	37	321
Iron	0.12	7.8	0.15	0.16	0.374	43	1500
Gold	0.031	19.3	0.70	1.18	0.648	75	1064
Copper	0.095	8.95	0.88	1.09	0.865	100	1065
Nickel	0.11	8.90	0.14	0.136	0.37	43	1452
Platinum	0.032	21.4	0.17	0.245	0.341	39	1745
Silver	0.057	10.5	0.99	1.67	0.77	89	962
Zinc	0.095	7.19	0.26	0.39	0.422	49	419
Tin	0.056	7.3	0.14	0.332	0.239	27	232
Tungsten	0.0338	19.1	0.383	0.59[a]	0.498	58	3200
Antimony	0.05	6.67	0.040	0.12[a]	0.115	13	630
Bismuth	0.0303	9.8	0.016	0.0546	0.069	8	271
Iridium	0.0323	22.4	0.133[e]	0.184[a]	0.31	36	2350
Molybdenum	0.0647	10.2	0.34[e]	0.515	0.474	55	2500

Metals and alloys	C	σ	K	x	$\sqrt{C\sigma K}$	$\sqrt{C\sigma K}$ in %	Melting point
Paradium	0.0617	11.5	0.182	0.242	0.36	42	1550
Rodium	0.058	12.1	0.19(e)	0.271(a)	0.365	42	1970
Constantan	0.102	8.88(c)	0.064	0.071	0.241	28	1290(d)
Manganin	0.10	8.5(c)	0.063	0.0746	0.232	27	—
German silver	0.095	8.44(b)	0.089	0.129	0.268	31	1100(b)
Brass	0.092	8.45(b)	0.254	0.372	0.445	51	900(b)
Bronze	0.104	8.8(c)	0.17	0.217	0.395	46	900(b)

In the above table the values of C, K and x are those at about 100°C and $\sqrt{C\sigma K}$ and those values of x marked with (a) were calculated from K, C and σ. The values of $\sqrt{C\sigma K}$ in percentage are based on that of copper, which is the largest and taken as 100.

These constants were found for the most part in Landolt, Roth and Börstein's Tabellen, but those lacking there, and marked (b), (c), (d) and (e) in the above list, were found in the following references:—

(b) : Pender's Handbook for Electrical Engineers

(c) : Kaye's Tables

(c) : Abraham's Constantes Physiques

(d) : Smithsonian's Physical Tables.

From the above table we have picked out those combinations of metals which can possibly be welded with success. They are as follows:—

aluminium—silver, aluminium—cadmium, aluminium—gold, aluminium—copper, alumium—tin, iron—nickel, iron—platinum, iron—paradium, iron—rodium, gold—copper, gold—silver, copper—silver, nickel—platinum, nickel—paradium, nickel—rodium, platinum—molybdenum, platinum—paradium, platinum—rodium, platinum—tungsten, tungsten—iridium, tungsten—molybdenum, tungsten—paradium, tungsten—rodium.

The following combinations of metals can not be welded with succes:—

aluminium—iron, aluminium—nickel, iron—silver, copper—nickel, copper—platinum, nickel—silver.

Chapter II. EXPERIMENTAL INVESTIGATIONS OF PERCUSSION WELDING.

§ 1. WELDING TIME, CURRENT AND VOLTAGE.

The apparatus used for our experiments was a Westinghouse percussion welder of style No. 457388, which is able to weld wires of a diameter up to 3/16 inch.

In the first place we welded various kinds of metal and alloy wires of B.S. No. 12 and also some combinations of them, and took oscillograms of the welding current and the voltage across the contact surface and thence found the welding time and the heat quantity which is produced at the contact.

These oscillograms are shown in Fig. 3. The flatter and longer curve is of the current, and the peaky and shorter one is of the voltage. The manner of change of the voltage is somewhat different for different kinds of metals.

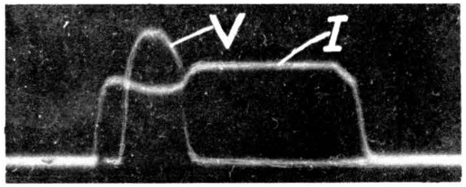
Direct current of 110 volts was used as the electric source and the current flowing through the contact surface of two wires was interrupted by separating the two contact surfaces by a small gap of about 0.5 mm for a very short time. A spark discharge through this air gap takes place and the welding heat is then produced. The voltage curve lasts only during the spark discharge.

In these oscillograms the time is taken as abscissa and 10 mm corresponds to 0.0105 second and 10 mm of the ordinate corresponds to 103 amp. for current and 17.8 volts for voltage.

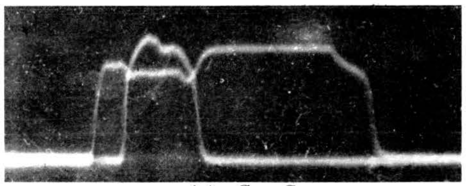
Now the durations of the voltage curves are for the most part are about 9 mm, which corresponds to 0.0095 sec. Hence we can ascertain that the spark discharge lasts only for a very short time, even less than one-hundrecth of a second and in this very short interval the welding process is finished.

By way of example. let us estimate the heat energy which is produced between the contact surfaces and then calculate the maximum temperature at a small distance from the contact, and make clear how the

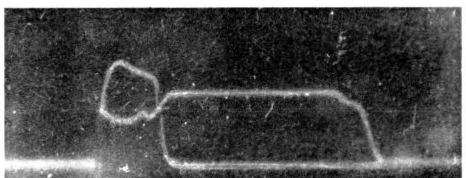
Fig. 3.



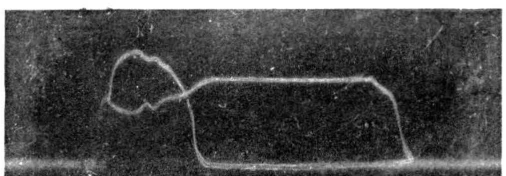
(1) Fe–Fe



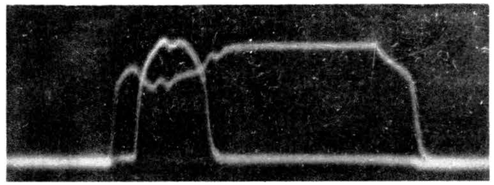
(2) Cu–Cu



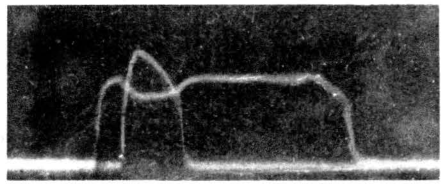
(3) Al–Al



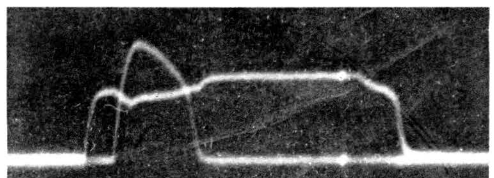
(4) Ag–Ag



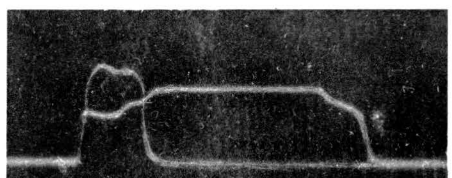
(5) Nichrome



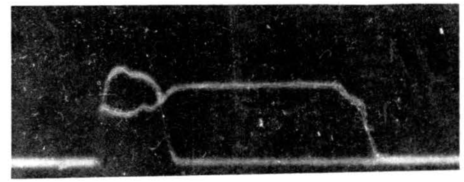
(6) Brass



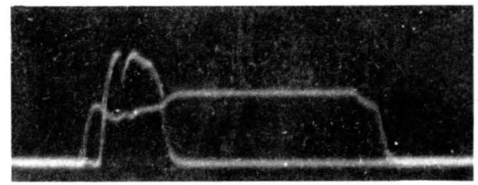
(7) German Silver



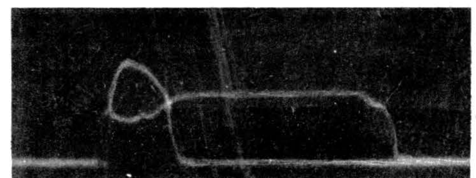
(8) Manganin



(9) Ag–Fe



(10) Cu–Al



(11) Ag–Al

influence of the temperature rise is limited to within a very short distance from the joint.

As is evident from the oscillogram (1), the manners of variation of the corresponding magnitudes of the voltage and the current have rather an opposite tendency. Hence we have taken the maximum value 28.5 volts for the voltage and the minimnm value 92.7 amperes for the current and their product, 2640 watts, for an approximate value of the electric power developed at the contact surface.

As the time interval is $\frac{1}{100}$ second, the energy converted to heat is 26.4 joules and the temperature θ becrmes

$$\theta = \frac{0.24\,Q}{2C\sigma S\sqrt{\pi\varkappa}} \cdot \frac{e^{-\frac{x^2}{4\varkappa t}-\lambda t}}{\sqrt{t}}$$

or neglecting the term λt

$$\theta = \frac{0.24\,Q}{C\sigma S} \cdot \frac{e^{-\frac{x^2}{4\varkappa t}}}{2\sqrt{\pi\varkappa t}},$$

where, as we shall show afterwards,

$$C = 0.165$$

$$\sigma = 7.8$$

$$S = \frac{\pi \times 0.2^2}{4} = 0.0314$$

$$\varkappa = 0.07.$$

For the value of the function $\phi = \frac{e^{-\frac{x^2}{4\varkappa t}}}{2\sqrt{\pi\varkappa t}}$ we refer to Fig. 2 and, as to a distance $x = 0.25$ cm, the temperature becomes maximum at 0.6 second and the maximum value is about 150°C.

As this example shows, the maximum temperature along the wire decreases very rapidly as the distance from the joint increases, and accordingly the effect of temperature on the metal, that is, the melting or the microstructural change and consequently the change of the mechanical properties of the wire is restricted to a small distance from the contact surtace.

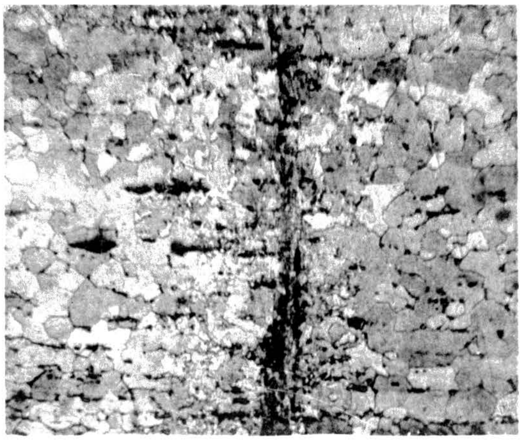
For this reason we can regard this as an extreme case of the butt welding process, where the welding time and the energy consumption is made as small as possible.

§ 2. METALLOGRAPHICAL OBSERVATIONS OF PERCUSSIVE WELDED JOINTS.

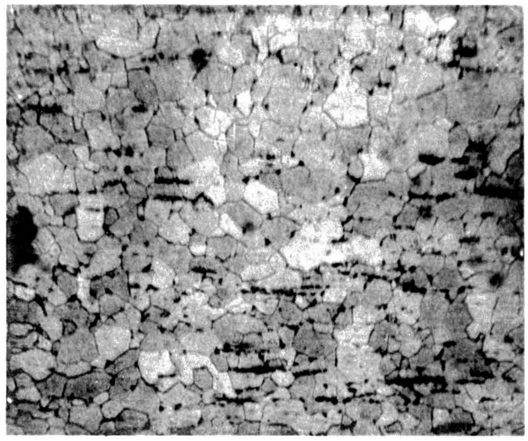
Fig. 4 shows microphotographs of longitudinal sections of percussive welded joints of various metal and alloy wires and some of their combinations. They are all magnified 200 times.

(1) shows the structure at the joint of iron wires; (2) that at a distance of 0.5 mm from the above joint; (3) that at the joint of copper wires; (4) that at a distance of 0.5 mm; (5) that at a distance of 1.0 mm; (6) that at a distance of 2.0 mm from the above joint; (7) that at the joint of iron and copper wires which shows a sharp line of demarkation, because this pair belongs to the group difficult to be welded; (8) that at the joint of silver and copper wires which shows a fairly good intermingling of both metals; (9) that at the joint of brass wires, along which we can recognize a stripe of light red color, this being perhaps a thin layer of copper as the other constituent, i. e. zinc vaporizes and escapes away, thus forming a weak joint; (10) that at the joint of copper and aluminium wires, which shows a good intermingling of both metals as the relation between the melting point and x is very favorable; (11) that at the joint of silver and aluminium showing a fairly gocd intermingling of both metals; (12) that at the joint of iron and silver wires showing a distinct line of demarkation; (13) that at the joint of german silver wires, the vaporization of zinc leaving a thin layer of the other constituents along the joint; (14) that at the joint of iron and aluminium wires showing a defective weld; (15) that at the joint of nichrome wires, showing a perfect weld; (16) that at the joint of manganin wires showing a thin layer as in the cases of brass and german silver wires; (17) that at the joint of alumium wires showing a fairly good weld but a small crack and

Fig. 4. (1)



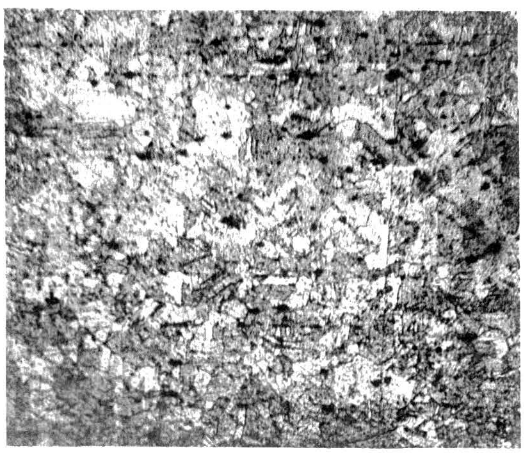
(1) Fe—Fe



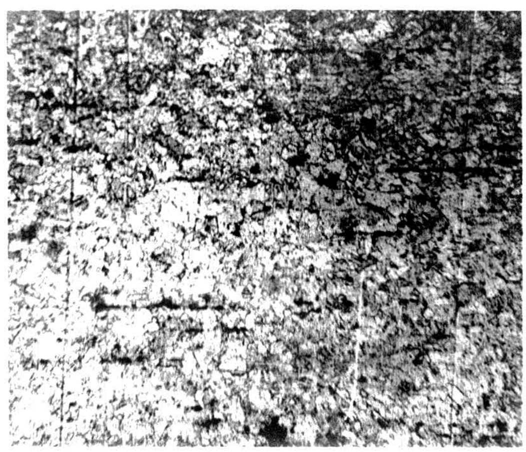
(2) Fe

(3) Cu – Cu

(4) Cu

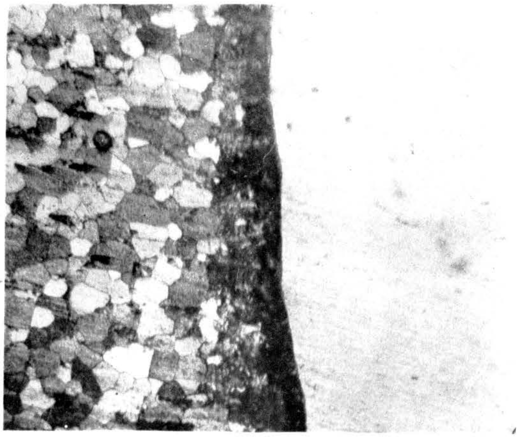


(5) Cu

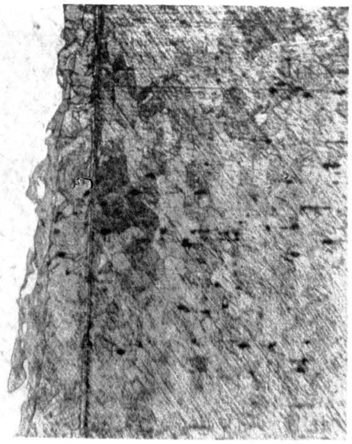


(6) Cu

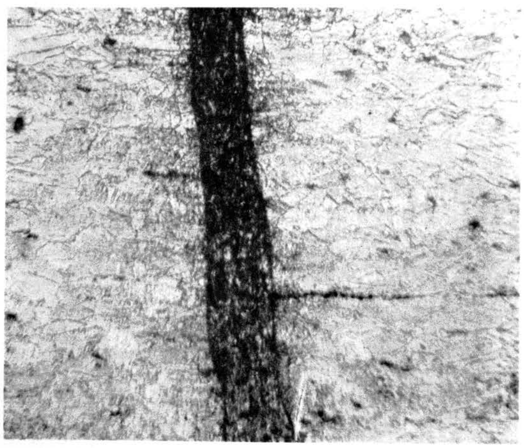
Fig. 4. (2)



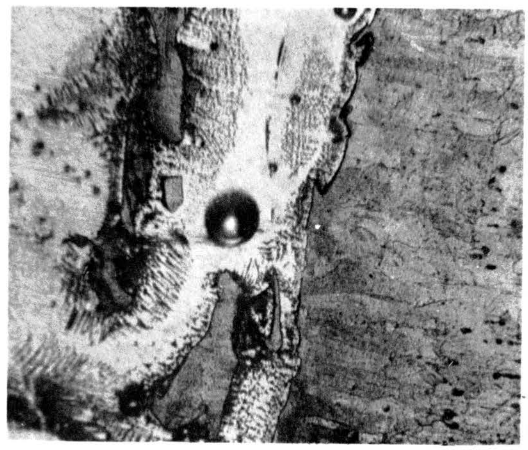
(7) Fe—Cu



(8) Ag—Cu



(9) Brass

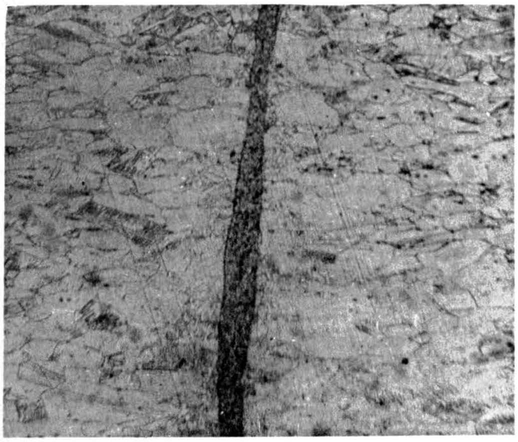


(10) Al—Cu

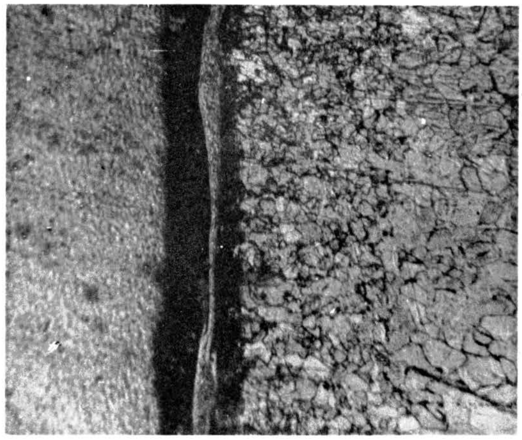
(11) Ag—Al

(12) Ag—Fe

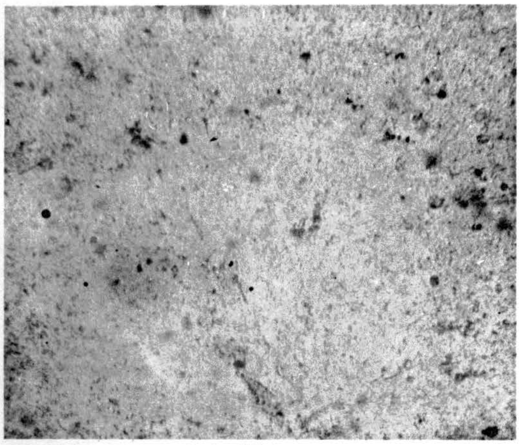
Fig. 4. (3)



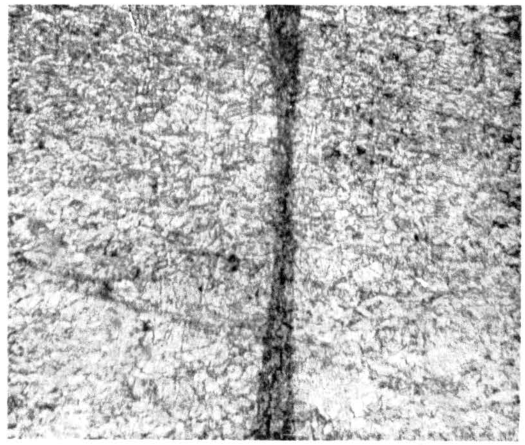
(13) German silver



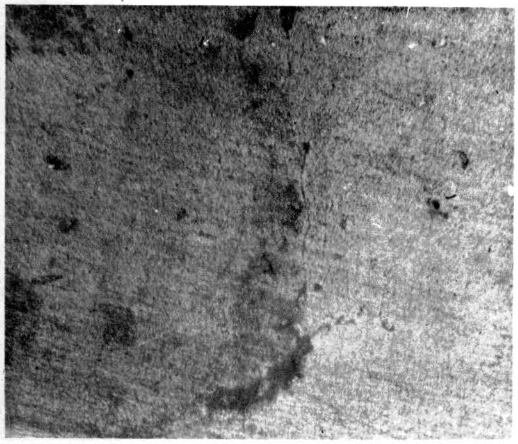
(14) Al—Fe



(15) Nichrome



(16) Manganin



(17) Al—Al

an oxidized spot at the periphery, which can not be avoided notwithstanding the short duration of the welding operation. The iron, copper and silver wires are welded with great success and the welded wire can be easily bent 180 degrees at the joint without revealing any crack.

Chapter III. DISTRIBUTION AND CHANGE OF TEMPERATURE IN BUTT WELDING.

§ 1. PROPERTIES OF METALS AND THEIR ADAPTABILITY FOR WELDING.

The heat quantity necessary to bring about the welding temperature is produced at the first outset in the contact surface and then afterwards in the metal itself in the neighborhood of the joint due to the increasing resistivity of the metal. In most cases the latter is more important and therefore the resistivity and its temperature coefficient have not a little effect on the result of welding.

There is another important factor which affects the result as much as the above two. This is the thermal conductivity of the metal. The heat produced near the contact surface is conducted away in both directions and accordingly the higher the valve of the conductivity is, the more difficult is it for the temperature to rise. As a general rule a metal which has a low value of electric resistivity has unfortunately a high value of thermal conductivity, and hence for such a metal the heat quantity produced near the joint is comparatively small and even this is carried away quickly and it is somewhat difficult to concentrate the intense heat near the joint. In such a case we require more time to get the welding temperature and as in the meanwhile the hot metal is oxidized especially at the periphery of the contact surface, a defective weld is obtained.

From this point of view, iron or steel is much more favorable than copper which it is rather difficult to weld by this proeess. Brass can be welded with success almost as well as steel, but aluminium is very difficult to weld because the oxidization of this metal is very quick at the high temperature.

In this welding process the electric resistivity, its temperature coefficient, the thermal conductivity, the speed of oxidization, the melting temperature and other physical and chemical properties determine the adaptability of the metal fɔr welding, bnt in the actual operation the result of welding depends much upon the selection of the welding current, the welding time, the spring pressure and the amount of the travel.

§ 2. WELDING CURRENT, VOLTAGE AND POWER.

We have recoaded by an oscillograph the manners of variation of the welding current which flows through the material to be welded, the voltage drop across the contact surface and that between the clamping block and the material to be welded, on films which were rotated slowly with a uniform speed.

As to the welding current, the primary current I_1 of the transformer has been recorded and the corresponding secondary current I has been obtained by multiplying the former by the number of turns of the primary coil, the number of turns of the secondary being only one.

All the preliminary experimental data and constants concerning the welding transformer and the oscillograph that are necessary to calculate the current, voltage, power and other numerical values are omitted here, as they have already been publisfied in detail in the original paper.

Fig. 5 shows the oscillograms of the primary current I_1 of the welding transformer, the voltage drop across the contact surface V_a, and that between the clamping block and the material to be welded, V_c. The voltage V_a is maximum at the outset of the welding process but decreases fairly rapidly and becomes zero after the lapse of a few seconds, as the contact surfaces fuse together and the contact resistance between them soon disappears. On the oscillogram, however, the voltage V_a does not disappear as it ought. This is owing to the fact that the voltage is measured between two terminals which are attached to two points each 1 mm, apart from the contact surface and hence the voltage drop in the material itself due to the electric resistance between these two points is contained in it. As to the welding current I_1, we see that the amplitude

Fig. 5. (1)

(1)

(2)

(3)

(4)

(5)

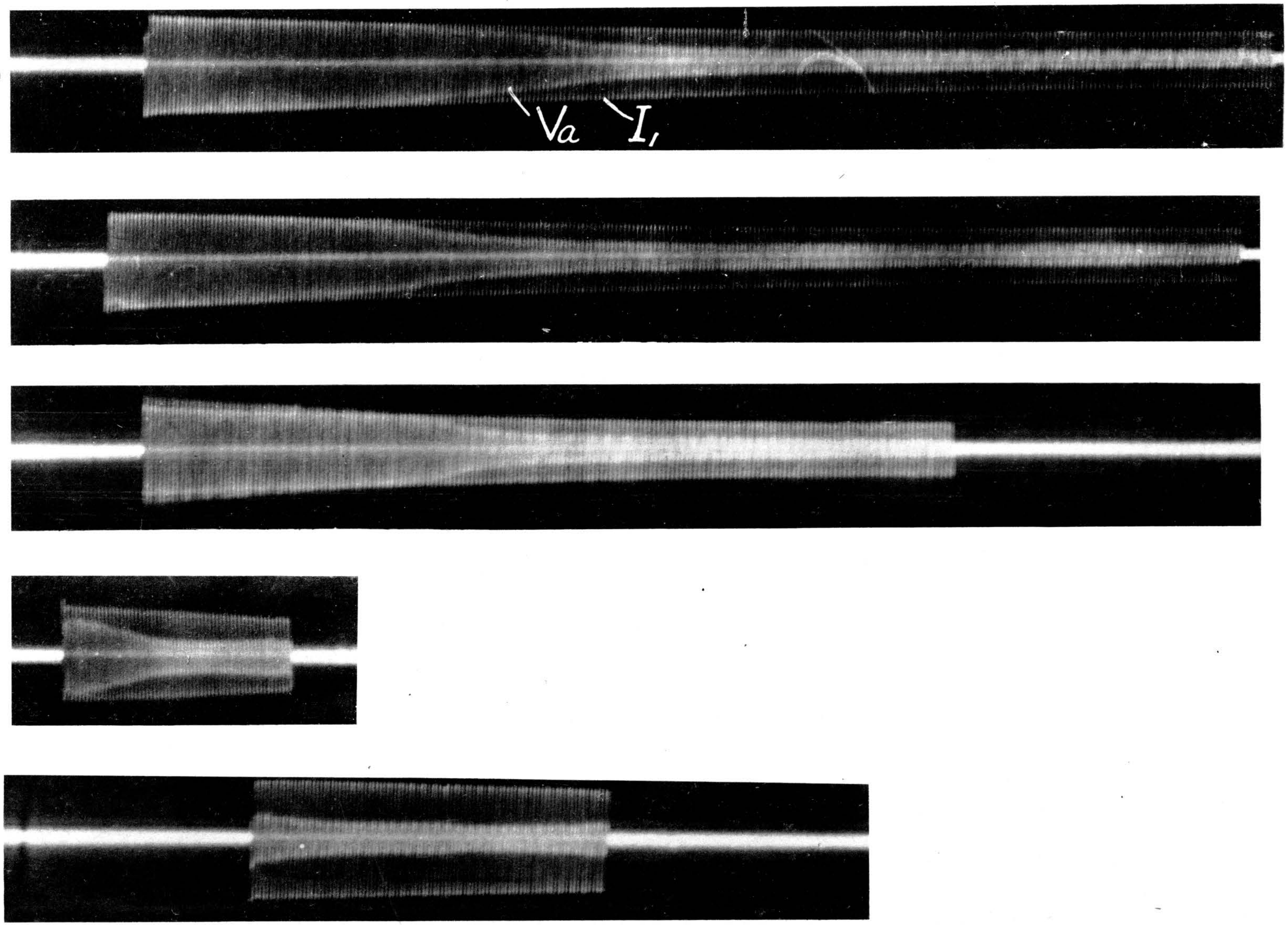
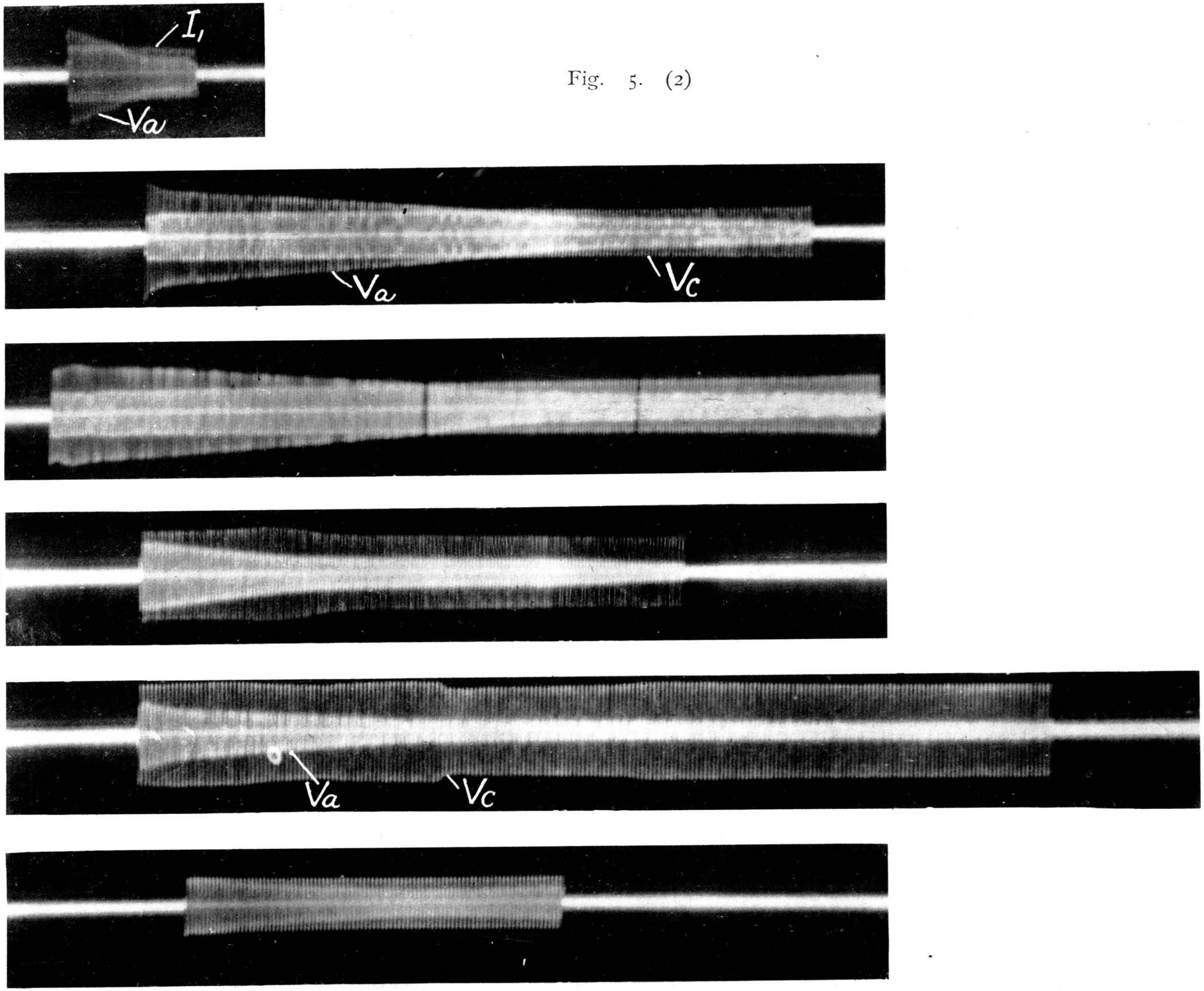


Fig. 5. (2)



(6) (7) (8) (9) (10) (11)

remains fairly constant throughout the welding time, especially when the material to be welded is of a comparatively large cross section and of a rather low resistivity and temperature coefficient, as the change of the resistance in the neighborhood of the joint does not affect so much the total resistance of the secondary circuit of the welding transformer.

We have measured at the same time by a stopwatch the welding time T_0 from the instant of closing the switch to the instant of opening the circuit by an automatically operated trip switch and also the energy consumption W_0 for each welding process by a standard watt-hour meter inserted on the primary side of the transformer.

We have from these calculated the mean input power P_0 of the transformer by the following formula.

$$P_0 = \frac{W_0 \times 60 \times 60}{T_0},$$

where W_0 is expressed in watt-hours, T_0 in seconds and P_0 in watts.

In the following table we have tabulated the above mentioned data for each oscillogram. The materials welded were round bars of soft steel, copper and brass. The currents and voltages are their effective values in amperes and volts respectively, and V_2 denotes the secondary no load voltage of the transformer.

No. of oscil.	Materials welded	I_1	I	V_a	V_c	T_0	P_0	V_2
(1)	1 cm dia. steel bar	30.0	3360	0.623	—	4.4	6.30	1.96
(2)	"	29.0	3250	0.643	—	4.6	6.10	1.96
(3)	"	42.0	4150	0.683	—	3.0	8.52	2.22
(4)	B.S. No. 4 copper bar	34.7	4820	0.120	—	1.0	6.65	1.58
(5)	B.S. No. 3 copper bar	26.5	3680	0.135	—	1.8	5.40	1.58
(6)	B.S. No. 4 brass bar	27.0	3750	0.270	—	0.65	5.50	1.58
(7)	1 cm dia. steel bar	—	—	0.760	0.283	3.2	8.21	2.22
(8)	"	—	—	0.675	0.297	4.4	6.13	1.96
(9)	5/16 " dia. steel bar	—	—	0.462	0.455	2.8	5.78	2.22
(10)	"	—	—	0.442	0.560	3.6	5.60	2.22
(11)	B.S. No. 3 copper bar	—	—	0.160	0.140	1.6	6.30	1.58

From these oscillograms and the data given in the table we can find various important facts.

The voltage drop V_a is much smaller for copper bars than for steel ones as is evident from (4), This is owing to the fact that the contact resistance of copper bars is small compared with that of steel bars. Moreover the electric resistivity and its temperature coefficient for copper are smaller than those for steel and the thermal conductivity is on the contrary much larger than that of steel, therefore we must make the current density much larger for copper than for steel and shorten the welding time as much as possible. These circumstances can easily be understood when we see that the current density is 5300 amp. per sq. cm for the steel bar of oscillogram (3) and 22700 amperes per sq. cm for the copper bar of oscillogram (4).

Brass bars are more easily welded than copper bars, because the contact resistance and the electric resistivity of brass are larger than those of copper and on the contrary the thermal conductivity is much less than that of copper as can be seen from oscillogram (6).

The oscillograms from (7) to (11) show simultaneously the voltage drops V_a and V_c. Although the former decreases in its amplitude fairly rapidly, the latter remains almost constant throughout the welding process, and the amount of this voltage drop depends largely upon the condition of the surface of the bar, as is evident when we compare oscillograms (7) and (8) with (9) and (10), the former two having lathed and well-polished surfaces and the latter two being ordinary soft steel bars on the market and having rough surfaces with a greyish color.

The voltage drop V_a is comparatively small and hence the heat quantity which appears on the contact surface is pretty small quite contrary to our expectation, and the heat necessary to raise the temperature is rather produced in the metal itself in the immediate neighborhood of the joint due to the increasing electric resistance and the heavy current flowing through it. Therefore it is far more difficult and requires a much larger current density to weld copper hars than steel or brass bars.

The voltage drop V_c occurs on both sides of the joint and the power loss due to this amounts to $2V_cI$, which is unexpectedly large. Now let us calculate how much of the electric power which enters the primary of the transformer is really utilized in the welding operation, that is to say, to heat the contact surface and the part of the materials to be welded next to it. We take as an example the case of oscillogram (7). The output of the transformer corresponding to the input 8.21 kilowatts is 6.31 kilowatts from the characteristic curves of the transformer in the appendices of the original paper. The current I is taken from the same curves to be 4030 amperes. As the power loss due to the voltage drop V_c is $2V_c I = 2 \times 0.283 \times 4030 = 2.28$ kilowatts, the remaining power which is available to heat the necessary part is $6.31 - 2.28 = 4.03$ kilowatts. This corresponds to 49.2 percent of the input power of the transformer and this may be looked upon as the efficiency of the welding.

Further calculations show that this efficiency is 47.7 for (8), 50.2, 57.2, 50.7 and 54.0 percent for similar oscillograms in the original paper.

This efficiency is reduced to an even lower value when the surface condition of the bar is not favorable, as can be seen from oscillograms (9) and (10), the efficiencies being 41.0 and 33.2 percent respectively. For the copper bar (11), it is 47.5 percent.

§ 3. THE DISTRIBUTION AND CHANGE OF THE TEMPERATURE.

Now we proceed to calculate the distribution and change of the temperature along the material to be welded during and after the welding process. It would be quite useful to know the maximum temperature and how the temperature changes at every point of the material, because the mechanical properties of the weld depend largely upon the effect of the temperature and its manner of change. As it is somewhat difficult to measure exactly the rapidly changing temperature at various points along the material, we have found it by calculation by means of equations (14) and (12). We first determine the physical constants of the material welded.

(II) Determination of constants.

The material welded was soft steel bars of 1 cm. diameter and the current, voltage and other experimental data are shown by oscillogram (1).

The chemical composition of the material is as follows:

Carbon	0.055%
Silicon	0.009%
Manganese	0.590%
Phosphor	0.081%
Sulphur	0.049%

The critical temperature Ac_1 is 720°C and Ac_3 is 800°C.

(A) Specific gravity σ.

$$\sigma = 7.8$$

(B) Specific heat C.

As to this specific heat we have referred to a paper "On the Specific Heat of Carbon Steels" by Dr. Saburo Unno, Report No. V (2) of the Research Institution of the Yawata Steel Works. Since we find a very little difference between the specific heats of a pure iron and a 0.009% carbon steel, and the true specific heat above 1000°C for the former is 0.166 and this is almost equal to the mean specific heat, we have taken this value as the specific heat of our material and assumed this to be constant throughout the varying temperature.

$$C = 0.166$$

(C) Thermal Conductivity K.

As to the thermal conductivity, we have referred to a paper "On the Thermal and Electrical Conductivities of Carbon Steels at High Temperature" by Kotaro Honda and Takeo Shimizu, The Science Reports of Tohoku Imperial University Vol. VI, p. 219. In this paper various curves expressing the relation between the temperature and the conductivity for different carbon contents are given. We have referred to a curve for Swedish iron which has 0.04 percent carbon content. The value of K decreases gradually with the increase of the temperature and becomes minimum at 800°C and then begins again to increase. Now we find the value at 1500°C. According to Lorenz's law the product of K and the electric resistivity ρ is proportional to the absolute temperature. Since this product at 900°C is 9.13×10^{-6} and the electric resistivity at 1500°C can be assumed to be 14.8×10^{-6} (see the next paragraphs), the conductivity at 1500°C is calculated as follows:

$$\frac{K \times 14.8 \times 10^{-6}}{9.13 \times 10^{-6}} = \frac{1500+273}{900+273},$$

whence we have

$$K = 0.093.$$

The value of K which we have used in the calculation is the mean value of 0.097 at 500°C, 0.08 at 1000°C and 0.093 at 1500°C, and is equal to 0.09. Hence we get

$$K = 0.09.$$

(D) Electric resistivity ρ.

We have measured the electric resistivity of soft steel bars at the room temperature of 10°C, as is shown in the appendices of the original paper. The resistivity reduced to 0°C is as follows:

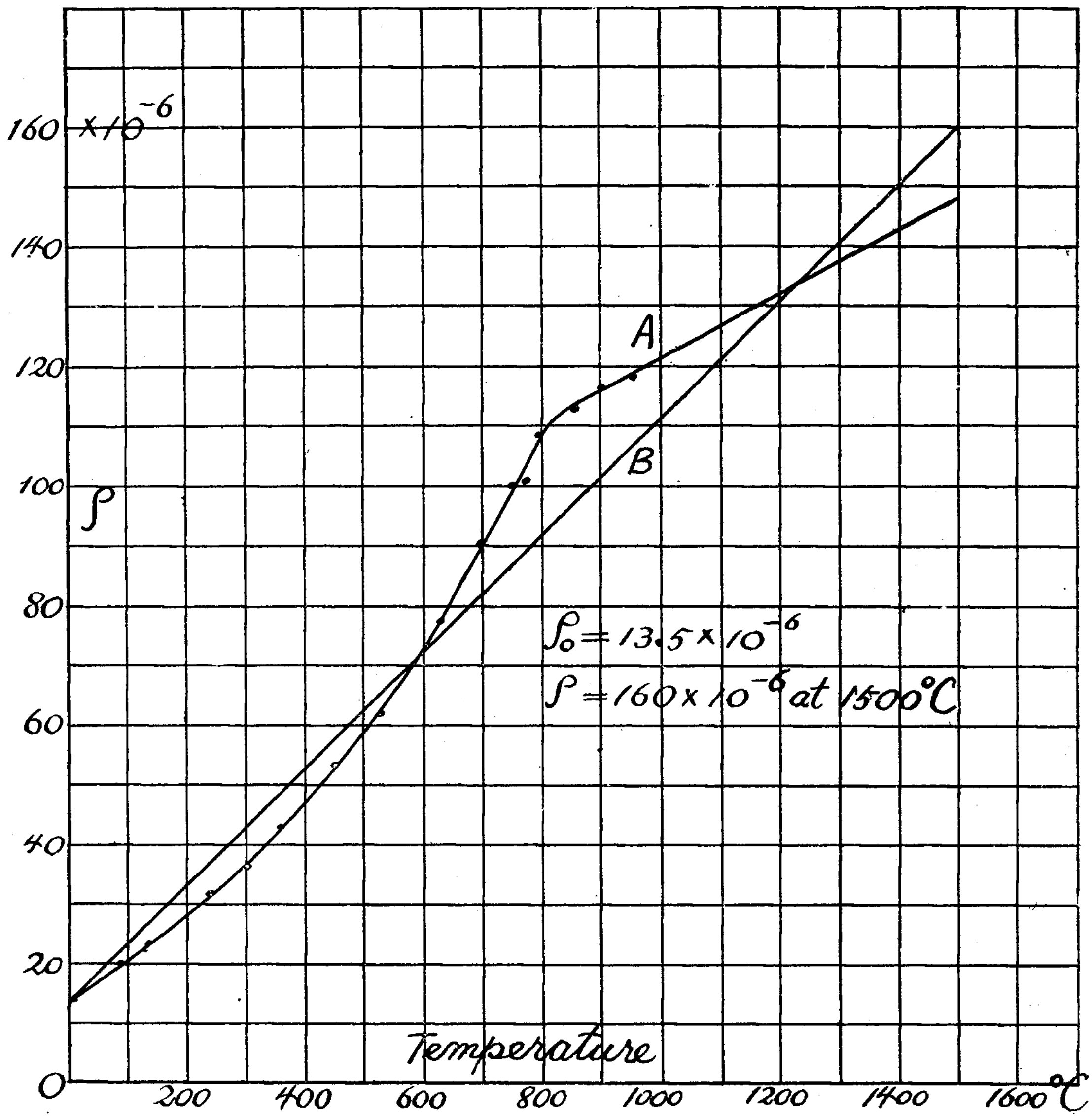
$$\rho_0 = 12.1 \times 10^{-6} \text{ ohm per cm}^3.$$

When we consider the electric resistivity in an alternating current circuit, it is usual to take into consideration the phenomenon of the so-called skin effect, owing to which the resistivity increases more or less according to the frequency and the size of the cross section. Since in the welding operation however there is a contact resistance at the joint and the resistivity of the metal near the joint increases owing to its high temperature and becomes much larger than in the cold state and moreover in the case of iron it becomes non-magnetic above the critical temperature, the influence of the skin effect upon the resistivity near the joint can be neglected, especially if the size of the cross section is not very large. This is also mathematically proved in the appendix.

(E) Temperature coefficient α of the electric resistivity.

As to the temperature coefficient of the electric resistivity, we have again referred to the same paper as in (C). The curve A in Fig. 6 shows the relation between the electric resistivity and the temperature for Swedish iron of 0.04 carbon content, which we assume as the same for our material. Although the value of α according to this curve is not constant throughout

Fig. 6.



the whole range of temperature, we replace for the sake of simplicity the curve A by the curve B and make the value of a costant. From this curve the valie of a is calculated as follows:

$$\rho = 13.5 \times 10^{-6}$$

and $\rho = 160 \times 10^{-6}$ at $1500°C$,

hence we have

$$\alpha = \frac{\rho - \rho_0}{\rho_0 \theta} = 0.0072.$$

(F) Emissivity H.

The heat loss from the outer surface of the material to be welded is for the most part due to radiation and convection. These losses are exactly speaking complicate functions of the temperature and difficult to express simply, but since they are only a small fraction of the heat generated in the material, we can put them approximately proportional to the temperature, as we often do. If p_e denote the heat loss in calories per sq. cm. per second and H the emmissivity of the surface, then we have

$$p_e = H\theta,$$

in which we have taken as H the value at 750°C. Now we proceed to calculate the emissivity H of the iron bar at this temperature.

As for the radiation loss, we have made use of Stephan-Bolzmann's low which can be written as follows:

$$p_R = k(\theta^4 - \theta_0^4) \simeq k\theta^4,$$

where p_R is the power loss in watts from 1 sq. cm of the surface of a black body, k a constant equal to 5.75×10^{-12} (see Pender's Handbook for Electrical Engineers, 1922, p. 737) and θ and θ_0 the absolute temperatures of the surface and the surrounding air respeciively. But as the loss from the surface of iron is 65 percent of that from a black body (see ditto. p. 738) we have

$$p_R = 0.65 \times 5.75 \times 10^{-12} \times (750 + 273)^4$$
$$= 4.1 \text{ watts.}$$

As for the convection loss, we have referred to Dulong et Petit's law which runs as follows:

$$p_c = 6.4 \times 10^{-5} k' (\theta - \theta_0)^{1.233},$$

where p_c denotes the power loss in watts from 1 sq. cm of the surface and k' a constant equal to

$$k' = 2.058 + \frac{3.82}{r}$$

As r is the radius of the bar and equal to 0.5 cm in our case, we have

$$k' = 9.698$$

and therefore

$$p_c = 6.4 \times 10^{-5} \times 9.698 \times 3392$$

$$= 2.1 \text{ watts.}$$

Hence we have

$$H = \frac{4.1 + 2.1}{750} \times 0.24$$

$$= 0.002.$$

(G) $\varkappa$

$$\varkappa = \frac{K}{C\sigma} = \frac{0.09}{0.166 \times 7.8} = 0.07$$

(H) λ_2

$$\lambda_2 = \frac{Hp}{C\sigma S} = \frac{0.002 \times 2\pi \times 0.05}{0.166 \times 7.8 \times \pi \times (0.5)^2}$$

$$= 0.006$$

(I) λ_1

$$\lambda_1 = \frac{Hp}{C\sigma S} - 0.24 \frac{I^2 \rho_0 a}{C\sigma S^2}$$

$$= 0.006 - 0.24 \times \frac{3360 \times 3360 \times 12.1 \times 10^{-6} \times 0.0072}{0.166 \times 7.8 \times 0.785 \times 0.785}$$

$$= -0.290$$

The value of the current I is taken from Table II (1). In this calculation we can see that the term λ_2 containing the emissivity H is fairly small compared with the other.

(II) Electric power appearing on the contact surface.

The power which appears on the contact surface of the two bars is given by the product of the current I and the voltage drop V_a which are taken from oscillogram (1) of Fig. 5 as follows:

Time t in seconds	Power in watts
0	3220
0.5	2690
1.0	2050
1.5	1330
2.0	733
2.5	487
3.0	428
3.5	400
4.0	377
4.4	363

But this power contains, as we have already mentioned, the power developed in the material itself between two points each 1 mm apart from the contact surface due to the electric resistance and the current flowing through it. In Fig. 7 the curve A is the total power measured and the curve B is the latter, the initial value of which is the product of the resistance between the two points and the square of the current and is equal to 82 watts. And as the temperature rise in the vicinity of the contact surface is pretty rapid, this power increases also rapidly presumably as is shown in the figure.

The power which appears really on the contact surface is the difference of these two and is shown in Fig. 8, in which $\tau - t$ is taken as abscissa instead of t for the sake of convenience in the following calculation.

Now we are in a position to be able to calculate the distribution and change of the temperature by applying the constants and the power so far determined or calculated in eq. (14) and (12).

(III) Calculation of the temperature.

(1) Temperature during the welding time $T_0 = 4.4$

Now let us write down here again eq. (14)

$$\theta = \frac{0.24}{2\,C\sigma S\sqrt{\pi\varkappa}}\int_0^{\tau}\frac{F(\tau-t)\,e^{-\frac{x^2}{4\varkappa t}-\lambda_1 t}}{\sqrt{t}}\,dt + \frac{a}{\lambda_1}\left(1-e^{-\lambda_1\tau}\right),$$

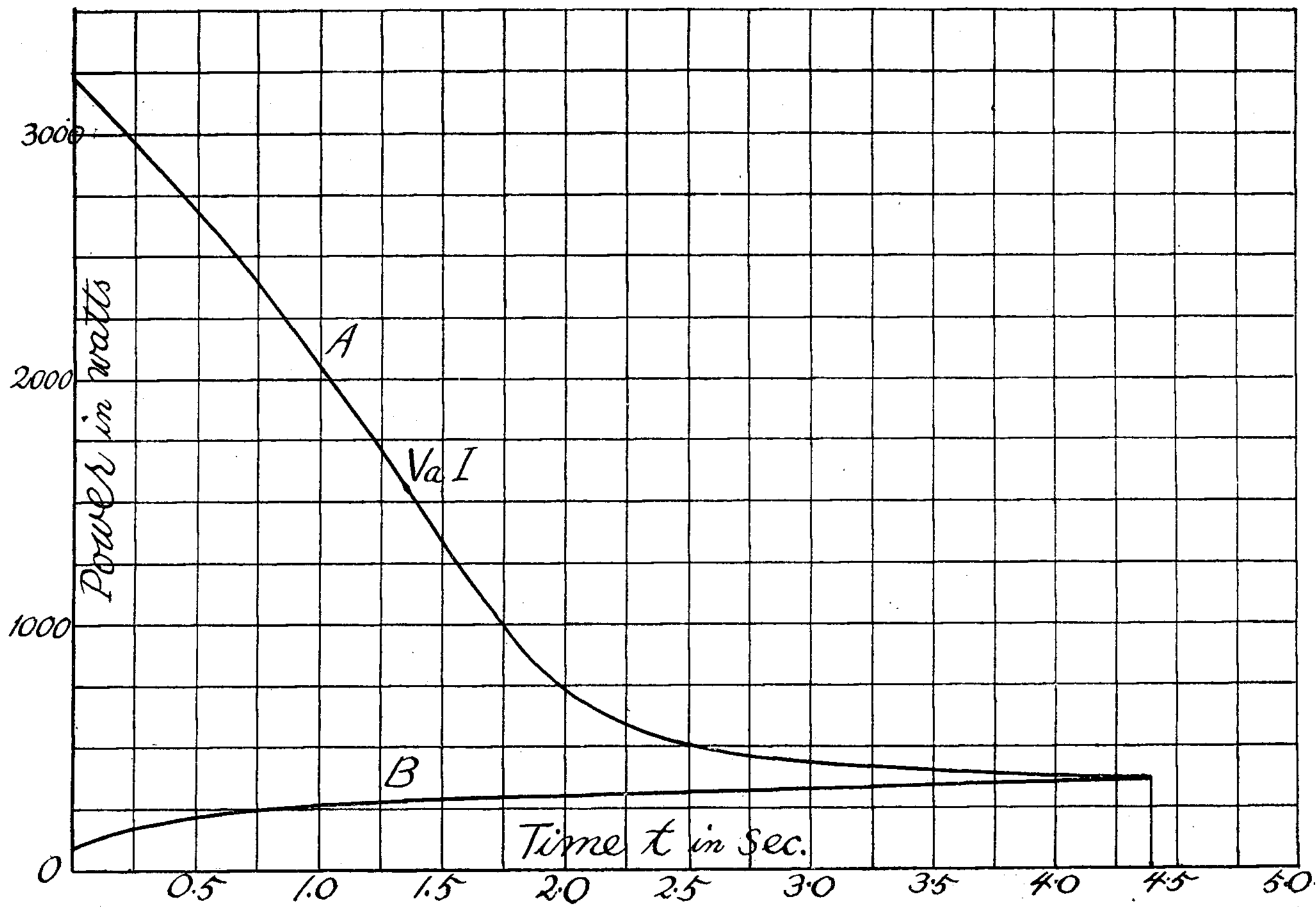
where

$$\frac{0.24}{2\,C\sigma S\sqrt{\pi\varkappa}} = 0.252$$

and from eq. (3) we get

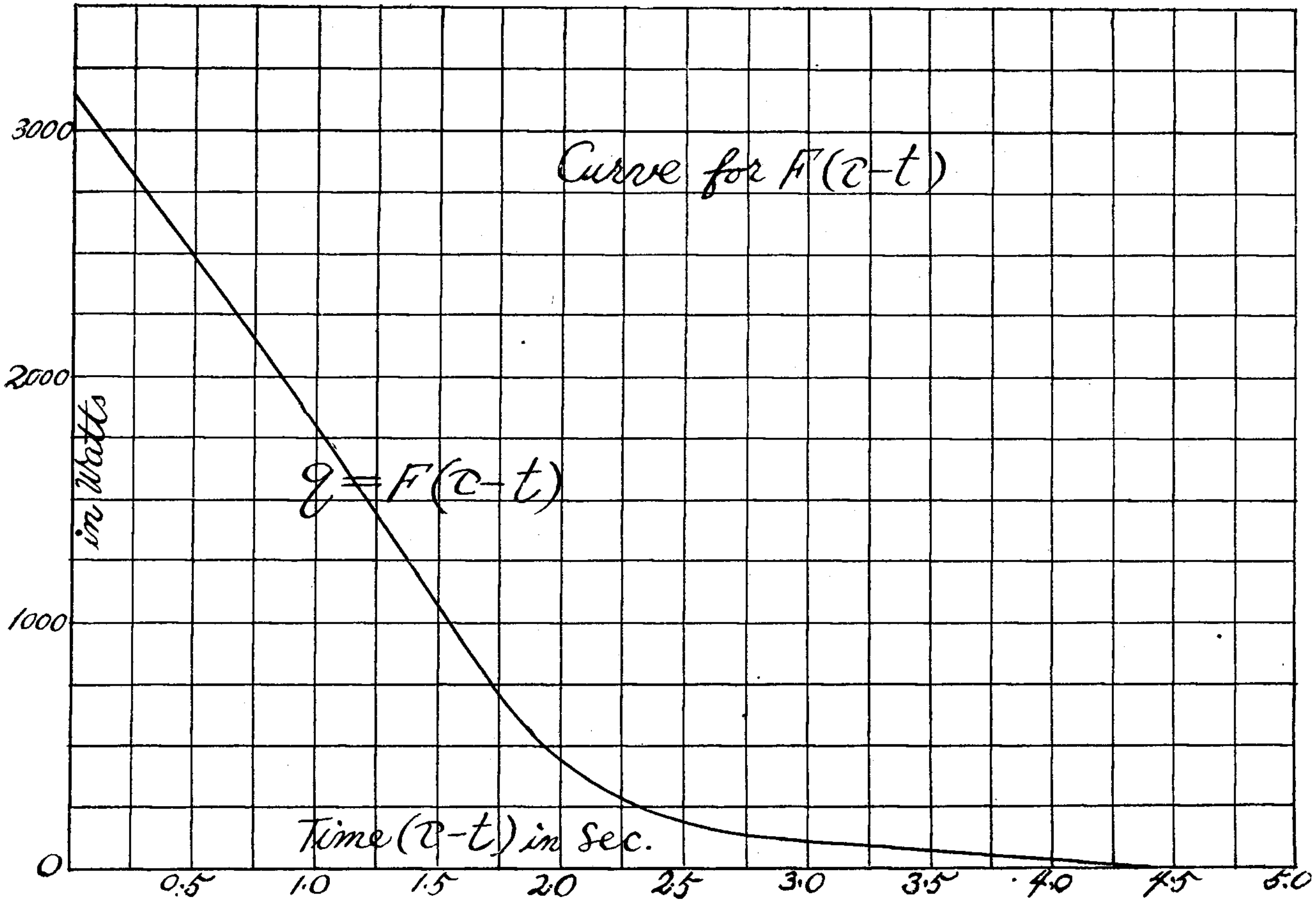
$$a = 0.24\,\frac{I^2\rho_0}{C\sigma S^2} = 41.4,$$

Fig. 7.



3000
2000
1000
0
Power in watts
A
Va I
B
Time t in sec.
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Fig. 8.


Curve for F(τ-t)
q=F(τ-t)
in Watts
3000
2000
1000
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Time (τ-t) in Sec.

and again

$$\lambda_1 = -0.290, \quad \varkappa = 0.07$$

The function $q = F(\tau - t)$ is given by the curve in Fig. 8.

The calculation was performed with regard to seven points, i.e. $x \cong 0$, 1, 3, 6, 10, 15 and 20 mm for the times $\tau = 1$, 2, 3, 4, and 4.4. We will now show by way of example the calculation with respect to the point $x = 1$ for the above mentioned times.

If the curve $F(\tau - t)$ could be expressed by an exponential function the calculation would be much simplified, as we have already explained in § 2 of Chapter II. But in this case it is somewhat difficult to apply this method as the deviation of the curve from a corresponding exponential one is a little too large to expect an exact result. Accordingly we have calculated the temperature by means of a graphical method.

We found first the value of the integrant B at several values of the time t from 0 to τ.

$$B = \frac{F(\tau - t)\, e^{-\frac{x^2}{4\varkappa t} - \lambda_1 t}}{\sqrt{t}}.$$

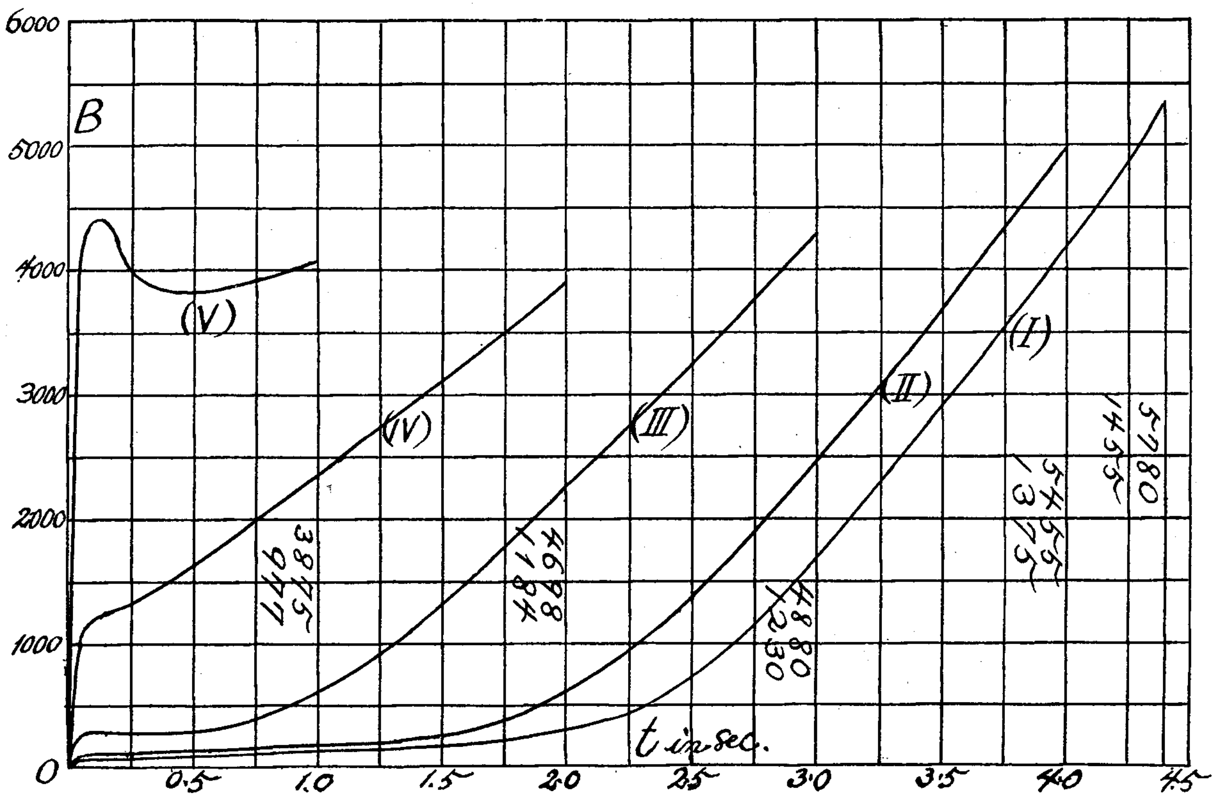
Then we plotted these values of B on curves taking B in ordinate and t in abscissa as shown in Fig. 9 and found the values of the integral $\int_0^\tau$ Bdt by measuring the areas bounded by these curves and the straight lines drawn vertically on the times τ.

Now let us show as an example the result of this process for the temperature at the end of the welding operation or for $\tau = 4.4$.
If A denote the exponent, then A becomes in this case

$$A = -\frac{x^2}{4\varkappa t} - \lambda_1 t = -\frac{0.0357}{t} + 0.29\, t.$$

In the following table the values of $\sqrt{t}$, A, e^A, $\tau - t$, $F(\tau - t)$ and B are shown for various values of t.

Fig. 9.


6000
5000
4000
3000
2000
1000
0
B
(V)
(IV)
(III)
(II)
(I)
3875
977
4698
1184
4880
1230
5455
1375
5780
1455
t in sec.
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

t	$\sqrt{t}$	A	e^A	$\tau-t$	$F(\tau-t)$	B
0	0	$-\infty$	0	4.4	0	0
0.5	0.707	0.074	1.08	3.9	40	61
1.0	1.00	0.254	1.29	3.4	75	97
1.5	1.23	0.411	1.51	2.9	120	147
2.0	1.41	0.562	1.75	2.4	220	274
2.5	1.58	0.711	2.04	1.9	530	684
3.0	1.73	0.858	2.36	1.4	1220	1660
3.5	1.87	1.01	2.75	0.9	1940	2850
4.0	2.00	1.15	3.16	0.4	2620	4140
4.4	2.10	1.27	3.56	0	3140	5320

The curve (I) of Fig. 9 expresses the integrant B in this case and the area measured by a planimeter is 5780, and this multiplied by the coefficient 0.252 gives the first term of eq. (14), these figures being written by one side of the vertical line drawn on the time τ.

Finally the second term of eq. (14) is calculated as follows:

$$\frac{a}{\lambda_1}\left(1-e^{-\lambda_1\tau}\right)=\frac{41.1}{0.29}\left(e^{0.299\times4.4}-1\right)=366$$

and hence the temperature θ at $x=0.1$ and $\tau=4.4$ becomes

$$\theta=1821^{\circ}\mathrm{C}$$

As to the temperature of the same point at $\tau=4.0$ seconds we can proceed in the same way, but most of the figures calculated in the above example can be here utilized and hence the labor of calculation can be much saved. The result is as follows:

t	$\sqrt{t}$	A	e^A	$\tau-t$	$F(\tau-t)$	B
0	0	$-\infty$	0	4.0	35	0
0.1	0.317	-0.328	0.720	3.9	40	91
0.5	0.707	0.074	1.08	3.5	70	107
1.0	1.00	0.254	1.29	3.0	110	142
1.5	1.23	0.411	1.51	2.5	180	221
2.0	1.41	0.562	1.75	2.0	440	546
2.5	1.58	0.711	2.04	1.5	1050	1360
3.0	1.73	0.858	2.36	1.0	1800	2460
3.5	1.87	1.01	2.75	0.5	2490	3660
4.0	2.00	1.15	3.16	0	3140	4960

The area bounded by the curve (II) is found by measuring to be 5455 and the first term of eq. (14) becames 1375 by multiplying by the coefficient 0.252. The second term becomes 310 and finally the temperature θ is

$$\theta = 1685°C.$$

We shall show once more the result of calculation as to the same point at $\tau = 3.0$ as follows:

t	$\sqrt{t}$	A	eA	$\tau - t$	$F(\tau - t)$	B
0	0	$-\infty$	0	3.0	110	0
0.01	0.10	-3.57	0.0282	2.99	110	30
0.025	0.158	-1.42	0.242	2.975	115	178
0.05	0.224	-0.700	c.497	2.95	115	255
0.1	0.317	-0.328	0.720	2.90	120	273
0.2	0.50	-0.070	0.932	2.75	130	242
0.5	0.707	0.074	1.08	2.50	180	275
1.0	1.00	0.254	1.29	2.0	440	568
1.5	1.23	0.411	1.51	1.5	1050	1290
2.0	1.41	0.562	1.75	1.0	1800	2230
2.5	1.58	0.711	2.04	0.5	2490	3210
3.0	1.73	0.858	2.36	0	3140	4280

The area of the curve (III) is 4880 and the first term, calculated as before, is 1230. The second term is 197 and hence the temperature θ becomes

$$\theta = 1437°C$$

The same process is repeated for times $\tau = 2.0$ and $\tau = 1.0$, thus completing the calculation of the variation of temperature at the point $x = 0.1$ cm.

Now we carry on the same calculations for the other points, namely, $x \simeq 0$, $x = 0.3$, $x = 0.6$, $x = 1.0$, $x = 1.5$ and $x = 2.0$ cm and find the manner of variation of the temperatures at these points.

We shall show in the following table only the final results of the calculations.

Table 3.

$x \simeq 0$

τ	= 0	1	2	3	4	4.4
the first term	= 0	1256	1275	1276	1418	1480
the second term	= 0	48	112	197	310	366
θ	= 0	1304	1387	1473	1728	1846

$x = 0.1$

τ	= 0	1	2	3	4	4.4
the first term	= 0	977	1184	1230	1375	1455
the second term	= 0	48	112	197	310	366
θ	= 0	1025	1296	1437	1685	1821

$x = 0.3$

τ	= 0	1	2	3	4	4.4
the first term	= 0	481	867	1075	1256	1358
the second term	= 0	48	112	197	310	366
θ	= 0	529	979	1272	1566	1724

$x = 0.6$

τ	= 0	1	2	3	4	4.4
the first term	= 0	105	388	660	920	1014
the second term	= 0	48	112	197	310	366
θ	= 0	153	500	857	1230	1380

$x = 1.0$

τ	= 0	1	2	3	4	4.4
the first term	= 0	5	82	237	449	536
the second term	= 0	48	112	197	310	366
θ	= 0	53	194	434	759	902

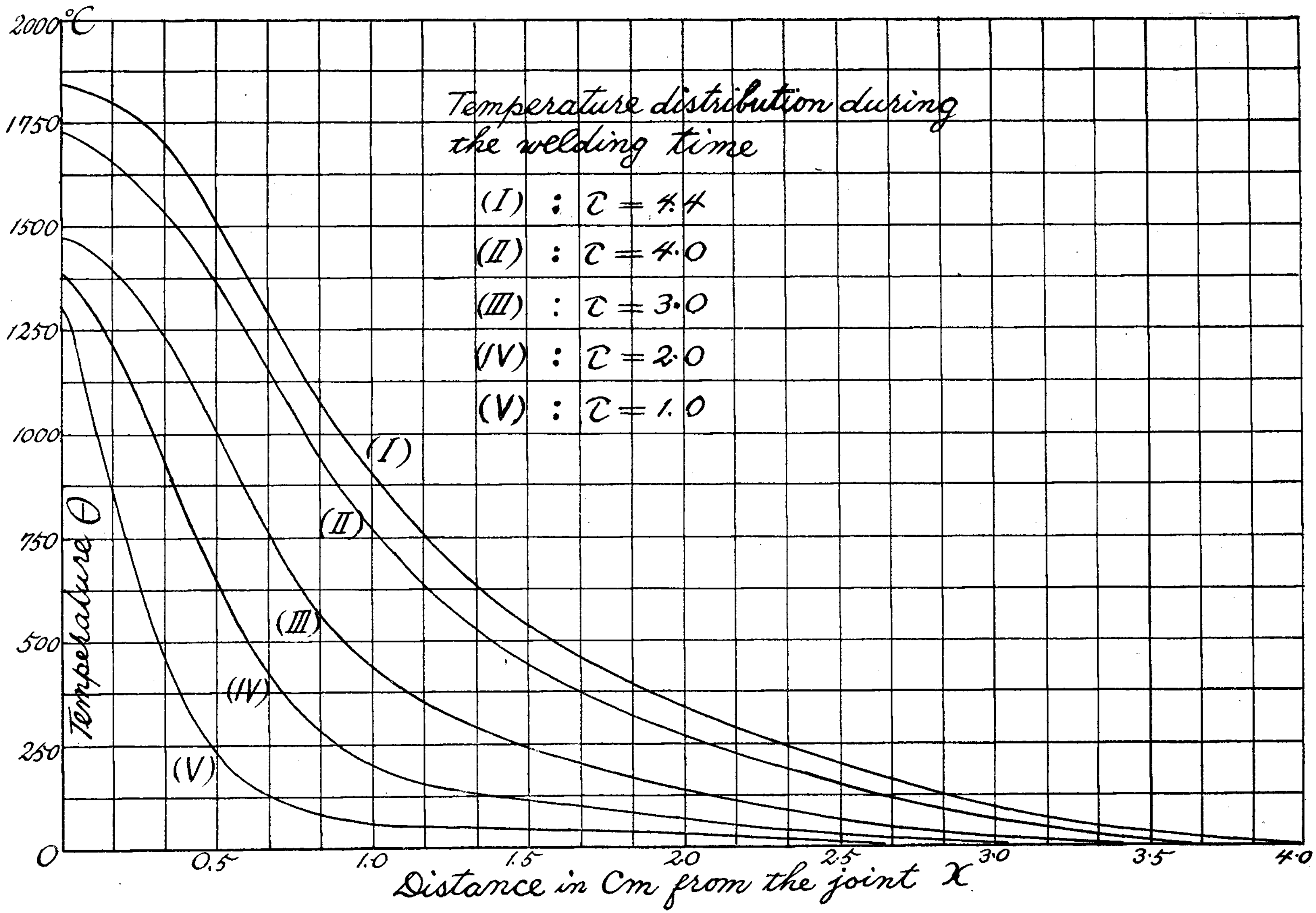
$x = 1.5$

τ	= 0	1	2	3	4	4.4
the first term	= 0	0	6	39	133	160
the second term	= 0	48	112	197	310	366
θ	= 0	48	118	236	443	526

$x = 2.0$

τ	= 0	1	2	3	4	4.4
the first term	= 0	0	0	4	20	32
the second term	= 0	48	112	197	310	366
θ	= 0	48	112	201	330	398

Fig. 10.



2000°C
1750
1500
1250
1000
750
500
250
0
Temperature Θ
Temperature distribution during the welding time
(I) : τ = 4.4
(II) : τ = 4.0
(III) : τ = 3.0
(IV) : τ = 2.0
(V) : τ = 1.0
(I)
(II)
(III)
(IV)
(V)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance in Cm from the joint X

These results are shown with separate curves in Fig. 10, taking x in abscissa and the temperature in ordinate, and we can see the distribution of temperature along the bar at the times $\tau = 1.0, 2.0, 3.0, 4.0$ and 4.4 seconds.

We have calculated the temperature as far as the point $x = 2.0$. Now the welding current enters the bar to be welded from the clamping block through the contact between them, and the current density in the bar is zero at the further end of the block, gradually increases and reaches its full value at the other end. As the breadth of the block was in our case 2.5 cm, the current density at the distance $x = 4.0$ can be assumed to be zero and hence the temperature at this point during the welding operation would be negligibly small and could be assumed to be zero. Under such a supposition the curves were drawn farther beyond the point $x = 2.0$ as far as $x = 4.0$.

(2) Temperature after the welding time $T_0 = 4.4$ seconds.

The temperature after the welding time is given by eq. (12), namely,

$$\theta = \frac{e^{-\lambda_2 t}}{2\sqrt{\pi \varkappa t}} \int_{-\infty}^{+\infty} f_0(x')\, e^{-\frac{(x-x')^2}{4\varkappa t}}\, dx',$$

where $f_0(x')$ denotes the temperature at the end of the welding time T_0 and

$\varkappa = 0.07$

$\lambda_2 = 0.006$

$2\sqrt{\pi\varkappa} = 0.94$

We will show the process of calculation of the temperature at $\tau = 5.0$ or $t = 0.6$ seconds and with regard to the temperatures at the other times $\tau = 6.0, 7.5, 10, 15$ and 20 seconds we will show only the final results.

Let us in the first place calculate the temperature at $x = 0.1$:

We find the values of the function $f_0(x')$ from curve I of Fig. 10 and calculate the values of $A = -\frac{(x-x')}{4\varkappa t}$ and e^A and also $B = f_0(x')\, e^A$ and then express this value of B with a curve taking B in ordinate and x' in abscissa and measure the area enclosed by the curve with a planimeter. The area multiplied by the coefficient $\frac{e^{-\lambda_2 t}}{2\sqrt{\pi\varkappa t}} = 1.37$ gives the temperature θ.

$x = 1.0$

x'	$(0.1-x')^2$	A	e^A	$f_0(x')$	B
0.1	0	0	1.00	1821	1821
0.2	0.01	−0.0575	0.944	1775	1680
0.3	0.04	−0.230	0.795	1724	1370
0.5	0.16	−0.92	0.399	1520	606
0.7	0.36	−2.07	0.126	1240	156
1.0	0.81	−4.66	0.0095	902	9
2.0	3.61	−20.7	0	340	0
0	0.01	−0.0575	0.944	1846	1740
−0.1	0.04	−0.230	0.795	1821	1450
−0.3	0.16	−0.92	0.399	1724	688
−0.5	0.36	−2.07	0.126	1520	192
−0.8	0.81	−4.66	0.0095	1110	10
−1.8	3.61	−20.7	0	410	0

Curve (I) of Fig. 11 expresses the value of B in function of x' and the area measured is 1270, as is written by one side of the curve and this multiplied by 1.37 gives the temperature $\theta = 1740°C$.

The same process is repeated for the other points $x = 0.3$, 0.6, 1.0, 1.5, 2.0 and 3.0 and Curves (II), (III), (IV), (V), (VI) and (VII) are obtained, which give finally the temperatures 1630, 1370,. 952, 578, 352 and 103°C respectively.

If we proceed in the same way we can get the temperatures at the other times. The following table shows only the final results·

Table 4.

$x = 0.1$	0.3	0.6	1.0	1.5	2.0	3.0
	$\tau = 5.0$	$(t = 0.6)$				
$\theta = 1740$	1630	1370	952	578	352	103
	$\tau = 6.0$	$(t = 1.6)$				
$\theta = 1550$	1480	1290	959	610	366	120
	$\tau = 7.5$	$(t = 3.1)$				
$\theta = 1410$	—	1220	971	656	402	129
	$\tau = 10$	$(t = 5.6)$				
$\theta = 1220$	—	1100	935	671	454	159
	$\tau = 15$	$(t = 10.6)$				
$\theta = 1000$	—	950	852	660	471	206
	$\tau = 20$	$(t = 15.6)$				
$\theta = 760$	—	720	655	550	444	222

Fig. 11.

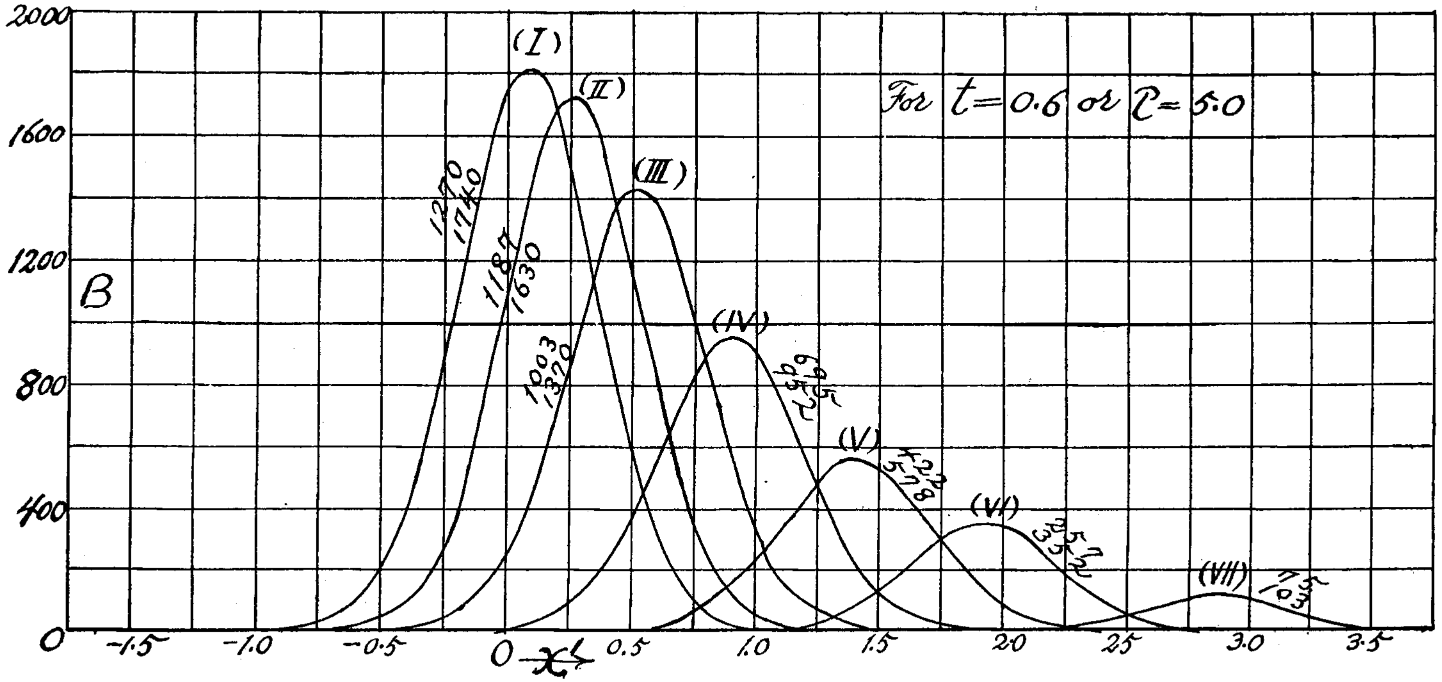

2000
1600
1200
800
400
0
B
(I)
(II)
(III)
(IV)
(V)
(VI)
(VII)
For t=0.6 or ζ=5.0
1270
1740
1187
1630
1003
1370
695
952
422
578
257
352
75
103
-1.5
-1.0
-0.5
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
x

Fig. 12.

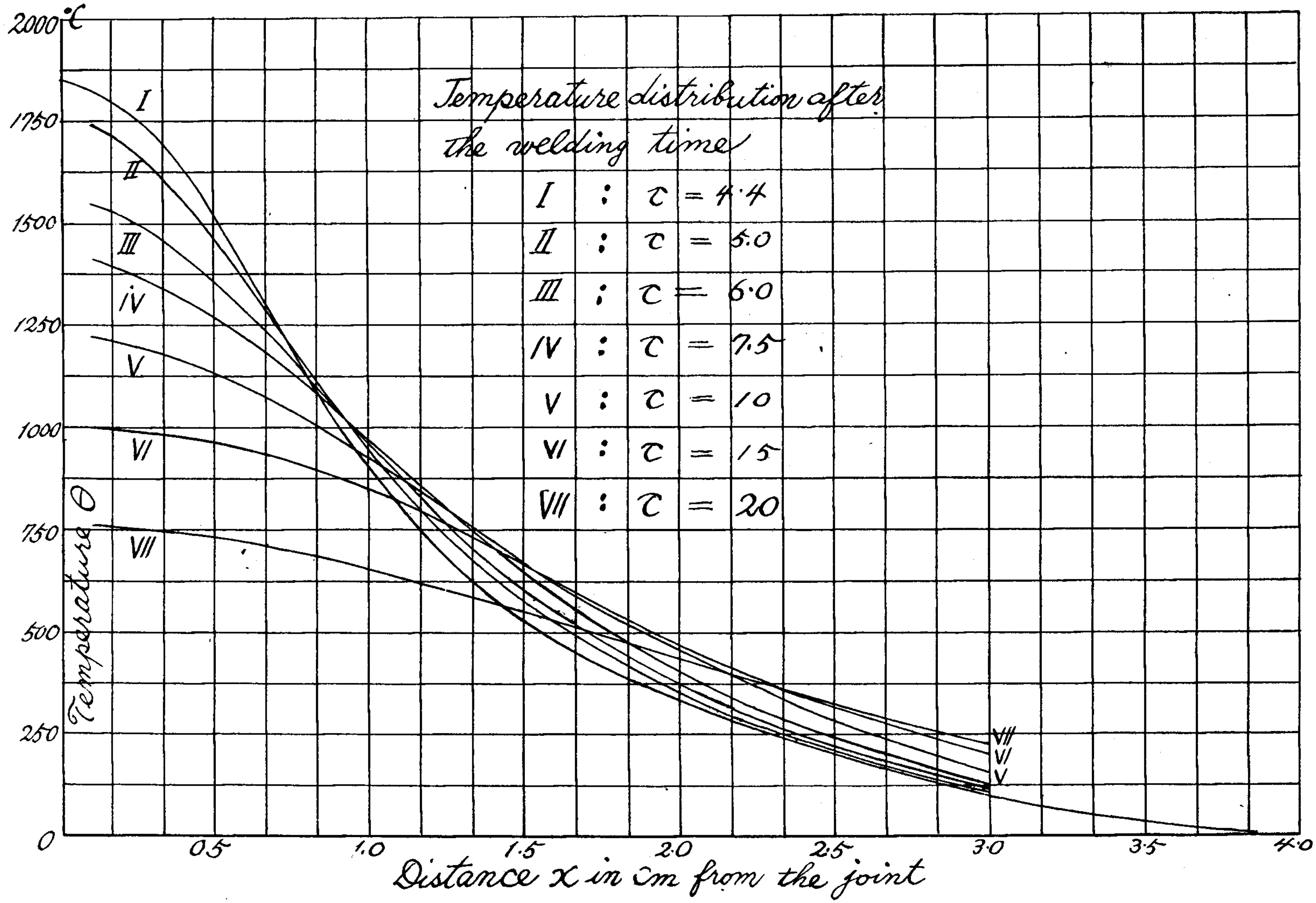
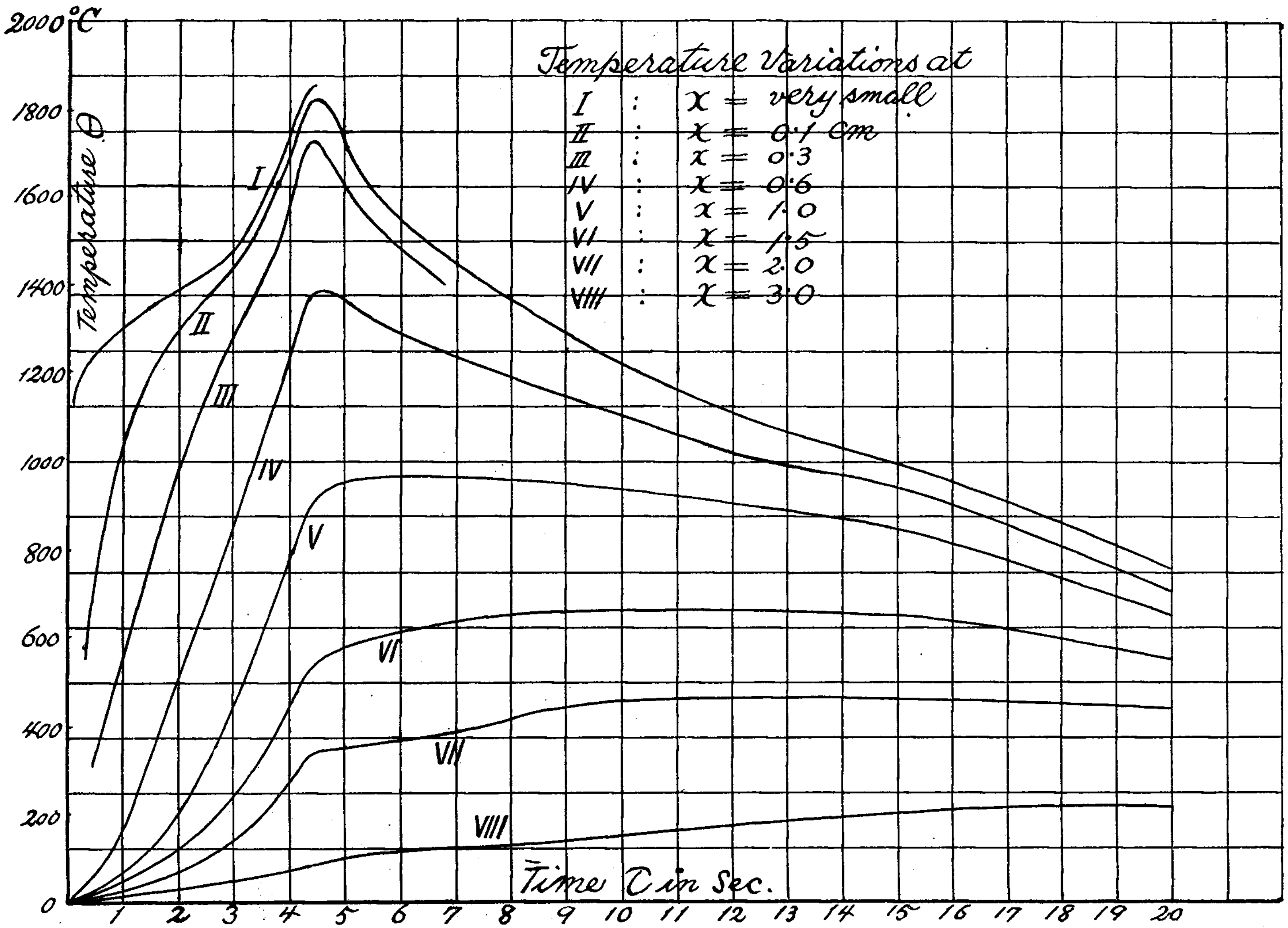

Temperature distribution after the welding time
I : τ = 4·4
II : τ = 5·0
III : τ = 6·0
IV : τ = 7·5
V : τ = 10
VI : τ = 15
VII : τ = 20
Temperature θ
°C
2000
1750
1500
1250
1000
750
500
250
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance x in cm from the joint

Fig. 13.


Temperature Variations at
I : x = very small
II : x = 0·1 cm
III : x = 0·3
IV : x = 0·6
V : x = 1·0
VI : x = 1·5
VII : x = 2·0
VIII : x = 3·0
2000°C
1800
1600
1400
1200
1000
800
600
400
200
0
Temperature θ
Time τ in Sec.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

These results are shown with curves in Fig. 12.

Fig. 13 shows the variations of temperature both during and after the welding time in order to make clear how the temperature varies at these points. From Fig. 12 we can see that the temperature rises above the melting point of the material i.e. 1500°C so far as the point 0.5 cm apart from the joint and should therefore expect the softening and melting of this part, but, since we could not take into consideration the effect of the latent heat of melting and also the transformation heat in the above calculation, the actual temperature of this part does not rise so much as the calculation shows and remains at about 1500°C except in the immediate neighborhood of the joint. With regard to the phenomenon of annealing or recrystallization it is quite the same. Although the temperature rises above Ac_3 as far as a point 1.2 cm from the joint, the change of the microstructure occurs only in a smaller range of 0.8 cm as we shall explain later in the metallographical observations.

As the part between about 0.5 and 1.0 cm remains fairly long at a temperature above 800°C or the annealing temperature, the material is more or less annealed and when pulled by the testing machine a contraction of the cross section can be noticed and the material often breaks at this point.

Chapter IV. CHANGE IN THE METALLOGRAPHICAL STRUCTURE AND THE HARDNESS.

§ 1. CHANGE IN THE METALLOGRAPHICAL STRUCTURE.

Since the material in the neighborhood of the joint, as we have just explained in the previous chapter, is subjected to a fairly severe change of temperature, a change in the microstructure and also in the mechanical properties accompanies the welding as a due consequence.

The *A*—series of Fig. 14 shows the microstructures at various points along the axis of the longitudinal section of the welded bar, of which the temperature was calculated in the previous chapter, namely, a soft steel bar of 1 cm. diameter welded with a welding time of 4.4 seconds, a spring pressure of 12 mm and a travel of 2.0 mm. (the spring pressure and the travel will be explained later). A_1 shows the structure at the middle of the joint, A_2 that at a point 1 mm from A_1, A_3 2 mm, A_4 4 mm, A_5 6 mm, A_6 7 mm, A_7 8 mm from A_1 respectively. At A_8, namely 8.5 mm from A_1, the structure reaches its maximum fineness and begins to become coarse again, thus undergoing a rapid change in the fineness of grains. A_9 shows the structure at 10 mm, which differs very little from the original one. The abrupt change in the structure, such as A_8 shows, should occur at a point 12 mm apart from the joint, but owing to the reasons above stated, it has shifted a little towards the joint.

The *B*—series shows the microstructures of a hard drawn steel bar of the same composition as that of the *A*—series and of a diameter of 3/8 inch, welded with the longer welding time of 7.0 seconds, a larger spring pressure of 17.5 mm and a travel of 1.8 mm. B_1 shows the structure at the middle of the joint, B_2 that at a point in the joint 4 mm nearer to the outer surface, showing a mixture of oxides, B_3 2 mm, B_4 5 mm, B_5 8 mm, B_6 9 mm, where a sudden change in the structure can be clearly seen as at A_8, B_7 10 mm and B_8 11 mm from the joint respectively. The structure at B_8 is almost the same as the original one.

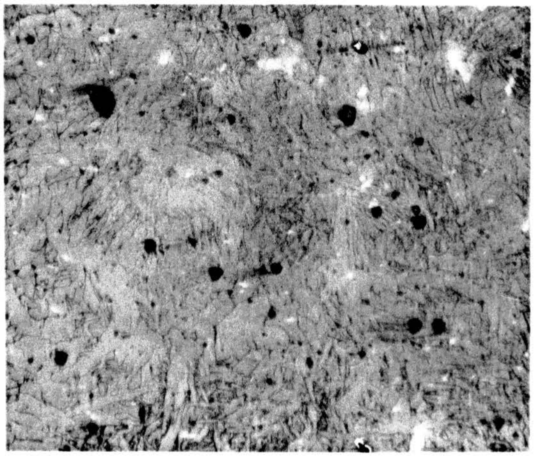
The *C*—series shows the microstructures of the same steel bar as in the *B*—series welded with similar conditions except a much reduced spring pressure, namely, a welding time of 7.6 seconds, a spring pressure of 8.0 mm and a travel of 1.6 mm. C_1 shows the structure at the middle of the joint, C_2 that at a point in the joint 3.5 mm nearer to the outer surface which shows a larger proportion of mixture of oxides and other impurities than that of B_2 owing to the smaller spring pressure and resulting in the poorer mechanical properties, C_3 2 mm, C_4 5 mm, C_5 8 mm, C_6 11 mm, where a rapid change in the fineness of the structure can be observed, and C_7 12 mm from the joint respectively.

In the tensile strength test of welded bars a contraction of the cross sectional area can be observed at a distance several millimeters from the joint and they break at this point if the joints are strong enough. This is due to the recrystallization and coarsening of the structure at this distance, where the temperature remains pretty long above 1000°C, as we have

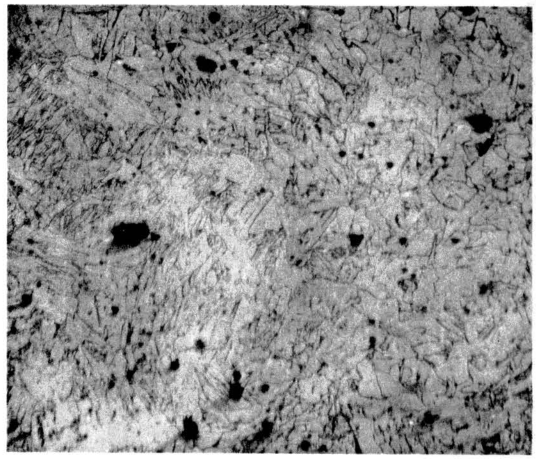
Fig. 14. (1)

A—Series

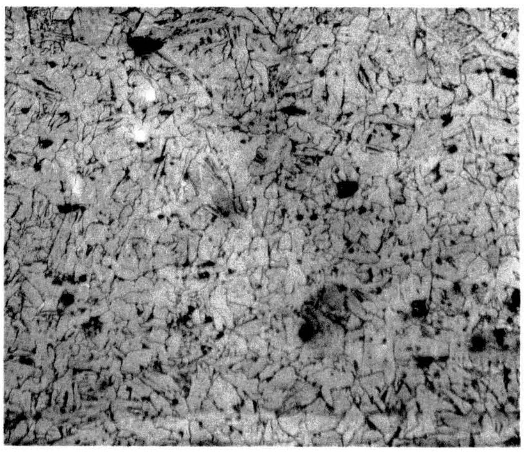
(Magnified 100 diameters)



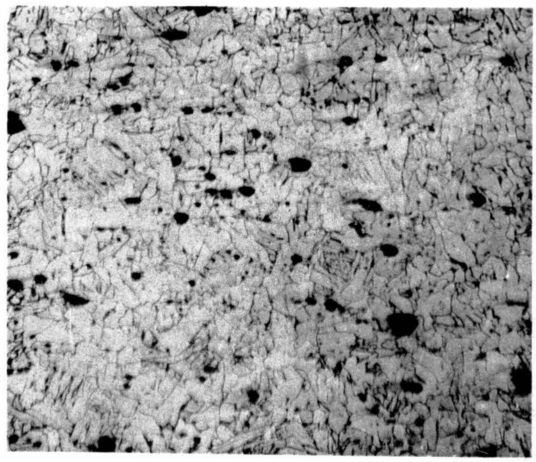
A_1



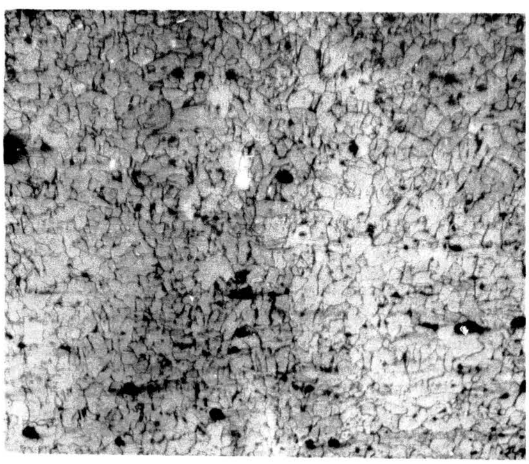
A_2



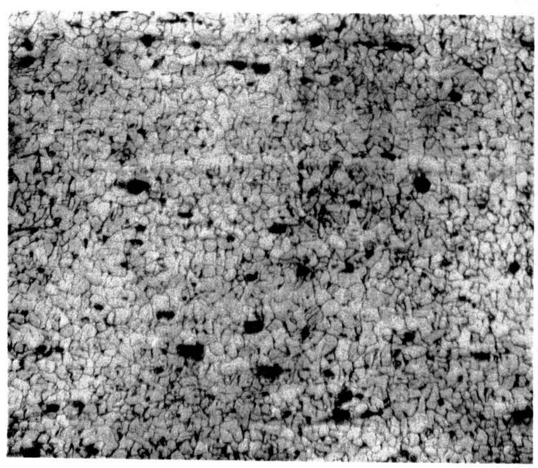
A_3



A_4

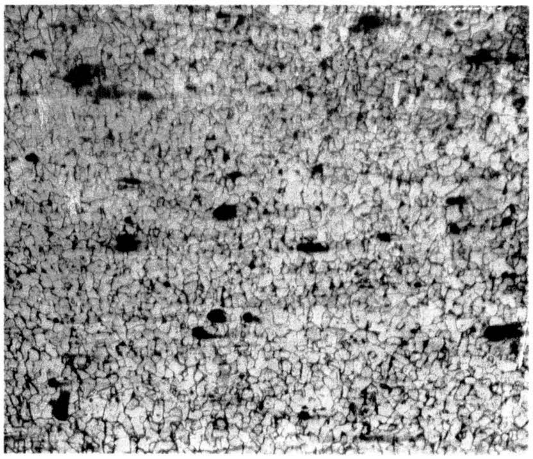


A_5

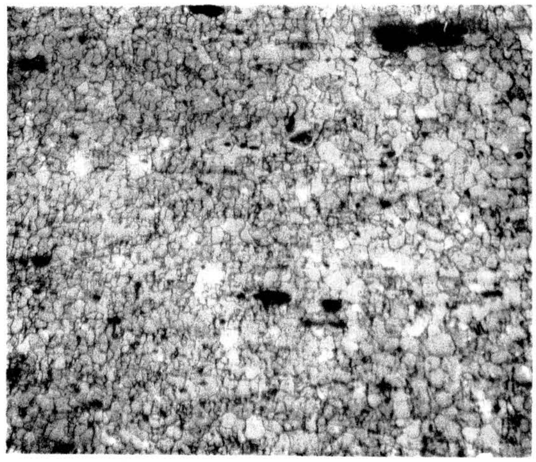


A_6

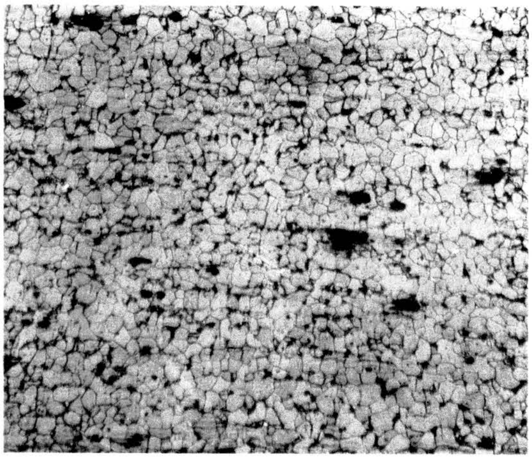
Fig. 14. (2)



A_7



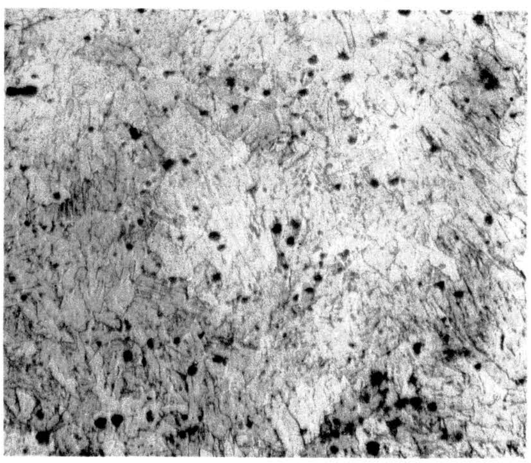
A_8



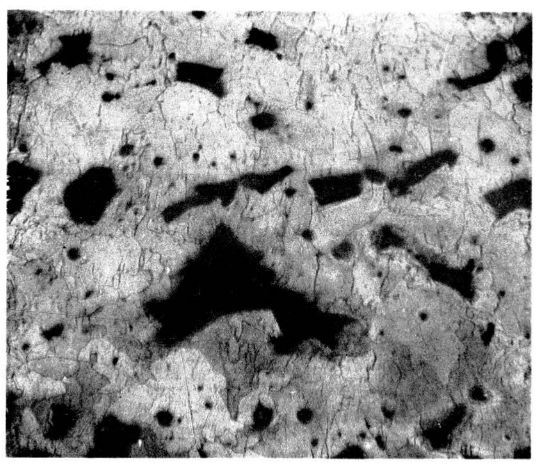
A_9

B—Series

(Magnified 100 diameters)

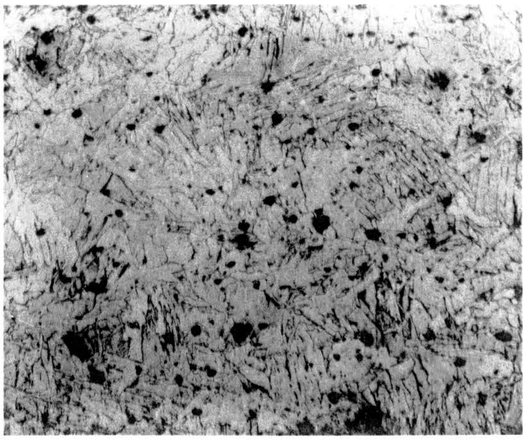


B_1

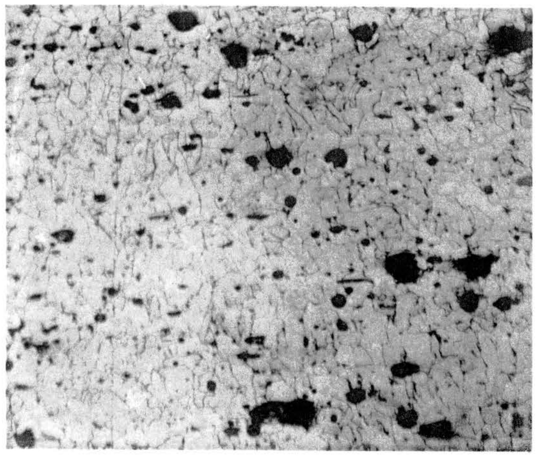


B_2

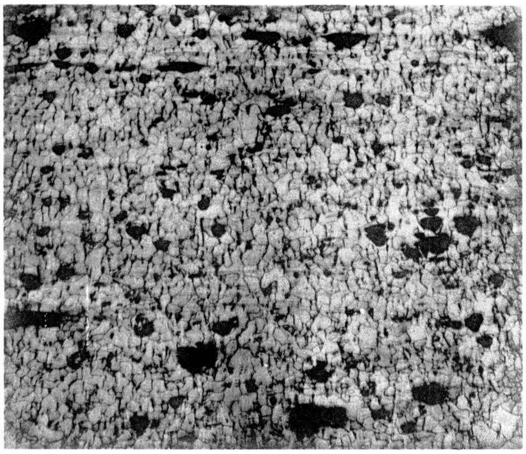
Fig. 14. (3)



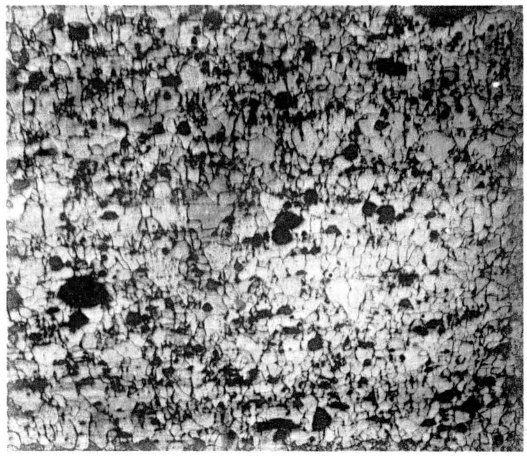
B3



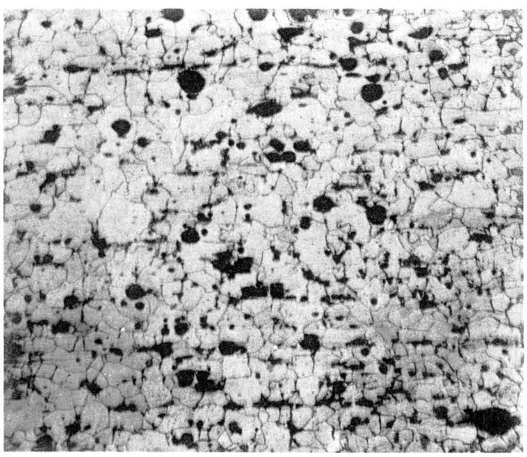
B4



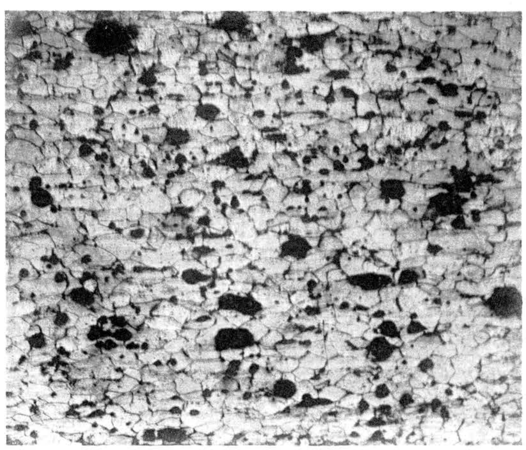
B5



B6



B7

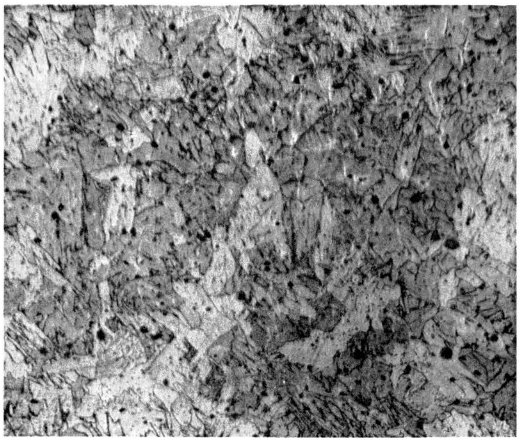


B8

Fig. 14. (4)

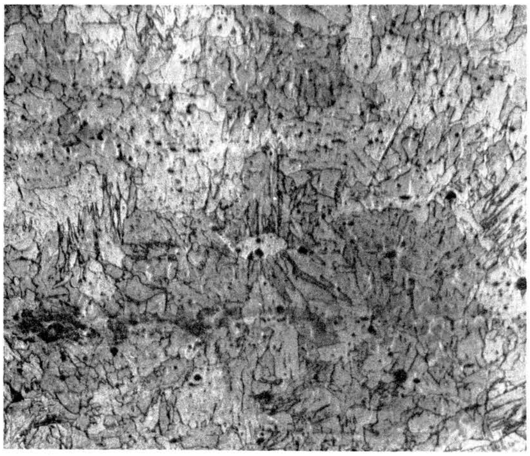
C—Series

(Magnified 100 diameters)

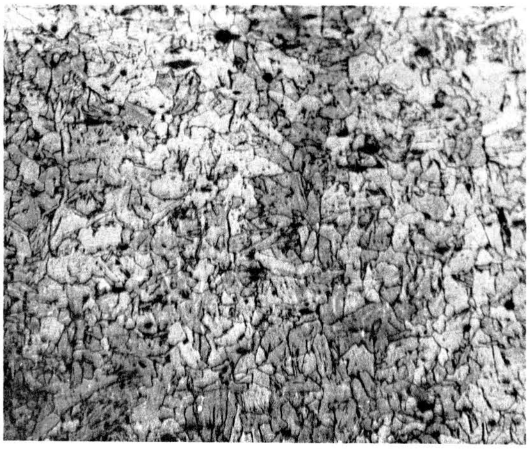


C_1

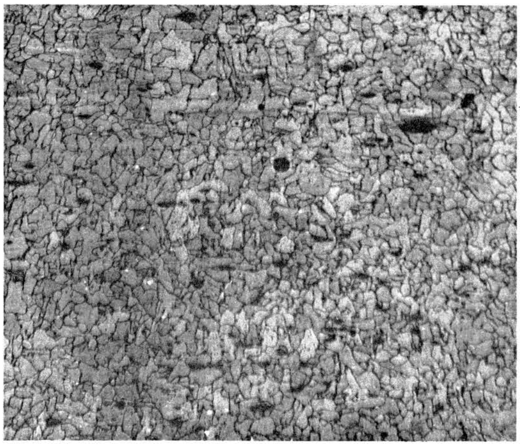
C_2



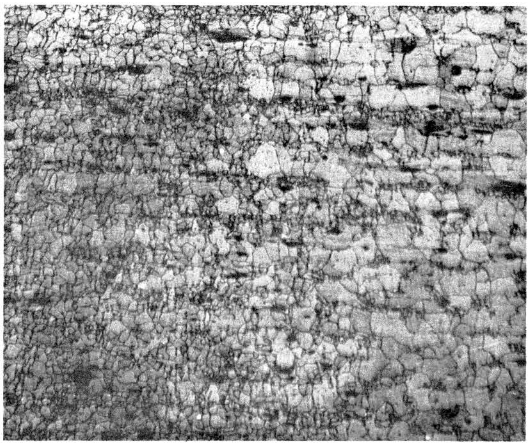
C_3



C_4

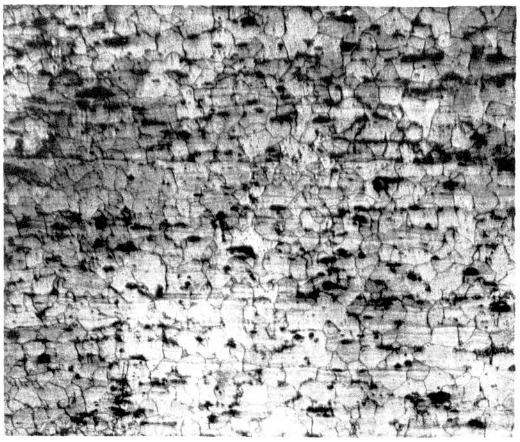


C_5



C_6

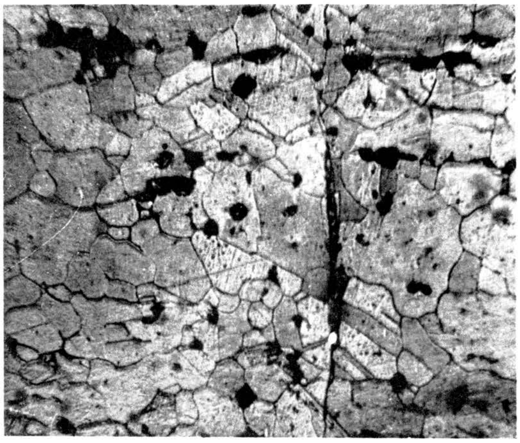
Fig. 14. (5)



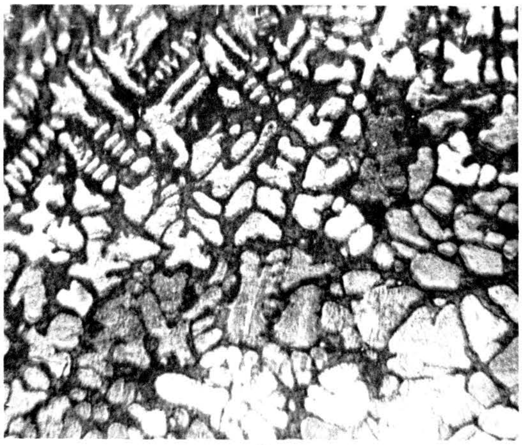
C_7

D—Series

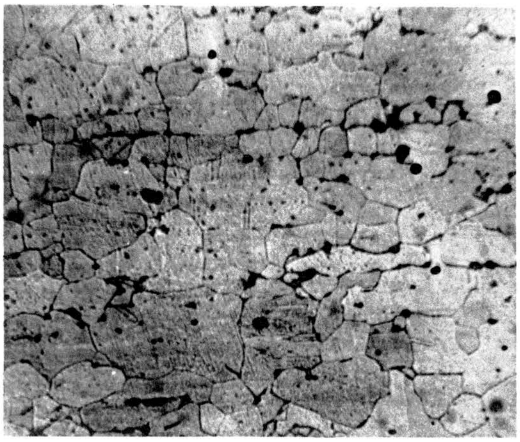
(Magnified 200 diameters)



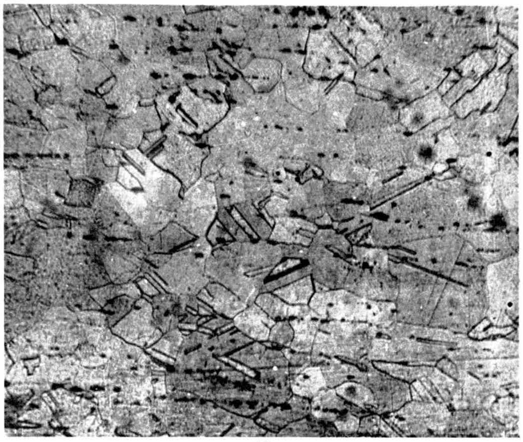
D_1



D_2

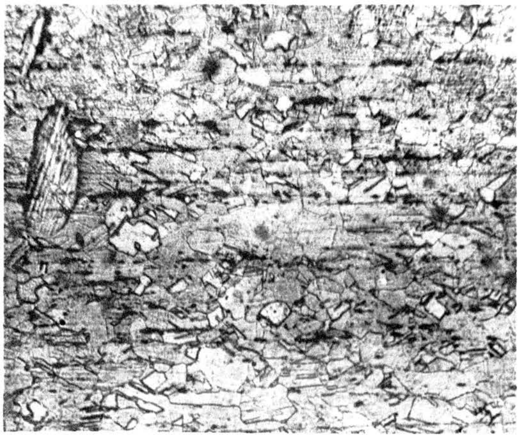


D_3

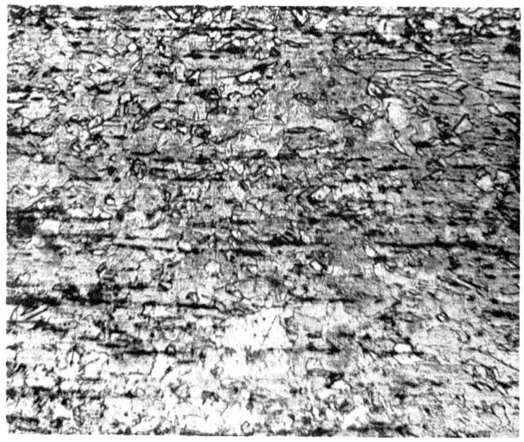


D_4

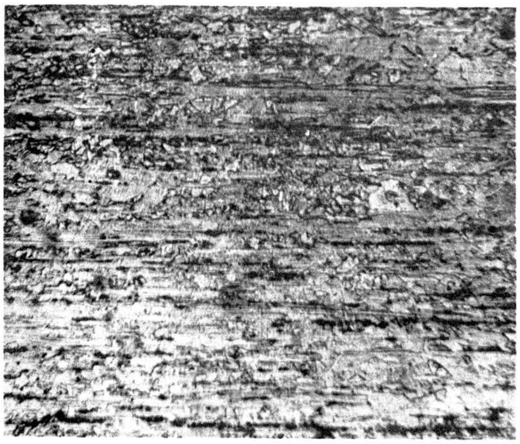
Fig. 14. (6)



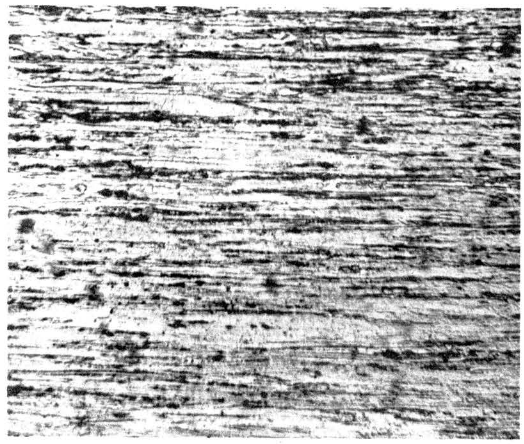
D5



D6



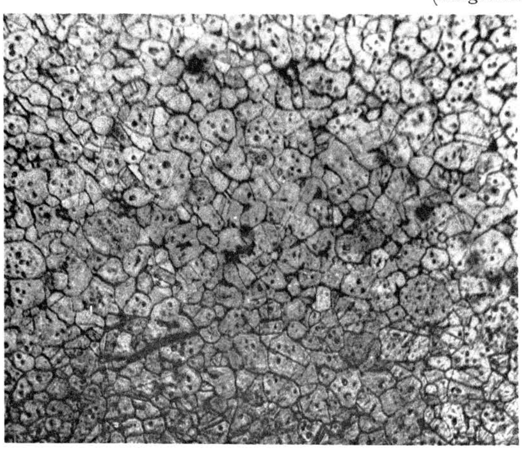
D7



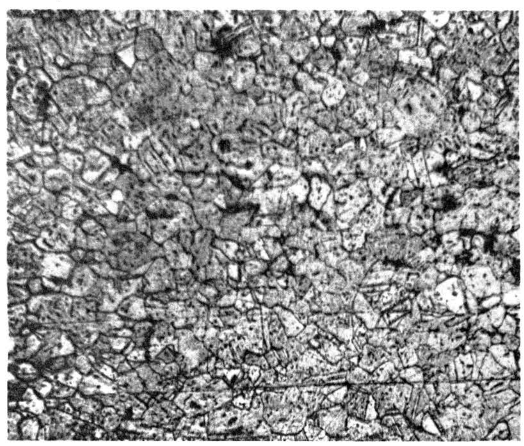
D8

E—Series

(Magnified 200 diameters)



E1



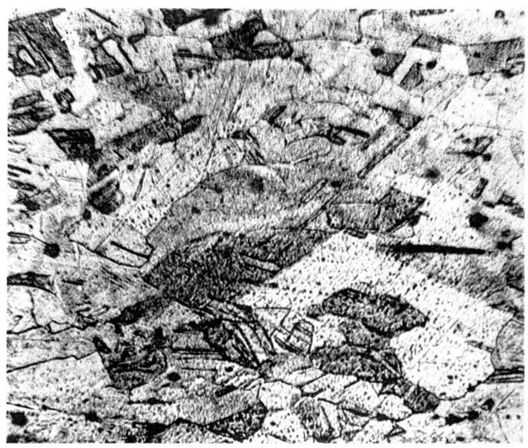
E2

Fig. 14. (7)

E_3

E_4

E_5



F_6

already explained in the previous chapter.

The *D*—series shows the microstructures of a copper wire B. S. No. 4 welded with a welding time of 1.0 second, a spring pressure of 8 mm and a travel of 1.2 mm. D_1 shows the structure at the middle of the joint, D_2 that at a point in the joint but near the outer surface containing in a large proportion copper oxide and its eutectic. The fact that most copper welds break at the joint in the tensile strength test is owing to the existence of the above mentioned impurities and also the coarsening of the structure near the joint. D_3 shows the structure at a point 3 mm from the joint, D_4 6 mm, D_5 9 mm, D_6 12 mm, D_7 14 mm, and D_8 16 mm from the joint respectively. The structure at D_8 or 16 mm, retains the original features but the structure at D_7 or 14 mm is slightly affected by the temperature variation and those at points as far as 5 mm are much influenced and can be seen to have become coarse. In the butt welding of such a metal as copper the heat which appears at and near the joint is comparatively small and even this is conducted and quickly carried away along the bar owing to its good thermal conductivity and therefore the range in which the structural change, and consequently the change of mechanical properties, take place, is fairly large.

The *E*—series shows the microstructures of a brass wire B. S. No. 4 welded with a welding time of 0.6 second, a spring pressure of 9 mm and a travel of 1.4 mm. E_1 is the structure at the middle of the joint, E_2 2 mm, E_3 5 mm, E_4 8 mm, E_5 10 mm and E_6 11 mm from the joint respectively. The structure at E_6 or 11 mm has remained almost unchanged and retains the original feature. The welding of brass is much easier and the result is also more reliable and stronger than that of copper. A contraction of the cross sectional area takes place at a distance a few millimeters from the joint just as in the case of welded steel bars and the welds break for the most part at this point.

§ 2. CHANGE IN THE HARDNESS.

We have measured the hardness at various points along the axis of the longitudinal section and also along lines parallel to this axis for various welded bars, some of which were the pieces tested for the metallographical study. The instrument used was Shore's dial recording scleroscope.

The results are tabulated below, where *D* denotes the distance from the joint in mm and *H* the hardness.

(I) 1 cm. diameter soft steel bar, welding time 4.4 seconds, spring pressure 12 mm, travel 2.0 mm (*A*—series).

D	0	1	2	4	6	7	8	10	12	14	16
H	20	20	20	20.5	20	19.5	19	17.5	18.5	18.5	18.5
H	20	20	20.5	20.5	20	16.5	20	20	19	16.5	17.5
	on the other side of the joint										
H	—	20	21	21	20	20	20	19.5	19	19	18.5
H	—	20.5	20.5	20.5	20.5	19.5	19.5	19.5	19	18.5	17.5

(II) 1 cm diameter soft steel bar, welding time 3.0 seconds, spring pressure 10 mm, travel 1.8 mm.

D	0	1	2	3	4	5	6	7	8	9	10	12	14	16
H	21	20	21	22	21	20	21	18	17	20	20	19	17	15
H	—	18	18.5	19	18	19	19	18	19	18	19	17	16	17.5

(III) 1 cm. diameter soft steel bar, welding time 4.4 seconds, spring pressure 12 mm, travel 2.0 mm.

D	0	1	2	3	4	5	6	7	8	9	10	12	14	16
H	21	19	20	19	20	19.5	18.5	15	16.5	16.5	14.5	15	17	15
H	—	20	20	19	18	17.5	19	20.5	18	20	20	19	20	19.5

(IV) 1 cm. diameter soft steel bar, welding time 4.4 seconds, spring pressure 12 mm, travel 2.0 mm.

D	0	1	2	3	4	5	6	7	8	9	10	12	14	16
H	22	21	21	21	20.5	20	20	22	20.5	20	22	21.5	18.5	18.5
H	17	18.5	18.5	19	19	18	18	18	17.5	18	17	18	17	19

(V) 1 cm. diameter soft steel bar, welding time 7.8 seconds, spring pressure 12 mm, travel 2.0 mm.

D	0	1	2	3	4	5	6	7	8	9	10	12	14	16
H	16	16.5	17.5	19	15	20	17	18.5	20	20	18.5	18.5	19.5	21

(VI) ½ inch diameter soft steel bar, welding time 7.4 seconds, spring pressure 18 mm, travel 2.0 mm.

D	0	1	2	3	4	5	6	7	8	9	10	12	14	16	19
H	17	18	17	19	19	18	18.5	18	17	17	17.5	17	16	16.5	15
H	20	19.5	18.5	19	19	20	19	18.5	15.5	16.5	15.5	17	18	16	17
D	22	25													
H	—	—													
H	17.6	16													

(VII) ⅜ inch diameter hard drawn steel bar, welding time 7.0 seconds, spring pressure 17.5 mm, travel 1.8 mm (*B*—series)

D	0	1	2	3	4	5	6	7	8	9	10	11	12	14	16	19
H	20	20	20	19	17.5	18	18	16	17	16	18	24	24	25	27	28

(VIII) ⅜ inch diameter hard drawn steel bar, welding time 7.6 seconds, spring pressure 8.0 mm, travel 1.6 mm (*C*—series)

D	0	1	2	3	4	5	6	7	8	9	10	11	12	13	15
H	12.5	18	18.5	19	18.5	19	19	18	18	17.5	19	18	17	25	28
D	17	19													
H	28	28													

Now in the test pieces (VII) and (VIII) the hardness is almost constant or seems to decrease a little as far as the point where the fineness of the structure reaches its minimum as we have already shown in the metallographical observations of the B– and C–series, and then increases soon to its original value of 27 or 28,

The welding time and the spring pressure seem to have some influence upon the hardness. If we compare (VII) with (VIII) the hardness is somewhat greater in the neighborhood of the joint for (VII) which was welded with a larger spring pressure. On the other hand the hardness seems to be smaller for test pieces welded with longer welding times, as will be understood when we compare (I), (II), (III) and (IV) with (V) and (VI).

Chapter V. EXPERIMENTAL RESEARCH ON BUTT WELDING OF SOFT STEEL BARS.

§ 1. PURPOSE OF THE EXPERIMENT.

We have welded a number of soft steel bars for each of the diameters 2/8″, 5/16″, 3/8″, 1 cm, 7/16″ and 1/2″ under various welding conditions, namely, varying the welding time, the welding current, the spring pressure or the travel. From these results we have found the relation between the electric power required and the welding time, that between the tensile strength and the welding time, that between the tensile strength and the spring pressure, that between the tensile strength and the travel, with the object of finding the most favorable conditions for obtaining good results.

§ 2. EXPERIMENTAL DATA.

Before proceeding to record the experimental and also the calculated results we shall explain the symbols used in the following pages.

T : the travel in mm, namely, the distance through which one of the bars to be welded is pushed against the other by the action of the spring pressure at the end of the welding process. At the same instant the primary current of the transformer is cut out by a switch which is automatically operated by this motion of the bar.

T_0 : the welding time in seconds measured by a stopwatch.

S : the pressure of the spring, which presses one of the bars against the other, expressed by the amount of its available deformation in mm, namely, the actual deformation minus the deformation of 2 mm which is required in order to overcome the friction of the moving system. One millimeter of the deformation corresponds to 3.45 kilograms.

Pl : the position of the plug indicated by the numbers 1 to 6, which regulates the number of the primary turns of the transformer or its output. At the position *Pl.* 1 the output is the largest and at *Pl.* 6 it is the smallest.

W_0 : the energy in watt-hours consumed by the transformer for one welding process, measured by a watt-hour meter.

P_0 : the mean power input in kilowatts of the transformer calculated from the energy consumption W_0 and the welding time T_0.

P : the mean power output of the transformer obtained by multiplying P_0 with the efficiency of the transformer at the corresponding load condition. The efficiency, power factor etc. of the transformer at each plug position are determined from experiments and drawn in curves for the output of the transformer in the appendix of the original paper, which is omitted in this translation.

TS : the tensile strenth in kilograms per square centimeter measured by a testing machine after lathing off the swell at the joint to the original diameter of the bar.

E : the elongation in mm, namely, the length measured between two gauge marks at the end of the tensile test. The gauge length is taken 8 times the diameter.

$E\%$: the elongation in percentage, namely,

$$E\% = \frac{E-\text{gauge length}}{\text{gauge length}} \times 100$$

d : the contracted or reduced diameter in mm. at the position of the break in the tensile test.

PB : the position of the break. The letter J indicates that the weld has broken at the joint, C that the break has taken place at the position of the contraction of the diameter several millimeters from the joint and the number indicates the distance of the break in mm. from the gauge mark, that asterisked denoting a break outside the gauge length.

In the next place we will briefly describe the welding conditions of each experiment.

(1) B—series. 73 welds of 5/16″ soft steel bars, the welding time being varied by changing the position of the plug. $S =$ about 10, $T = 1.8$.

(2) *C*—series. 85 welds of 5/16″ soft steel bars welded with varying the spring pressure. $T = 1.8$, $Pl = 4$.

(3) *D*—series. 50 welds of 3/8″ soft steel bars welded with varying the welding time. $S =$ about 6, $T =$ about 1.4.

(4) *E*—series. 52 welds of 7/16″ soft steel bars welded with varying the welding time. $S = 11$ to 15, $T = 2.0$.

(5) *F*—series. 54 welds of 1/2″ soft steel bars welded with varying the welding time. $S = 15$–17, $T = 2.0$.

(6) *G*—series. 41 welds of 1 cm soft steel bars welded with varying the welding time. $S =$ about 10, $T = 1.8$.

(7) *H*—series. 49 welds of 5/16″ hard drawn bars welded with varying the welding time. $S =$ about 10, $T = 1.8$.

(8) *I*—series. 49 welds of 3/8″ soft steel bars welded with varying the welding time. $S = 12$, $T = 1.8$.

(9) *J*—series. 20 welds of 1 cm soft steel bars welded with varying the welding time. $S = 15$, $T = 2.0$–3.0. All the welds of this series were tested with the swells at the joint unlathed.

(10) *K*(I)—series. 40 welds 3/8″ hard drawn bars welded with varying the spring pressure $Pl = 5$, $T = 2.0$. In the following series 3/8″ hard drawn bars were welded under various welding conditions.

(11) *K*(II)—series. 24 welds welded with varying the spring pressure. $Pl = 6$, $T =$ about 2.0.

(12) *K*(III)—series. 15 welds welded with varying the travel. $S =$ 15 mm, $Pl = 6$.

(13) *K*(IV)—series. 26 welds welded with varying the welding time. $S = 17.5$, $T = 2.0$–3.0.

(14) *K*(V)—series. 37 welds welded with varying the welding time. $S = 8.0$, $T = 2.0$–3.0.

(15) *K*(VI)—series. 38 welds welded with varying the welding time. $S = 12.5$. All the welds were annealed at a temperature of 840°C and then tested.

(16) *K*(VII)—series. 5 welds were made with varying the spring

pressure in order to make photographs of the typical forms of the joint.

(17) *K*(VIII)—series. 37 welds welded with varying the spring pressure. $Pl = 4$, $T = 2.0$–3.0.

(18) *K*(IX)—series. 18 welds welded with varying the welding time. $S = 12.5$, $T =$ about 3.0. All the welds were tested with the swells at the joints unlathed.

(19) *K*(X)—series. 26 welds welded with varying the welding time. $S =$ about 8, $T =$ about 2.5. All the welds were made with the contact surface surrounded with borax powder.

Table 5.

(1) *B*—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	1.8	10.4	9.5	5	8.7	3.01	2.65	—	—	—	—
2	"	7.0	"	"	6.4	3.29	2.88	4240	J	13.7	7.9
3	"	5.8	"	"	6.7	4.15	3.53	4100	26*		5.0
4	"	5.2	"	"	5.9	4.08	3.48	4120	13*		5.0
5	"	5.6	"	"	6.1	3.92	3.35	3680	16.7	22.5	4.8
6	"	8.4	"	6	6.3	2.70	2.30	3900	26*		5.2
7	"	3.6	"	4	5.8	5.80	4.85	3980	18*		4.8
8	"	2.6	"	3	5.8	8.03	6.63	3900	J	7.7	7.9
9	"	2.2	"	2	5.1	8.35	6.97	3580	"	13.4	7.9
10	"	9.4	"	6	7.4	2.83	2.38	—	—	—	—
11	"	10.2	"	6	7.3	2.58	2.20	4240	29*		5.3
12	"	10.2	"	6	7.6	2.68	2.27	4240	4	24.4	5.0
13	"	13.4	"	6	8.9	2.39	2.05	3980	7.5	25.8	5.3
14	"	29.0	"	6	15.0	1.86	1.63	4240	10	24.0	5.1
15	"	8.0	"	5	8.5	3.83	3.28	4100	7	25.1	4.9
16	"	5.0	"	"	6.5	4.68	3.92	3800	J	9.8	7.8
17	"	4.0	"	"	5.5	4.95	4.10	3980	"	5.7	7.7
18	"	4.6	"	"	6.1	4.78	3.98	2770	"	9.5	7.8
19	"	4 8	"	"	6.7	5.02	4.14	3260	"	12.0	7.9
20	"	4.8	"	"	6 6	4.95	4.10	4270	42*		5.0
21	"	4.8	"	"	5.9	4.42	3.72	43co	32*		5.5
22	"	4.2	"	4	6.3	5.40	4.57	3920	5	23.2	4.8
23	"	3.0	"	"	5.1	6.12	5.06	3190	7*		5.0

No.	T	T_0	S	Pl	W_0	V_0	P	TS	PB	$E\%$	d
24	1.8	4.4	9.5	4	6.4	5.23	4.44	3580	J	16.2	7.5
25	"	3.0	"	"	5.3	6.36	5.21	4080	9*		4.5
26	"	5.8	"	"	7.5	4.65	4.02	3840	J	13.9	8.0
27	"	4.8	"	"	6.9	5.18	4.42	3740	"	10.1	7.8
28	"	5.2	"	"	7.2	4.98	4.27	3260	"	14.0	7.7
29	"	4.0	"	"	6.3	5.67	4.77	3280	"	15.0	7.7
30	"	3.6	"	"	5.4	5.40	4.57	3580	17*		5.0
31	"	3.8	"	"	6.1	5.78	4.84	3780	J	14.2	7.7
32	"	3.4	"	"	5.6	5.93	4.93	4140	19*		4.5
33	"	2.0	"	3	4.4	7.93	6.56	4060	30*		5.0
34	"	2.0	"	"	5.0	9.00	7.28	3560	32*		4.9
35	"	2.2	"	"	5.2	8.51	6.95	2730	J	13.9	7.5
36	"	1.8	"	"	4.3	8.60	7.00	4210	17*		5.0
37	"	2.0	"	"	4.9	8.82	7.15	4240	J	13.5	7.5
38	"	2.0	"	2	—	—	—	4140	"	7.4	7.9
39	"	2.2	"	"	5.8	9.50	7.75	3480	"	3.9	8.0
40	"	1.8	"	"	5.0	10.0	8.07	3390	"	8.3	7.6
41	"	1.4	"	"	4.2	10.8	8.55	—	—	—	—
42	"	2.0	"	"	5.4	9.72	7.90	2770	J	3.9	7.9
43	"	2.6	"	"	6.1	8.45	7.05	3240	"	4.3	7.8
44	"	2.2	"	"	5.9	9.65	7.85	2730	"	13.1	7.6
45	"	1.6	"	1	4.9	11.0	9.10	4140	33*		5.0
46	"	1.6	"	"	4.9	11.0	9.10	3480	J	14.6	7.7
47	"	1.6	"	"	5.1	11.5	9.43	3970	"	9.8	7.7
48	"	1.8	"	"	5.4	10.8	8.95	3500	"	8.7	7.7
49	"	1.4	"	"	4.6	11.8	9.68	3540	14*		5.0
50	"	1.6	"	"	4.9	11.0	9.10	3340	J	8.0	7.8
51	"	14.0	10	6	8.4	2.16	1.87	3880	"	14.3	7.7
52	"	11.6	"	"	7.7	2.39	2.05	4020	25*		4.8
53	"	10.2	"	"	6.7	2.36	2.02	3480	J	7.9	6.7
54	"	17.0	"	"	9.6	2.03	1.77	4340	7*		4.8
55	"	9.2	"	"	6.5	2.54	2.16	3780	J	8.3	7.7
56	"	8.6	"	"	6.3	2.54	2.16	3480	"	4.3	7.9
57	"	7.2	"	"	6.2	3.10	2.60	3100	"	4.6	7.8
58	"	10.6	"	"	7.4	2.51	2.13	3800	"	7.2	7.8
59	"	4.2	"	5	5.3	4.54	3.82	2770	"	1.9	7.9
60	"	6.4	"	"	6.8	3.82	3.27	2590	"	2.4	8.0
61	"	4.0	"	"	5.3	4.77	3.97	3170	"	2.4	7.8
62	"	4.6	"	"	5.6	4.38	3.70	3170	"	2.4	7.8
63	"	4.0	"	"	4.7	4.23	3.58	3820	"	3.6	7.8
64	"	4.2	"	"	5.2	4.46	3.75	3520	14		4.1

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
65	1.8	3.8	10	5	4.8	4.55	3.82	3500	11*		4.2
66	„	4.6	„	„	5.5	4.30	3.64	3500	J	10.9	7.7
67	„	3.6	„	„	4.7	4.70	3.93	3480	11*		4.2
68	„	4.0	„	„	5.2	4.68	3.92	2830	J	8.5	7.7
69	„	3.4	„	„	4.4	4.66	3.75	3480	27.3	24.4	4.4
70	„	6.8	„	6	5.7	3.02	2.53	3480	J	7.1	7.7
71	„	8.0	„	„	6.1	2.74	2.32	2630	„	6.3	7.9
72	„	6.6	„	„	5.2	2.84	2.40	3030	„	6.8	7.8
73	„	6.8	„	„	5.4	2.86	2.40	2690	„	4.3	7.2

(2) *C*—Series

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	1.8	3.2	10	4	5.2	5.85	4.88	4350	J	18.0	7.2
2	„	3.0	„	„	5.4	6.48	5.30	3700	„	7.8	7.5
3	„	3.4	„	„	5.6	5.93	4.93	3890	C	24.4	4.1
4	„	4.0	„	„	5.9	5.31	4.50	4710	J	11.8	7.5
5	„	3.0	„	„	4.9	5.88	4.90	4150	„	15.9	7.1
6	„	3.0	„	„	5.1	6.12	5.05	4400	20	20.3	5.0
7	„	3.2	„	„	4.8	5.40	4.57	4100	19	21.3	4.4
8	„	4.2	„	„	6.3	5.40	4.57	3940	J	10.1	7.6
9	„	3.0	„	„	4.9	5.88	4.90	3480	„	9.3	7.3
10	„	3.2	„	„	5.2	5.85	4.88	3900	„	12.9	7.3
11	„	3.0	„	„	5.2	6.24	5.14	3740	„	11.8	„
12	„	3.2	11	„	5.5	6.19	5.10	3380	„	9.3	„
13	„	3.6	„	„	5.9	5.90	4.92	3440	„	6.3	7.6
14	„	3.4	„	„	5.4	5.72	4.80	2460	16	27.6	4.3
15	„	3.2	„	„	5.0	5.62	4.72	4140	C	22.8	4.6
16	„	2.0	„	„	4.1	7.38	5.84	3900	„	26.0	4.6
17	„	3.4	„	„	5.6	5.93	4.93	3860	13*		4.6
18	„	2.8	„	„	5.2	6.69	5.43	4070	C	26.0	4.5
19	„	2.8	„	„	4.7	6.04	5.02	3580	J	8.8	7.5
20	„	3.0	„	„	5.2	6.24	5.14	4040	„	15.0	„
21	„	2.4	„	„	4.9	7.35	5.83	4550	C	18.1	4.7
22	„	2.5	„	„	4.4	6.34	5.20	4000	J	15.6	6.8
23	„	3.0	„	„	5.0	6.00	5.00	3740	C	26.0	4.5
24	„	2.8	„	„	4.9	6.30	5.18	3740	12*		4.9
25	„	3.0	„	„	5.0	6.00	5.00	4320	C	26.0	4.9
26	„	2.4	„	„	4.5	6.75	5.45	4300	J	2.1	7.2
27	„	2.6	„	„	4.7	6.51	5.32	4320	10*		4.8
28	„	2.6	„	„	4.9	6.79	5.49	4140	8*	13.4	4.6

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
29	1.8	4.2	12	4	6.0	5.14	4.38	4350	15*	18.1	4.5
30	,,	4.4	,,	,,	6.0	4.90	4.20	4350	9	26.0	4.9
31	,,	3.4	,,	,,	5.4	5.72	4.80	4350	15*		4.3
32	,,	3.2	,,	,,	5.5	6.19	5.11	4680	18*		5.0
33	,,	2.2	,,	,,	4.6	7.53	5.93	4530	11	22.8	4.5
34	,,	3.6	,,	,,	5.6	5.76	4.83	4380	13*		4.3
35	,,	3.6	,,	,,	5.4	5.55	4.67	4270	J	11.6	7.1
36	,,	4.2	,,	,,	5.8	4.97	4.25	4410	,,	13.1	7.3
37	,,	4.2	,,	,,	5.3	4.54	3.93	4490	14	22.8	4.8
38	,,	4.6	,,	,,	6.4	5.00	4.28	4380	6*		4.2
39	,,	4.4	9	,,	6.4	5.23	4.44	4240	J	8.2	7.5
40	,,	3.6	,,	,,	5.3	5.30	4.50	4580	,,	11.8	7.4
41	,,	3.8	,,	,,	5.9	5.58	4.70	4040	,,	6.9	7.4
42	,,	5.8	,,	,,	7.3	4.53	4.93	4450	,,	18.9	7.2
43	,,	3.6	,,	,,	5.6	5.60	4.72	4140	,,	6.9	7.8
44	,,	4.4	,,	,,	6.5	5.32	4.52	3840	,,	3.5	7.7
45	,,	2.8	,,	,,	4.5	5.78	4.84	4210	,,	9.9	7.3
46	,,	3.4	,,	,,	5.4	5.72	4.80	4450	,,	10.2	7.3
47	,,	4.5	,,	,,	6.2	4.96	4.24	4380	,,	9.9	7.5
48	,,	4.2	,,	,,	6.3	5.40	4.58	3680	,,	6.8	7.6
49	,,	7.0	8	,,	9.0	4.63	4.00	2890	,,	1.6	7.9
50	,,	3.4	,,	,,	5.6	5.93	4.93	—	—	—	—
51	,,	4.8	,,	,,	6.9	5.17	4.40	2120	J	1.1	7.7
52	,,	2.8	,,	,,	5.0	6.43	5.25	3940	14	18.1	4.8
53	,,	2.6	,,	,,	4.7	6.50	5.31	4490	J	10.2	7.3
54	,,	3.2	,,	,,	5.3	5.96	4.95	3940	,,	3.3	7.7
55	,,	3.5	,,	,,	5.7	5.86	4.88	4300	,,	9.9	7.7
56	,,	3.0	,,	,,	5.2	6.24	5.14	4550	,,	19.7	7.0
57	,,	4.5	,,	,,	6.4	5.12	4.37	4780	,,	5.0	7.7
58	,,	5.2	14	,,	6.4	4.43	3.83	4550	19	29.2	4.5
59	,,	3.2	,,	,,	5.4	6.08	5.04	4450	6*		4.6
60	,,	4.2	,,	,,	6.4	5.48	4.63	4570	3.5*		4.5
61	,,	4.8	,,	,,	6.3	4.72	4.07	4550	22	24.4	4.5
62	,,	3.4	,,	,,	5.3	5.61	4.72	—	—	—	—
63	,,	3.2	,,	,,	4.8	5.40	4.57	4610	24*		4.3
64	,,	3.2	,,	,,	5.0	5.62	4.73	4550	17*		4.6
65	,,	3.3	5	,,	5.4	5.90	4.92	4550	7	26.0	4.3
66	,,	4.5	,,	,,	6.1	4.88	4.20	3640	J	4.6	7.7
67	,,	4.0	,,	,,	5.7	5.13	4.37	4180	,,	6.8	7.5
68	,,	4.3	,,	,,	5.5	4.60	3.97	3960	,,	3.5	7.2
69	,,	3.8	,,	,,	5.9	5.59	4.71	4140	,,	7.6	7.4

No.	T	T_0	S	Pl	W_0	F_0	P	TS	PB	$E\%$	d
70	1.8	3.4	5	4	5.3	5.61	4.72	—	—	—	—
71	,,	3.6	,,	,,	5.6	5.60	4.72	2630	J	1.3	7.8
72	,,	4.0	10	,,	5.8	5.22	4.43	4180	,,	10.2	7.4
73	,,	4.6	,,	,,	6.3	4.93	4.23	3840	,,	5.5	7.6
74	,,	3.8	,,	,,	5.4	5.12	4.36	4450	17	21.3	4.5
75	,,	4.6	,,	,,	6 3	4.93	4.23	4420	18	22.8	4.7
76	,,	3.0	,,	,,	4.5	5.40	4.57	5050	8*		4.5
77	,,	4.0	,,	,,	5.7	5.13	4.37	3740	J	5.5	7.7
78	,,	3.2	,,	,,	5.1	5.74	4.80	4240	,,	10.2	7.3
79	,,	3.6	16	,,	5.2	5.20	4.43	4350	13	27.6	4.3
80	,,	3.2	,,	,,	5.0	5.62	4.73	4270	C	26.0	4.3
81	,,	3.8	,,	,,	5.5	5.21	4.43	5090	,,	26.0	4.7
82	,,	3.4	,,	,,	5.2	5.51	4 65	—	—	—	—
83	,,	4.0	,,	,,	5.8	5.22	4.43	4300	12*		4.2
84	,,	4.2	,,	,,	5.7	4.88	4.19	4170	18	22.8	4.3
85	,,	3.8	,,	,,	5.2	4.92	4.22	4080	C	18.1	4.0

(3) *D*—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	1.2	4.2	5	6	2.8	2.40	2.05	2960	J	7.1	6.1
2	,,	4.0	,,	,,	2.5	2.25	1.96	2510	,,	7.3	6.2
3	,,	3.4	,,	,,	2.4	2.54	2.16	3270	,,	8.9	6.2
4	,,	4.0	,,	,,	2.7	2.43	2.08	2920	,,	7.1	6.2
5	,,	5.8	,,	,,	3.4	2.11	1.83	2450	,,	8.3	6.2
6	,,	4.0	,,	,,	2.5	2.55	1.96	3340	,,	9.1	6.2
7	,,	2.8	,,	5	2.9	3.73	3.20	2140	,,	8.9	6.2
8	,,	3.0	,,	,,	2.8	3.36	2.94	3110	,,	7.9	6.2
9	,,	3.4	,,	,,	2.9	3.07	2.70	2580	,,	8.1	6.2
10	,,	3.2	,,	,,	2.9	3.26	2.85	2580	,,	7 1	6.2
11	1.4	3.2	6	,,	2.6	2.93	2.58	3370	,,	10.6	6.7
12	,,	2.6	,,	,,	2.2	3.05	2.68	3900	15	27.2	4.0
13	,,	3.4	,,	,,	3.0	3.18	2.79	4020	9	23.6	3.7
14	,,	3.2	,,	,,	2.8	3.15	2.76	3890	5*		3.7
15	,,	2.2	,,	4	2.5	4.09	3.58	—	—	—	—
16	,,	3.0	,,	,,	2.9	3.48	3.08	3930	17*		3.8
17	,,	2.8	,,	,,	3.1	3.99	3.50	4000	19*		3.5
18	,,	1.8	,,	,,	2.2	4.40	3.83	3840	8*		3.6
19	,,	2.2	,,	,,	2.6	4.26	3.71	3710	J	14.9	6.0
20	,,	2.2	,,	,,	2.4	3.93	3.45	3870	8		3.7
21	,,	2.4	,,	,,	2.8	4.20	3.67	3960	J	14.9	6.0

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
22	1.4	2.6	6	4	2.9	4.02	3.52	3590	J	12.0	6.0
23	,,	1.4	,,	3	2.2	5.66	4.93	3960	10*		3.8
24	,,	1.4	,,	,,	2.5	6.43	5.50	3780	12*		3.8
25	,,	2.0	,,	,,	3.0	5.40	4.72	4070	10*		3.5
26	,,	1.6	,,	,,	2.3	5.18	4.55	3780	18*		3.5
27	,,	1.8	,,	,,	2.5	5.00	4.40	3810	13*		3.5
28	,,	1.6	,,	,,	2.4	5.40	4.72	3710	8	27.4	3.5
29	,,	1.4	,,	,,	2.4	6.17	5.31	3900	14*		3.5
30	,,	2.0	,,	,,	2.9	5.22	4.58	3710	J	11.8	6.1
31	,,	1.6	,,	,,	2.3	5.18	4.55	3610	9*		3.5
32	,,	1.2	,,	,,	2.2	6.60	5.63	3870	10	26.8	4.0
33	,,	1.4	,,	,,	3.0	7.71	6.41	3650	7.5	27.2	3.6
34	,,	1.2	,,	2	2.1	6.30	5.45	4010	O	23.6	3.7
35	,,	1.4	,,	,,	2.2	5.66	4.95	3930	12	29.2	3.6
36	,,	1.6	,,	,,	2.8	6.30	5.45	3810	15*		3.5
37	,,	1.2	,,	,,	2.0	6.00	5.22	4000	14	27.0	3.6
38	,,	1.0	,,	,,	2.3	8.28	6.92	4010	12*		3.8
39	,,	1.2	,,	,,	2.2	6.60	5.68	3750	,,		3.5
40	,,	1.2	,,	,,	2.3	6.90	5.91	3870	14*		3.5
41	,,	0.8	,,	1	2.1	9.45	8.00	4180	5	24.0	3.8
42	,,	1.0	,,	,,	2.3	8.28	7.15	3680	2	23.4	3.6
43	,,	1.2	,,	,,	2.4	7.20	6.28	3510	16*		3.5
44	,,	1.0	,,	,,	2.1	7.56	6.57	3490	25*		3.5
45	,,	1.2	,,	,,	2.4	7.20	6.28	3290	10*		3.5
46	,,	1.0	,,	,,	2.3	8.28	7.15	3590	O		3.5
47	,,	2.0	,,	4	2.3	4.14	3.63	3150		13.6	6.0
48	,,	2.4	,,	,,	2.7	4.05	3.55	3870	,,	12.4	6.0
49	,,	2.0	,,	,,	2.3	4.14	3.63	3930	,,	16.9	6.0
50	,,	2.6	,,	,,	2.8	4.88	3.41	3780	,,	14.2	6.0

(4) *E*—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	2.0	6.8	15	4	12.6	6.67	5.40	4040	15*		6.6
2	,,	5.2	,,	,,	10.1	7.00	5.62	3400	J	7.9	10.3
3	,,	6.4	,,	,,	11.4	6.42	5.25	3890	26	25.9	6.4
4	,,	6.6	14	,,	11.8	6.44	5.26	3530	J	10.1	10.2
5	,,	5.6	,,	,,	10.8	6.95	5.58	3560	,,	9.0	10.3
6	,,	10.8	13	,,	16.1	5.37	4.55	3560	,,	9.0	10.3
7	,,	7.8	,,	,,	13.3	6.14	5.07	3710	,,	10.1	10.2
8	,,	6.4	14	,,	11.6	6.53	5.32	3900	,,	15.7	10.3

No.	I	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
9	2.0	7.4	17	4	12.6	6.13	5.06	3950	27*		6.5
10	"	5.8	"	"	11.5	7.14	5.70	3840	13*		6.3
11	"	6.6	"	"	12.3	6.71	5.43	3760	J	13.5	9.9
12	"	3.8	15	3	10.0	9.48	7.57	3740	"	13.5	9.0
13	"	5.4	"	"	12.9	8.60	7.00	3500	"	10.1	10.0
14	"	3.6	"	"	9.6	9.60	7.65	3770	15*		6.0
15	"	4.2	"	"	11.0	9.44	7.55	3040	J	5.6	10.4
16	"	3.6	"	"	10.1	10.1	7.94	3810	"	15.7	10.2
17	"	4.2	13	"	11.2	9.60	7.65	3380	"	6.7	10.5
18	"	3.8	"	"	10.1	9.57	7.63	3670	"	12.4	10.1
19	"	3.6	11	"	10.5	10.5	8.15	3260	"	5.6	10.3
20	"	5.4	"	"	12.4	8.27	6.80	3300	"	6.7	10.4
21	"	4.4	"	"	11.1	9.10	7.35	3750	"	16.9	10.0
22	"	3.6	"	2	10.8	10.8	8.56	3810	"	15.7	10,0
23	"	3.6	"	"	10.7	10.7	8.50	3810	"	19.1	9.7
24	"	3.8	"	"	10.9	10.3	8.25	3880	10*		6.2
25	"	3.6	"	"	10.0	10.0	8.07	3860	11*		6.2
26	"	2.2	"	1	9.0	14.7	11.8	3860	14*		6.0
27	"	2.4	"	"	9 5	14.2	11.4	3860	4*		6.3
28	"	2.4	"	"	9.8	14.7	11.8	3860	15*		6.0
29	"	2.6	"	"	10.2	14.1	11.3	3920	9*		6.2
30	"	7.4	"	5	11.5	5.60	4.53	3060	J	5.6	10.3
31	"	10.0	"	"	15.0	5.40	4.40	2170	"	1.1	10.8
32	"	14.0	15	"	18.1	4.65	3.90	3920	"	16.9	10.2
33	"	11.8	"	"	16.1	4.91	4.07	3710	10	23.6	6.0
34	"	7.8	"	"	12.2	5.63	4.55	3560	"	9.0	10.4
35	"	7.4	"	"	12.0	5.85	4.68	3580	"	9.0	10.5
36	"	10.4	"	"	15.1	5.23	4.29	3200	"	6.7	10.5
37	"	12.2	"	"	15.9	4.69	3.92	3860	"	20.2	10.4
38	"	6.0	"	4	12.1	7.27	5.78	2630	"	1.1	10.8
39	"	7.0	"	"	13.6	7.00	5.62	3810	"	15.7	9.8
40	"	9.2	"	"	15.7	6.15	5.08	3920	25*		6.4
41	"	8.6	"	"	15.5	6.50	5.30	3900	J	16.9	10.2
42	"	7.2	"	"	13.8	6.90	5.55	3610	"	11.2	10.5
43	"	9.0	"	"	15.2	6.08	5.04	2790	"	1.1	10.8
44	"	8.2	"	"	14.9	6.55	5.33	2750	"	1.1	10.8
45	"	14.0	13	5	18.1	4.65	3.90	2830	"	1.1	10.7
46	"	9.0	15	"	13.4	5.36	4.37	3040	"	2.2	10 8
47	"	13.4	"	"	17.7	4.76	3.97	2830	"	1.1	10.8
48	"	12.8	"	"	16.9	4.75	3.96	3070	"	1.1	10.8
49	"	3.4	"	1	11.8	12.5	10.0	3650	"	10.1	10 5

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
50	2.0	3.0	15	1	10.6	12.7	10.2	3970	8*		6.0
51	,,	2.8	,,	,,	10.7	13.8	11.0	3880	5*		6.1
52	,,	3.0	,,	,,	10.8	13.0	10.4	3860	15*		6.4

(5) *F*—Serics.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	2.0	10.6	15	4	22.0	7.47	5.90	—	—	—	—
2	,,	7.6	,,	,,	17.0	8.06	6.23	—	—	—	—
3	,,	10.8	17	,,	20.7	6.96	5.55	3740	J	5.9	12.7
4	,,	16.6	15	,,	27.3	5.92	4.93	3040	,,	4.9	12.6
5	,,	8.2	,,	,,	18.2	8.00	6.20	3290	,,	6.9	12.5
6	,,	10.6	,,	,,	21.4	7.27	5.78	3680	,,	7.8	12.6
7	,,	8.0	,,	,,	17.9	8.07	6.23	3410	,,	5.9	12.7
8	,,	8.4	,,	,,	19.6	8.40	6.40	2830	,,	4.9	12.7
9	,,	8.2	,,	,,	18.1	7.95	6.16	3750	,,	4.9	12.6
10	,,	7.2	,,	3	20.2	10.1	7.93	3980	10	22.5	7.0
11	,,	5.8	,,	,,	18.1	11.2	8.52	3650	J	4.9	12.7
12	,,	6.6	,,	,,	20.3	11.1	8.47	3430	,,	4.9	12.7
13	,,	6.4	13	,,	18.2	10.2	7.99	3950	,,	18.6	12.0
14	,,	7.6	,,	,,	20.9	9.90	7.82	3580	,,	6.9	12.6
15	,,	7.4	,,	,,	19.9	9.68	7.70	3700	,,	7.8	12.7
16	,,	7.0	17	,,	20.6	10.6	8.20	3950	19	20.6	7.1
17	,,	11.4	,,	,,	24.0	7.58	6.33	3900	J	12.7	12.7
18	,,	6.6	,,	,,	19.0	10.4	8.10	4120	,,	12.7	12.5
19	,,	6.8	,,	,,	18.2	9.64	7.66	3390	,,	4.9	12.7
20	,,	5.2	,,	2	17.0	11.8	9.32	3870	13	24.5	7.5
21	,,	5.6	,,	,,	17.9	11.5	9.09	3950	11	21.6	7.5
22	,,	4.8	,,	,,	16.2	12.1	9.56	4090	C	21.6	10.1
23	,,	5.8	15	,,	18.1	11.2	8.80	4090	O	20.6	7.2
24	,,	5.6	,,	,,	17.3	11.1	8.75	3880	10	22.5	7.0
25	,,	5.4	,,	,,	17.6	11.7	9.25	4090	J	15.7	12.5
26	,,	4.6	,,	1	17.4	13.6	10.9	3780	9	20.6	7.2
27	,,	4.0	17	,,	16.1	14.5	11.6	3580	J	10.8	12.2
28	,,	4.6	,,	,,	18.4	14.4	11.5	3620	,,	9.8	12.5
29	,,	4.6	14	,,	16.8	13.2	10.6	3650	5	20.6	7.2
30	,,	11.2	17	5	20.5	6.59	5.09	4080	18	25.5	7.5
31	,,	11.2	,,	,,	20.1	6.46	5.03	4080	10	24.5	7.0
32	,,	9.0	18	,,	17.2	6.89	5.24	3500	J	4.9	12.7
33	,,	15.0	,,	,,	24.9	5.98	4.77	3500	,,	4.9	12.7
34	,,	12.8	16	,,	22.6	6.35	4.97	3860	10	20.6	

No.	T'	T	S	Pl	W'_0	F_0	P	TS	PB	$E\%$	d
35	2.0	11.6	16	5	21.0	6.52	5.05	3780	11	20.6	
36	,,	4.2	17	1	18.6	15.9	12.4	3730	J	12.7	
37	,,	4.4	,,	,,	18.1	14.8	11.5	3310	,,	6.9	
38	,,	4.2	,,	,,	18.4	15.8	12.3	3310	,,	6.9	
39	,,	3.8	,,	,,	16.6	15.7	12.2	3700	,,	10.8	
40	,,	12.6	,,	4	25.5	7.28	5.79	3660	,,	8.8	
41	,,	12.6	,,	,,	26.0	7.36	5.82	3620	,,	9.8	
42	,,	8.2	,,	,,	23.0	10.1	7.07	3860	5	21.6	
43	,,	9.6	,,	,,	21.6	8.10	6.25	3670	J	16.7	
44	,,	7.4	,,	,,	18.3	8.90	6.64	4050	18	27.5	
45	,,	7.4	,,	,,	17.6	8.56	6.47	3840	J	2.0	
46	,,	10.4	,,	5	18.8	6.51	5.05	4030	,,	6.9	
47	,,	19.6	,,	,,	28.6	5.25	4.30	3860	16	20.6	
48	,,	11.2	,,	,,	19.9	6.40	5.00	3570	J	8.8	
49	,,	11.8	,,	,,	20.7	6.32	4.95	3570	,,	7.8	
50	,,	16.4	,,	,,	25.7	5.49	4.46	3860	,,	6.9	
51	,,	11.4	,,	,,	19.9	6.51	5.05	3980	,,	14.7	
52	,,	12.6	,,	,,	22.3	6.38	4.99	4010	,,	8.8	
53	,,	12.0	,,	,,	21.5	6.45	5.02	4050	,,	7.8	
54	,,	11.4	,,	,,	20.0	6.32	4.95	4160	9	25.5	

(6) *G*—Series.

No.	T	T_0	S	Pl	W_0	F_0	P	TS	PB	$E\%$	d
1	1.8	2.2	11	2	6.8	11.1	8.75	3950	20	18.8	6.3
2	,,	2.4	,,	,,	6.9	10.3	8.26	4520	20	22.5	5.7
3	,,	2.4	,,	,,	7.6	11.4	8.90	4460	J	16.3	9.4
4	,,	2.2	,,	,,	7.2	11.8	9.20	4570	17	21.3	5.9
5	,,	2.2	,,	,,	7.0	11.5	8.95	4570	17	21.3	5.9
6	,,	2.4	,,	,,	7.4	11.1	8.75	4620	2	20.0	6.2
7	,,	2.2	,,	,,	7.2	11.8	9.20	4550	13	21.3	5.8
8	,,	3.0	,,	3	7.5	9.00	7.28	4500	25	21.3	6.0
9	,,	3.2	,,	,,	8.2	9.22	7.42	4460	J	10,0	9.6
10	,,	2.8	,,	,,	7.5	9.65	7.67	4480	,,	12.5	9.3
11	,,	2.8	10	,,	7.4	9.51	7.60	4520	7	17.5	5.9
12	,,	3.0	,,	,,	7.6	9.12	7.35	—	—	—	—
13	,,	2.8	,,	,,	7.8	10.0	7.87	4330	J	7.5	9.7
14	,,	3.0	,,	,,	7.3	8.76	7.10	4460	,,	16.3	9.2
15	,,	3.8	,,	4	7.5	7.10	5.67	4430	,,	15.0	9.3
16	,,	3.8	,,	,,	8.0	7.58	5.95	4430	,,	15.0	9.7
17	,,	3.8	,,	,,	7.8	7.39	5.85	4430	22	21.5	5.5

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
18	1.8	4.6	10	4	9.0	7.05	5.65	4080	J	2.5	9.8
19	,,	4.0	,,	,,	7.8	7.02	5.62	4430	,,	10.1	9.5
20	,,	4.2	,,	,,	9.1	7.80	6.07	3910	,,	2.5	9.9
21	,,	4.2	,,	,,	8.6	7.37	5.83	4270	,,	10.0	9.8
22	,,	5.0	,,	5	7.9	5.69	4.60	4430	,,	8.8	9.7
23	,,	4.6	,,	,,	7.5	5.87	4.70	4330	,,	10.0	9.6
24	,,	4.8	,,	,,	8.0	6.00	4.78	4270	,,	6.3	9.8
25	,,	5.4	,,	,,	8.7	5.80	4.65	3830	,,	1.3	10.0
26	,,	5.2	,,	,,	8.1	5.61	4.53	4240	,,	8.8	9.8
27	,,	5.4	9	,,	8.9	5.93	4.72	3700	,,	1.3	10.0
28	,,	4.8	,,	,,	8.1	6.07	4.82	3840	,,	3.8	9.6
29	,,	8.0	,,	6	9.0	4.05	3.20	3680	,,	0	10.0
30	,,	8.0	,,	,,	8.6	3.87	3.08	3670	,,	0	10.0
31	,,	8.2	,,	,,	8.9	3.91	3.10	3620	,,	0	10.0
32	,,	8.0	10	,,	8.9	4.00	3.17	3570	,,	1.3	10.0
33	,,	7.8	,,	,,	8.9	4.10	3.23	3620	,,	1.3	10.0
34	,,	8.4	,,	,,	8.8	3.77	3.04	3540	,,	2.5	9.8
35	,,	7.2	,,	,,	8.2	4.10	3.23	3290	,,	2.5	10.0
36	,,	8.6	,,	,,	9.3	3.89	3.10	3250	,,	0	10.0
37	,,	8.8	,,	,,	9.7	3.97	3.15	3060	,,	0	10.0
38	,,	8.0	,,	,,	8.9	4.00	3.17	3000	,,	0	10.0
39	,,	8.4	,,	,,	9.4	4.03	3.20	2980	,,	0	10.0
40	,,	8.4	,,	,,	9.2	3.94	3.13	3120	,,	0	10.0
41	,,	8.6	,,	,,	9.5	3.98	3.15	3110	,,	0	10.0

(7) *H*—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	1.8	1.2	9	1	3.3	9.90	8.34	4370	C	11.8	4.8
2	,,	1.2	10	,,	3.5	10.5	8.75	4350	,,	11.8	4.9
3	,,	1.0	,,	,,	3.3	11.9	9.52	4300	,,	11.5	4.8
4	,,	1.0	,,	,,	3.3	11.9	9.52	—	—	—	—
5	,,	1.2	,,	,,	3.6	10.8	8.95	4610	,,	11.8	4.7
6	,,	1.4	,,	,,	3.9	10.0	8.40	4380	,,	12.6	4.8
7	,,	1.6	,,	2	3.8	8.55	7.12	4160	J	5.5	7.9
8	,,	1.6	,,	,,	3.7	8.33	6.95	4430	C	11.8	4.8
9	,,	1.6	,,	,,	3.6	8.10	6.80	—	—	—	—
10	,,	1.6	,,	,,	3.6	8.10	6.80	4320	,,	11.8	4.8
11	,,	1.8	,,	,,	4.0	8.00	6.73	4180	,,	10.2	5.0
12	,,	1.6	,,	,,	3.8	8.55	7.12	4610	J	7.1	7.5
13	,,	2.4	,,	3	4.3	6.45	5.52	4470	C	11.0	5.0

No.	T	T_0	S	Fl	W_0	P_0	P	TS	PB	$E\%$	d
14	,,	2.0	10	3	3.8	6.85	5.80	4560	J	5.5	7.8
15	,,	2.2	,,	,,	4.6	7.53	6.30	4580	C	11.8	4.8
16	,,	2.2	,,	,,	3.9	7.02	5.93	4080	J	5.5	7.8
17	,,	2.2	,,	,,	3.9	7.02	5.93	4520	,,	7.1	7.6
18	,,	2.4	,,	,,	4.2	6.30	5.40	4550	C	13.4	5.0
19	,,	2.0	,,	,,	3.9	7.02	5.93	4520	J	5.5	7.8
20	,,	2.8	,,	4	4.3	5.53	4.66	4430	,,	7.1	7.6
21	,,	2.8	,,	,,	4.4	5.66	4.75	4450	C	13.4	5.8
22	,,	3.0	,,	,,	4.2	5.04	4.32	3760	J	7.1	7.8
23	,,	2.8	,,	,,	4.3	5.53	4.66	4450	C	13.4	4.8
24	,,	2.6	,,	,,	4.0	5.54	4.67	4390	J	7.1	7.2
25	,,	2.6	,,	,,	3.8	5.26	4.45	4450	C	13.4	4.6
26	,,	2.8	,,	,,	4.2	5.40	4.57	4360	J	8.7	7.3
27	,,	3.6	,,	5	4.1	4.10	3.50	—	—	—	—
28	,,	4.0	,,	,,	4.6	4.14	3.53	4060	,,	7.1	7.8
29	,,	3.6	,,	,,	4.3	4.30	3.64	—	—	—	—
30	,,	3.6	,,	,,	4.2	4.20	3.56	—	—	—	—
31	,,	3.8	,,	,,	4.5	4.27	3.60	4240	,,	7.1	7.5
32	,,	—	—	—	—	—	—	—	—	—	—
33	,,	4.0	8	,,	4.5	4.05	3.45	3390	,,	3.9	7.8
34	,,	3.8	,,	,,	4.5	4.27	3.60	3530	,,	3.9	7.8
35	,,	3.8	,,	,,	4.3	4.07	3.47	3760	,,	5.5	7.5
36	,,	3.6	,,	,,	4.2	4.20	3.56	3790	,,	3.9	7.6
37	,,	3.4	,,	,,	4.0	4.23	3.58	3790	,,	6.1	7.3
38	,,	3.8	,,	,,	4.5	4.27	3.60	3000	,,	3.0	7.9
39	,,	6.4	,,	6	4.9	2.76	2.33	2490	,,	2.4	7.9
40	,,	6.0	,,	,,	4.6	2.76	2.33	3180	,,	1.9	7.9
41	,,	5.8	,,	,,	4.9	3.04	2.55	3180	,,	1.9	7.9
42	,,	6.6	,,	,,	4.8	2.62	2.22	—	—	—	—
43	,,	7.0	10	,,	5.3	2.72	2.31	3090	,,	2.2	7.9
44	,,	6.4	,,	,,	5.1	2.87	2.41	3480	,,	2.8	7.7
45	,,	5.6	,,	,,	4.7	3.02	2.53	3590	,,	3.9	7.8
46	,,	6.4	,,	,,	5.3	2.98	2.50	4040	,,	10.4	7.5
47	,,	6.4	,,	,,	5.0	2.81	2.37	4040	,,	8.5	7.9
48	,,	5.8	,,	,,	5.0	3.10	2.60	3840	,,	5.5	7.9
49	,,	5.8	,,	,,	4.9	3.04	2.55	4350	,,	7.1	7.7

(8) *I*—Series.

No.	T	T_0	S	Fl	W_0	P_0	P	TS	PB	$E\%$	d
1	1.8	14.0	12	5	21.0	5.40	4.40	3940	16*		5.5

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
2	1.8	8.6	12	5	10.0	4.18	3.55	3860	3*		5.5
3	,,	9.0	,,	,,	10.6	4.24	3.60	3940	25*		5.2
4	,,	10.8	,,	,,	12.1	4.03	3.43	4010	26		5.2
5	,,	11.6	,,	,,	12.3	3.82	3.27	4020	J		9.2
6	,,	8.0	15	,,	9.8	4.41	3.72	4010	O		5.0
7	,,	7.8	,,	,,	9.1	4.20	3.56	3940	37		5.4
8	,,	7.0	,,	,,	9.1	4.68	3.91	4000	28*		5.0
9	,,	8.4	,,	,,	10.1	4.33	3.65	3970	28		5.3
10	,,	11.4	12	,,	12.0	3.79	3.25	3940	27		5.0
11	,,	13.2	,,	,,	13.0	3.55	3 06	4010	13		5.3
12	,,	5.0	,,	4	8.5	6.12	5.06	4010	J		9.2
13	,,	5.2	,,	,,	8.7	6.02	5.00	—	,,		9.2
14	,,	4.4	,,	,,	7.7	6.30	5.18	3700	,,		9.1
15	,,	5.2	,,	,,	8.5	5.88	4.90	4010	14*		5.5
16	,,	5.0	,,	,,	8.7	6.27	5.15	3980	2*		5.3
17	,,	6.6	,,	,,	10.1	5.51	4.65	3380	J		9.4
18	,,	5.4	,,	,,	8.7	5.70	4.79	3450	,,		9.2
19	,,	12.8	,,	,,	14.8	4.16	3.63	3880	22		5.0
20	,,	8 4	,,	,,	11.6	4.98	4.27	4190	34*		5.3
21	,,	4.8	,,	3	9.8	7.35	6.15	3490	J		9.3
22	,,	4.4	,,	,,	9.4	7.69	6.40	3620	,,		9.4
23	,,	6.2	,,	,,	11.2	6.50	5.55	4010	4		5.0
24	,,	3.6	,,	,,	8.0	8.00	6.60	4050	26*		5.0
25	,,	3.8	,,	,,	8.3	7.86	6.50	3710	J		9.2
26	,,	5.0	,,	,,	10.0	7.20	6.05	3700	,,		9.3
27	,,	4.6	,,	,,	9.6	7.50	6.27	3630	,,		9.4
28	,,	5.2	,,	,,	10.3	7.14	6.02	3800	,,		9.4
29	,,	4.0	,,	,,	8.3	7 47	6.24	3800	,,		9.0
30	,,	4.2	,,	,,	9.0	7.71	6.41	3500	,,		9.4
31	,,	3.4	,,	2	8.2	8.68	7.20	4010	20*		5.5
32	,,	3.0	,,	,,	7.8	9.36	7 66	3660	J		9.1
33	,,	3.4	,,	,,	8.5	9.00	7.43	3980	,,		9.0
34	,,	2.8	,,	,,	8.6	11.1	8.75	3670	,,		9.5
35	,,	3.0	,,	,,	8.2	9.84	7.97	4040	29*		5.7
36	,,	2.8	,,	,,	7.7	9.90	8.01	3940	15*		5.3
37	,,	3.0	,,	,,	8.2	9.84	7.97	2810	J		9.4
38	,,	2.6	,,	,,	7.5	10.4	8.32	2810	,,		9.3
39	,,	2.8	,,	,,	8.2	10.5	8.38	3940	,,		9.2
40	,,	2.8	,,	,,	8.0	10.3	8.25	3970	8*		5 5
41	,,	2.2	,,	1	7.2	11.8	9.44	4080	15*		5.3
42	,,	2.4	,,	,,	8.3	12.5	1.00	4050	10		5.2

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
43	1.8	2.2	12	1	7.9	12.9	10.3	4130	21*		5.3
44	,,	2.6	,,	,,	8.5	11.8	9.44	4020	2*		5.3
45	,,	2.4	,,	,,	8.3	12.5	10.0	4050	6*		5.2
46	,,	5.2	,,	5	7.5	5.19	4.26	4050	J		9.1
47	,,	10.0	,,	,,	11.6	4.18	3.55	4110	8*		5.0
48	,,	15.0	,,	,,	15.1	3.63	3.13	4180	18*		5.0
49	,,	11.4	,,	,,	12.5	3.95	3.36	4080	14*		5.3

(9) *J*—Series.

In the following series the output P is omitted except those necessary and R denotes the electric resistance in ohm inserted in the primary circuit of the transformer in order to regulate the welding time more gradually.

No.	T	T_0	S	Pl	W_0	P_0	R	TS	PB	$E\%$	d
1	2.4	3.6	15	4	8.0	8.00		4650	J	12.1	
2	2.0	4.0	,,	,,	7.8	7.02		4330	5.0	24.4	
3	2.0	4.0	,,	,,	8.0	7.20		4440	6.5	30.4	
4	2.2	4.2	,,	,,	8.6	7.37		3460	4.3	24.0	
5	2.4	3.2	,,	3	8.1	9.11		4450	5.0	26.3	
6	2.4	3.0	,,	,,	8.3	9.96		4070	J	7.5	
7	2.4	2.6	,,	,,	8.0	11.1		4230	,,	14.4	
8	2.4	2.6	,,	,,	7.5	10.4		3830	,,	8.75	
9	2.8	5.0	,,	5	8.4	6.05		4270	,,	—	
10	3.0	5.0	,,	,,	8.5	6.12		4530	27	24.7	
11	2.4	6.0	,,	,,	8.5	5.10	0.34	4500	22	27.4	
12	2.4	5.6	,,	,,	8.6	5.53	0.34	4530	23.7	26.3	
13	3.0	8.0	,,	6	8.8	3.93		4420	20	27.4	
14	2.4	7.0	,,	,,	7.8	4.01		4410	18	25.0	
15	2.4	8.8	,,	,,	9.1	3.72		4400	27	23.8	
16	2.0	8.4	,,	,,	8.9	3.81	0.34	4470	5.0	26.3	
17	3.0	10.2	,,	,,	9.8	3.46	0.72	4520	5.0*	18.8	
18	2.6	9.2	,,	,,	9.1	3.56	0.72	4520	0	18.8	
19	2.4	10.0	,,	,,	8.7	3.13	1.0	4330	25	26.3	
20	2.4	10.6	,,	,,	9.3	3.16	1.0	4370	6.0	23.8	

(10) *K*(I)—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
1	2.0	3.6	10	5	6.3	6.30		3730	J	5.3	9.0
2	,,	3.4	,,	,,	6.0	6.35		5600	,,	5.3	8.9

No.	T	T_0	S	Pl	W_0	F_0	P	TS	PB	$E\%$	d
3	2.0	3.6	10	5	6.6	6.60		3620	J	4.0	9.0
4	,,	4.2	,,	,,	7.0	6.00		3620	,,	4.0	9.1
'	,,	4.0	,,	,,	6.7	6.03		4220	,,	5.3	8.9
6	,,	3.6	12.5	,,	6.3	6.30		4200	,,	6.6	8.8
7	,,	3.4	,,	,,	6.0	6.35		4170	,,	6.6	8.6
8	,,	3 2	,,	,,	5.8	6.52		4270	,,	5.3	8.6
9	,,	3.2	,,	,,	5.7	6.41		4000	,,	5.3	8.9
10	,,	3.6	,,	,,	5.9	5.90		4160	,,	5.3	8.8
11	,,	4.0	15	,,	6.4	5.76		4300	C	13.2	5.5
12	,,	3.8	,,	,,	6.2	5.88		3760	J	6.6	8.7
13	2.0	3.6	,,	,,	6.2	6.20		4250	,,	6.6	8 7
14	1.2	3.8	,,	,,	6.1	5.78		4370	,,	9 2	8.7
15	,,	4.2	,,	,,	6.7	5.74		4310	,,	17.1	8.9
16	,,	3.6	17.5	,,	5.9	5.90		4760	C	13.2	5.7
17	,,	3.8	,,	,,	6.1	5.78		4720	,,	11.8	5.8
18	1.4	3.8	,,	,,	6.5	6.16		4690	,,	11.8	5.7
19	2.0	4.0	,,	,,	6.2	5.58		4690	J	6.6	8.6
20	,,	3.6	,,	,,	6.1	6.10		4670	C	11.8	6.0
21	—	—	—	—	—	—	—	—	—	—	—
22	1.0	4.0	8	,,	6.3	5.67		4370		5.3	8.9
23	2 0	3.6	,,	,,	6.5	6.50		4250	,,	5.3	8.9
24	1.0	3.6	,,	,,	6.1	6.10		4620	,,	5.3	8.9
25	1.2	3.6	,,	,,	6.3	6.30		4450	,,	4.0	8.9
26	1.4	3.6	,,	,,	6.4	6.40		4410	,,	4.0	8.9
27	2.0	3.8	,,	,,	6.8	6.45		4130	,,	5.3	9.0
28	1.4	3.8	,,	,,	6.3	5.97		4500	,,	4.0	9.0
29	1.0	4.0	,,	,,	6,7	6.03		4570	,,	6.6	8.8
30	1.2	3.6	,,	,,	6.3	6.30		4080	,,	5.3	9.1
31	2.0	3.8	9	,,	6.2	5.87		4270	,,	6.6	8.6
32	1.0	3.6	,,	,,	6.1	6.10		4250	,,	6.6	8.8
33	1.0	3.6	,,	,,	6.5	6.50		4200	,,	4.0	9.3
34	1.2	3.8	,,	,,	6.5	6.16		4070	,,	5.3	9.0
35	,,	3.8	,,	,,	6.4	6.06		3970	,,	5.3	9.0
36	,,	3.8	10	,,	6.4	6.[illegible]6		4300	,,	7.9	8.8
37	,,	3.4	,,	,,	6.6	6.99		4020	,,	4.0	9.0
38	,,	3.8	,,	,,	6.5	6.16		4020	,,	6.6	8.9
39	,,	3.6	,,	,,	6.3	6.30		3970	,,	5.3	8.9
40	1.0	3.4	,,	,,	6.2	6.57		3920	,,	5.3	8.9

(11) *K*(II)—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
41	2.0	6.6	8	6	7.4	4.03		3660	J	4.0	9.4
42	,,	6.6	,,	,,	7.4	4.03		3630	,,	2.6	9.4
43	1.2	7.0	,,	,,	7.3	3.75		3520	,,	2.6	9.5
44	,,	6.4	,,	,,	7.2	4.05		3520	,,	4.0	9.4
45	,,	6.0	9	,,	6.7	4.02		4580	,,	7.9	9.0
46	1.0	5.8	,,	,,	6.5	4.03		4620	,,	6.6	8.9
47	1.2	6.4	,,	,,	7.0	3.94		4350	,,	4.0	9.3
48	1.4	6.2	,,	,,	6.9	4.00		4180	,,	4.0	9.5
49	1.2	6.2	10	,,	6.8	3.95		4500	,,	5.3	9.1
50	1.4	5.8	,,	,,	6.3	3.91		4430	,,	4.0	9.5
51	2.0	6.4	,,	,,	7.1	3.99		4530	,,	6.6	9.0
52	,,	6.2	,,	,,	6.7	3.89		4470	,,	5.3	9.2
53	,,	6.2	12.5	,,	6.9	4.00		4500	,,	5.3	9.0
54	,,	6.4	,,	,,	7.2	4.05		4470	,,	5.3	9.3
55	,,	6.4	,,	,,	7.0	3.95		4270	,,	5.3	9.2
56	,,	6.6	,,	,,	7.2	3.93		4500	,,	5.3	9.0
57	,,	5.6	15	,,	6.7	4.30		4530	,,	5.3	8.9
58	,,	6.6	,,	,,	7.2	3.93		4210	,,	9.2	8.9
59	,,	6.0	,,	,,	6.5	3.90		4250	,,	6.6	8.9
60	,,	5.8	,,	,,	6.7	4.16		4100	,,	5.3	9.1
61	,,	5.6	17.5	,,	6.7	4.30		4470	,,	7.9	8.8
62	,,	5.8	,,	,,	6.5	4.03		4440	,,	7.9	8.6
63	,,	5.8	,,	,,	6.8	4.22		4380	C	14.5	5.5
64	,,	6.0	,,	,,	6.8	4.08		4380	,,	14.5	5.5

(12) *K*(III)—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
65	1.0	6.0	15	6	6.7	4.02		4330	J	7.9	8.5
66	,,	6.0	,,	,,	6.7	4.02		4370	,,	11.8	8.0
67	1.6	6.2	,,	,,	6.9	4.01		4280	,,	7.9	9.0
68	,,	6.4	,,	,,	7.0	3.94		4370	,,	7.9	9.0
69	3.0	6.0	,,	,,	6.6	3.96		4500	,,	7.9	9.0
70	2.6	5.2	,,	,,	6.4	4.43		4450	,,	5.3	9.2
71	1.4	6.6	,,	,,	6.9	3.76		4620	C	14.5	5.8
72	1.4	6.0	,,	,,	6.5	3.90		4130	J	4.0	8.9
73	1.8	6.0	,,	,,	6.2	3.72		4700	C	11.8	5.6
74	,,	6.4	,,	,,	6.8	3.83		4320	J	5.3	9.0
75	2.0	6.2	,,	,,	6.6	3.83		4550	,,	6.6	8.6
76	,,	6.6	,,	,,	7.1	3.87		4570	,,	7.9	8.8

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
77	3.0	6.6	15	6	7.0	3.82		4390	J	4.0	9.1
78	2.3	7.8	,,	,,	7.5	3.46		4150	,,	4.0	9.1
79	2.2	6.0	,,	,,	6.5	3.90		4600	,,	5.3	8.9

(13) K(IV)—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
80	2.8	6.2	17.5	6	6.6	3.83	3.05	4720	C	11.2	6.4
81	2.2	6.4	,,	,,	6.9	3.88	3.10	4730	,,	11.2	6.3
82	,,	6.8	,,	,,	7.0	3.71	3.00	4780	J	7.9	8.5
83	2.0	5.8	,,	,,	6.5	4.03	3.18	4720	C	11.8	6.1
84	,,	6.8	,,	,,	7.5	3.97	3.15	3800	J	2.6	9.4
85	3.0	7.0	,,	,,	7.3	3.75	3.03	4830	30	11.8	6.0
86	2.4	3.8	,,	5	6.1	5.78	4.65	4620	J	7.9	8.7
87	2.0	3.4	,,	,,	6.0	6.35	4.95	4080	,,	1.3	9.4
88	,,	4.0	,,	,,	6.5	5.85	4.68	4500	,,	5.3	8.9
89	,,	3.8	,,	,,	6.0	5.68	4.57	4420	,,	5.3	8.6
90	2.2	3.6	,,	,,	6.0	6.00	4.77	4500	,,	5.3	8.7
91	2.0	2.8	,,	4	5.8	7.46	5.88	4530	,,	5.3	8.7
92	,,	2.8	,,	,,	5.9	7.58	5.95	4220	,,	4.0	8.8
93	3.0	3.8	,,	,,	6.2	5.87	4.90	4390	,,	2.6	9.1
94	2.2	2.6	,,	,,	5.9	8.17	6.28	4310	,,	2.6	9.1
95	2.4	2.8	,,	,,	6.0	7.71	6.02	4700	,,	5.3	8.9
96	3.0	8.0	,,	6	6.7	3.01	2.53	4720	C	10.5	5.6
97	,,	8.6	,,	,,	7.2	3.01	2.53	4650	,,	11.8	5.5
98	2.4	9.4	,,	,,	7.2	2.76	2.34	4620	,,	11.0	5.8
99	3.0	11.0	,,	,,	7.8	2.55	2.17	4880	,,	11.0	5.8
100	2.5	11.0	,,	,,	7.5	2.45	2.10	4530	,,	11.0	5.5
101	2.4	3.6	,,	4	6.9	6.90	5.55	3580	J	7.9	8.9
102	,,	4.0	,,	,,	7.2	6.48	5.30	3520	,,	4.0	9.3
103	2.6	3.2	,,	,,	6.3	7.09	5.67	3660	,,	4.0	9.0
104	2.4	3.2	,,	,,	6.6	7.43	5.86	3450	,,	5.3	9.1
105	1.0	3.0	,,	,,	6.0	7.20	5.75	4500	C	11.8	6.0

(14) K(V) - Series.

The data in parentheses denote the resistance R

No.	T	T_0	S	Pl	W_0	P_0	P or R	TS	PB	$E\%$	d
106	2.4	3.8	8	4	7.1	6.72	5.44	3520	J	2.6	9.3
107	2.0	3.8	,,	,,	7.1	6.72	5.44	3420	,,	4.0	9.0
108	2.0	3.8	,,	,,	7.0	6.63	5.39	3940	,,	4.0	9.0

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
109	2.6	3.8	8	4	7.2	6.82	5.50	4080	J	4.0	9.1
110	3.0	2.8	,,	3	6.9	8.87	7.20	4420	,,	5.3	8.8
111	—	—	—	—	—	—	—	—	—	—	—
112	,,	3.6	,,	,,	6.9	8.28	6.80	3980	,,	5.3	9.1
113	,,	2.6	,,	,,	6.9	9.55	7.63	3910	,,	6.6	8.4
114	2.6	2.6	,,	,,	6.9	9.55	7.63	3940	,,	5.3	9.0
115	3.0	2.8	,,	,,	7.0	9.00	7.28	4020	,,	5.3	9.0
116	3.0	5.0	,,	5	7.3	5.26	4.32	3870	,,	2.6	9.0
117	,,	5.2	,,	,,	7.8	5.40	4.40	3420	,,	2.6	9.1
118	,,	5.0	,,	,,	7.8	5.62	4.54	3340	,,	2.6	9.3
119	,,	4.8	,,	,,	7.7	5.77	4.64	3130	,,	2.6	9.3
120	2.4	4.8	,,	,,	7.0	5.25	4.30	3680	,,	2.6	9.3
121	2.0	6.8	,,	6	7.3	3.86	3.07	3310	,,	1.3	9.3
122	2.4	6.8	,,	,,	7.2	3.81	3.05	2770	,,	1.3	9.4
123	—	—	—	—	—	—	—	—	—	—	—
124	2.0	6.6	,,	,,	7.2	3.93	3.12	3210	,,	2.6	9.3
125	3.0	5.8	,,	,,	6.8	4.22	3.30	3440	,,	2.6	9.1
126	2.2	6.2	,,	,,	7.0	4.07	3.22	3520	,,	2.6	9.3
127	2.2	7.2	,,	,,	7.3	3.65	(0.34)	3660	,,	2.6	9.2
128	2.0	7.0	,,	,,	6.9	3.55	,,	3990	,,	2.6	9.4
129	2.2	7.0	,,	,,	7.1	3.65	,,	3310	,,	2.6	9.5
130	,,	7.8	,,	,,	7.4	3.41	(0.72)	3170	,,	1.3	9.4
131	,,	8.4	,,	,,	7 6	3.26	(1.00)	2990	,,	1.3	9.4
132	2.4	8.2	,,	,,	7.6	3.34	,,	2510	,,	1.3	9.4
133	3 0	9.2	,,	,,	7.8	3.05	(1.4)	2700	,,	1.3	9.4
134	2.2	8.8	,,	,,	7.5	3.07	,,	3320	,,	1.3	9.3
135	1.8	10.0	,,	,,	7.6	2.74	(1.8)	3100	,,	1.3	9.5
136	2.2	10.4	,,	,,	7.6	2.63	,,	2960	,,	1.3	9.4
137	1.6	11.6	,,	,,	8.1	2.27	,,	2820	,,	1.3	9.4
138	2.0	3.6	,,	4	6.6	6.60	(0.34)	3590	,,	4.0	9.1
139	1.6	4.4	,,	,,	6.7	5.48	(0.72)	4050	,,	4 0	9.1
140	2.0	4.6	,,	,,	7.0	5.48	,,	3520	,,	2.6	9.3
141	1.8	7.0	17.5	6	7.2	3.70	—	—	—	—	—
142	1.6	7.6	8.0	,,	7.4	3.51	—	—	—	—	—

(15) *K*(VI)—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
147	1.6	3.4	12.5	4	6.1	6.46		3440	J	18.9	8.2
148	,,	3.2	,,	,,	6.3	6.98		3530	,,	—	8.6
149	1.2	3.2	,,	,,	6.3	6.98		3560	,,	—	8.3

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
150	1.2	2.8	12.5	3	6.2	7.97		3630	J	18.9	7.7
151	,,	2.6	,,	,,	6.1	8.45		3390	,,	13.5	8.7
152	1.3	2.8	,,	,,	6.1	7.85		3640	,,	20.3	8.1
153	1.2	3.0	,,	,,	6.1	7.32		3600	,,	16.2	8.8
154	1.8	3.8	,,	4	6.6	6.25		3390	,,	12.2	8.9
155	1.4	3.6	,,	,,	6.4	6.40		3440	,,	16.2	8.5
156	,,	3.2	,,	,,	6.5	7.31		3600	,,	18.3	8.8
157	1.8	3.4	,,	,,	6.8	7.20		3330	,,	13.5	8.9
158	,,	4.0	,,	5	6.6	5.94		3010	,,	10.8	9.0
159	2.0	4.2	,,	,,	6.9	5.91		—	—	—	—
160	,,	4.6	,,	,,	6.9	5.40		3090	,,	9.5	9.1
161	,,	4.0	,,	,,	6.4	5.76		3330	,,	12.2	8.9
162	,,	4.2	,,	,,	6.5	5.56		3260	,,	13.5	8.5
163	1.9	5.0	,,	,,	7.0	5.03		2940	,,	9.5	9.0
164	2.0	4.8	,,	,,	6.8	5.10		3060	,,	10.8	8.9
165	,,	4.8	,,	,,	7.0	5.25		2980	,,	9.5	9.0
166	,,	5.0	,,	,,	7.1	5.11		3220	,,	10.8	9.0
167	2.2	5.6	,,	,,	7.0	4.50		3200	,,	12.2	9.0
168	,,	5.4	,,	,,	6.9	4.60		3220	,,	9.5	8.9
169	—	—	—	—	—	—	—	—	—	—	—
170	2.0	7.0	,,	6	7.4	3.81		2900		10.8	9.0
171	,,	6.4	,,	,,	7.0	3.94		2940		—	9.2
172	1.8	6.4	,,	,,	7.1	3.99		3000	,,	6.8	9.0
173	2.0	6.8	,,	,,	7.2	3.81		3080	,,	9.5	9.0
174	1.8	6.6	,,	,,	7.3	3.98		2820	,,	5,4	9.0
175	2.0	7.0	,,	,,	7.4	3.81		2660	,,	2.7	9.1
176	1.8	6.8	,,	,,	7.0	3.70		3350	,,	10.8	9.0
177	2.0	8.6	,,	,,	7.7	3.22		2720	,,	6.8	9.1
178	,,	7.8	,,	,,	7.1	3.27		3090	,,	6.8	9.1
179	,,	7.8	,,	,,	7.4	3.41		2790	,,	8.1	8.9
180	,,	6.6	,,	,,	6.9	3.77		3240	,,	—	9 0

(16) *K*(VII)—Series.

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
181	2.0	6.8	17.5	6	—	—	—	—	—	—	—
182	—	—	—	—	—	—	—	—	—	—	—
183	—	—	—	—	—	—	—	—	—	—	—
184	,,	8.4	8	,,	—	—	—	—	—	—	—
185	,,	5.0	,,	5	—	—	—	—	—	—	—

(17) *K*(VIII) – Series.

No.	T	T_0	S	Pl	W_0	F_0	P	TS	PB	$E\%$	d
186	2.2	3.8	8	4	7.0	6.63		3790	J	4.0	9.1
187	3.0	3.8	,,	,,	7.4	7.01		3660	,,	4.0	9.0
188	2.2	3.8	,,	,,	7.1	6.73		3870	,,	2.6	8.9
189	2.0	3.4	,,	,,	6.4	6.78		3870	,,	4.0	9.1
190	,,	3.4	,,	,,	6.6	6.99		3820	,,	5.3	8.9
191	2.2	3.6	9	,,	7.0	7.00		3800	,,	4.0	8.9
192	,,	3.4	,,	,,	6.6	6.99		3900	,,	5.3	8.8
193	,,	3.4	,,	,,	6.4	6.78		4150	,,	5.3	8.8
194	,,	3.2	,,	,,	6.4	7.20		4020	,,	5.3	8.5
195	2.0	3.2	,,	,,	6.2	6.97		3940	,,	5.3	8.5
196	2.2	3.0	10	,,	5.9	7.08		3940	,,	5.3	8.5
197	3.0	3.4	,,	,,	6.6	6.99		3800	,,	4.0	8.5
198	2.4	3.4	,,	,,	6.4	6.78		3940	,,	5.3	8.5
199	3.0	3.4	,,	,,	6.4	6.78		4080	,,	5.3	8.6
200	2.4	3.0	,,	,,	6.1	7.32		4040	,,	4.0	8.5
201	,,	2.8	,,	,,	5.9	7.58		4200	,,	4.0	8.5
202	3.0	3.0	12.5	,,	6.4	7.68		3870	,,	2.6	9.1
203	,,	3.0	,,	,,	6.1	7.32		4300	,,	5.3	8.5
204	2.4	3.0	,,	,,	6.1	7.32		4080	,,	6.6	8.0
205	2.2	3.0	,,	,,	5.5	6.60		4500	,,	5.3	8.6
206	3.0	2.8	,,	,,	5.5	7.07		4370	,,	2.6	8.9
207	1.6	2.6	15	,,	5.7	7.89		4130	,,	4.0	8.8
208	3.0	2.4	,,	,,	5.3	7.95		4220	,,	5.3	8.7
209	2.4	3.2	,,	,,	5.8	6.52		4200	,,	2.6	8.7
210	,,	3.2	,,	,,	5.8	6.96		4300	,,	2.6	8.7
211	3.0	3.4	,,	,,	6.8	7.20		4480	,,	7.9	8.8
212	,,	3.8	,,	,,	7.1	6.73		4430	,,	7.9	8.8
213	,,	3.8	17.5	,,	7.0	6.63		4500	,,	7.9	8.6
214	,,	3.6	,,	,,	6.8	6.80		4310	,,	4.0	9.0
215	,,	3.4	,,	,,	6.3	6.67		4080	,,	4.0	8.9
216	,,	3.2	,,	,,	6.3	6.98		4080	,,	2.6	9.0
217	,,	3.2	,,	,,	6.0	6.75		3910	,,	1.3	9.1
218	,,	6.6	8	6	7.3	3.98		4300	,,	4.0	9.1
219	,,	6.6	,,	,,	6.9	3.76		3320	,,	0	9.4
220	,,	6.6	,,	,,	7.3	3.98		3320	,,	1.3	9.2
221	,,	6.0	,,	,,	6.5	3.90		4130	,,	4.0	9.1
222	,,	6.8	,,	,,	7.3	3.87		3860	,,	2.6	9.2

(18) *K*(IX)—Series.

No.	*T*	T_0	*S*	*Pl*	W_0	P_0	*P*	*TS*	*PB*	*E*%	*d*
223	3.0	6.2	12.5	6	6.9	4.01		4380	27	11.6	
224	,,	7.0	,,	,,	7.2	3.70		4670	26	11.6	
225	,,	6.4	,,	,,	7.1	3.99		4160	J	2.6	
226	,,	7.0	,,	,,	7.3	3.75		4470	,,		
227	,,	7.8	,,	,,	8.0	3.69		4300	23	11.6	
228	,,	6.6	,,	,,	6.8	3.71		4630	26	10.9	
229	,,	4.0	,,	5	6.3	5.76		4480	J		
230	,,	4.2	,,	,,	6.7	5.75		3660	,,		
231	,,	3.6	,,	,,	6.1	6.10		4540	,,		
232	,,	4.0	,,	,,	6.2	5.58		3700	,,		
233	,,	4.0	,,	,,	6.1	5.49		3950	25	10.9	
234	,,	4.2	,,	,,	6.7	5.75		4100	J		
235	,,	2.8	,,	4	5.9	7.59		4010	,,		
236	,,	3.2	,,	,,	6.3	7.09		4120	29	13.8	
237	,,	3.0	,,	,,	5.9	7.08		4000	29	13.8	
238	,,	2.6	,,	,,	6.0	8.30		4170	29	13.8	
239	2.4	3.0	,,	,,	5.9	7.08		4170	28.5	9.2	
240	3.0	3.0	,,	,,	5.8	6.97		4130	28.5	9.2	

(19) *K*(X)—Series.

No.	*T*	T_0	*S*	*Pl*	W_0	P_0	*P*	*TS*	*PB*	*E*%	*d*
241	2.0	6.4	8	6	7.2	4.05		3980	J	3.3	
242	,,	6.8	,,	,,	7.4	3.91		4460	,,		
243	,,	7.4	,,	,,	7.5	3.65		4170	,,		
244	,,	7.0	,,	,,	7.4	3.80		3940	,,	5.0	
245	,,	7.8	,,	,,	7.7	3.55		3080	,,		
246	2.5	4.8	,,	5	7.7	5.77		3500	,,		
247	,,	4.6	,,	,,	6.8	5.32		3750	,,	3.7	
248	,,	4.4	,,	,,	7.2	5.89		3790	,,		
249	,,	4.4	,,	,,	7.3	5.97		3680	,,	3.3	
250	,,	4.8	,,	,,	7.2	5.40		3760	,,	4.0	
251	,,	3.4	,,	4	7.0	8.00		4170	,,		
252	,,	3.6	,,	,,	6.8	6.80		4560	,,		
253	,,	3.8	,,	,,	7.5	7.10		4160	,,	4.6	
254	,,	3.2	,,	,,	6.3	7.08		4450	,,	4.6	
255	,,	3.0	,,	,,	6.4	7.68		4560	,,	9.2	
256	,,	2.6	,,	3	6.4	8.85		4320	,,		
257	,,	2.6	,,	,,	6.8	9.42		4140	,,	6.6	

No.	T	T_0	S	Pl	W_0	P_0	P	TS	PB	$E\%$	d
258	2.5	2.6	8	3	6.3	8.72		4520	J	7.3	
259	,,	2.2	,,	,,	6.1	9.98		4330	C	13.2	
260	,,	2.4	,,	,,	6.6	9.90		4130	J	9.0	
261	,,	4.4	,,	5	6.7	5.48		4120	,,		
262	,,	4.6	,,	,,	6.2	5.63		4240	,,	5.0	
263	,,	4.6	,,	,,	6.2	5.63		3830	,,	3.7	
264	2.0	4.0	12.5	,,	6.5	5.85		4240	,,	8.6	
265	,,	4.0	,,	,,	6.9	6.21		4170	,,	6.6	
266	,,	4.4	,,	,,	6.8	5.57		4240	,,	6.6	

Chapter VI. RELATIONS BETWEEN THE WELDING TIME, POWER AND ENERGY CONSUMPTION.

§ 1. RELATION BETWEEN THE WELDING TIME AND THE POWER.

We have in the first place found the relations between the welding time and the power input and output of the transformer. Fig. 15 shows an example in order to find the curves expressing these relations for the *G*—series taking the welding time T_0 in abscissa and the power input P_0 and the output P in ordinate. In the same way the curves for bars of the other diameters were found and are expressed in Fig. 16 and Fig. 17, in which the curves denoted by 3/8″ P, 5/16″ P and 1 cm P are those for bars with polished or lathed outer surfaces.

If we compare the curves for the polished and the ordinary surfaces of the above mentioned diameters, we will find that there exists a remarkable difference with regard to the power consumption. This fact can also be clearly explained by comparing, in the oscillograms in Fig. 5, the voltage drops between the bar and the clamping block.

The power consumption and the welding time are largely influenced by the condition of the outer surface for the ordinary round bar and the welding time is more or less irregular even under the same welding conditions. We must accordingly make the surface of the bars to be welded, especially the part clamped by the clamping blocks, as clean and free from rust as possible in order to obtain regular and good results with a shorter

Fig. 15.

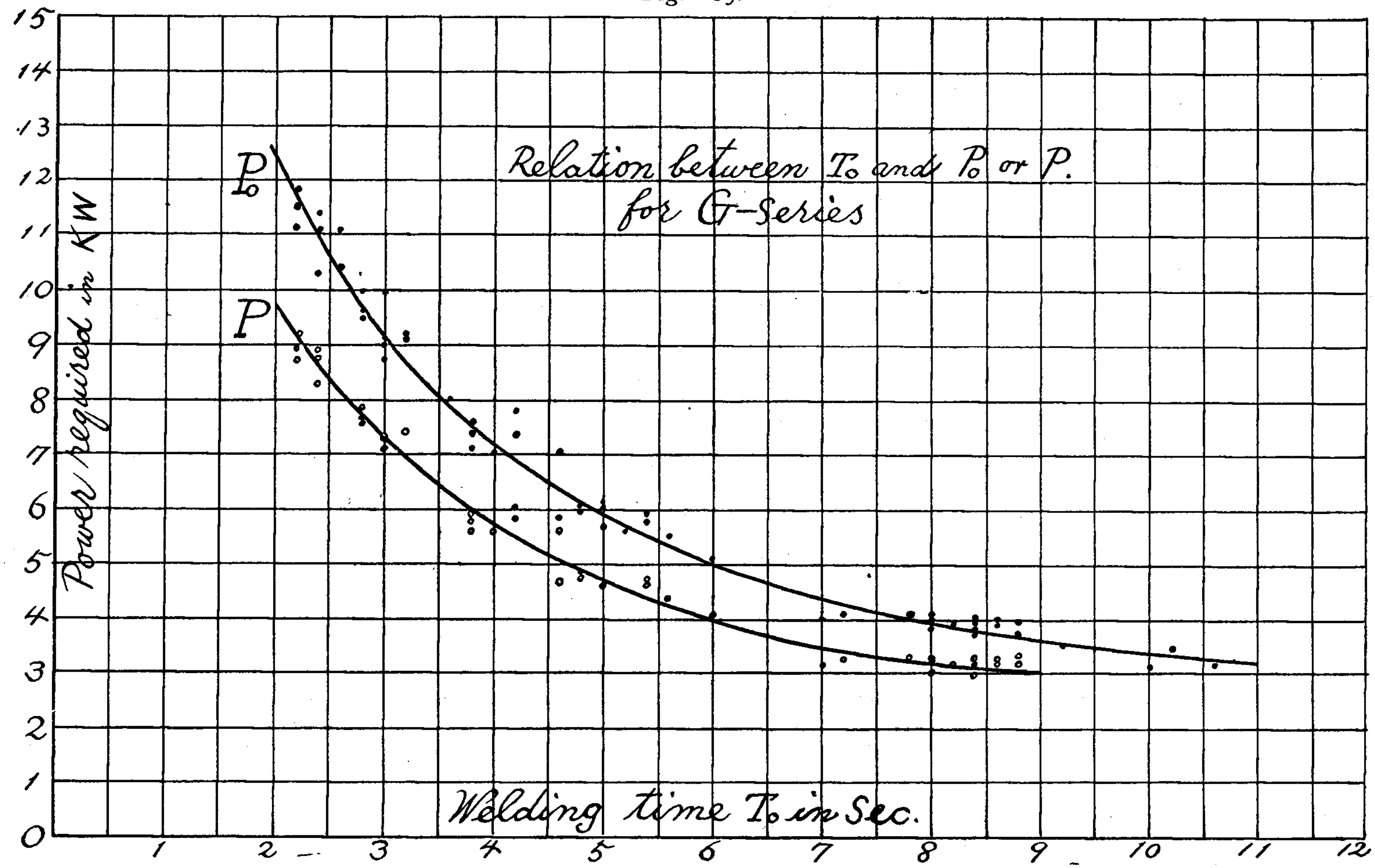

Relation between T_0 and P_0 or P.
for G-Series
P_0
P
Power required in KW
Welding time T_0 in Sec.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Fig. 16.

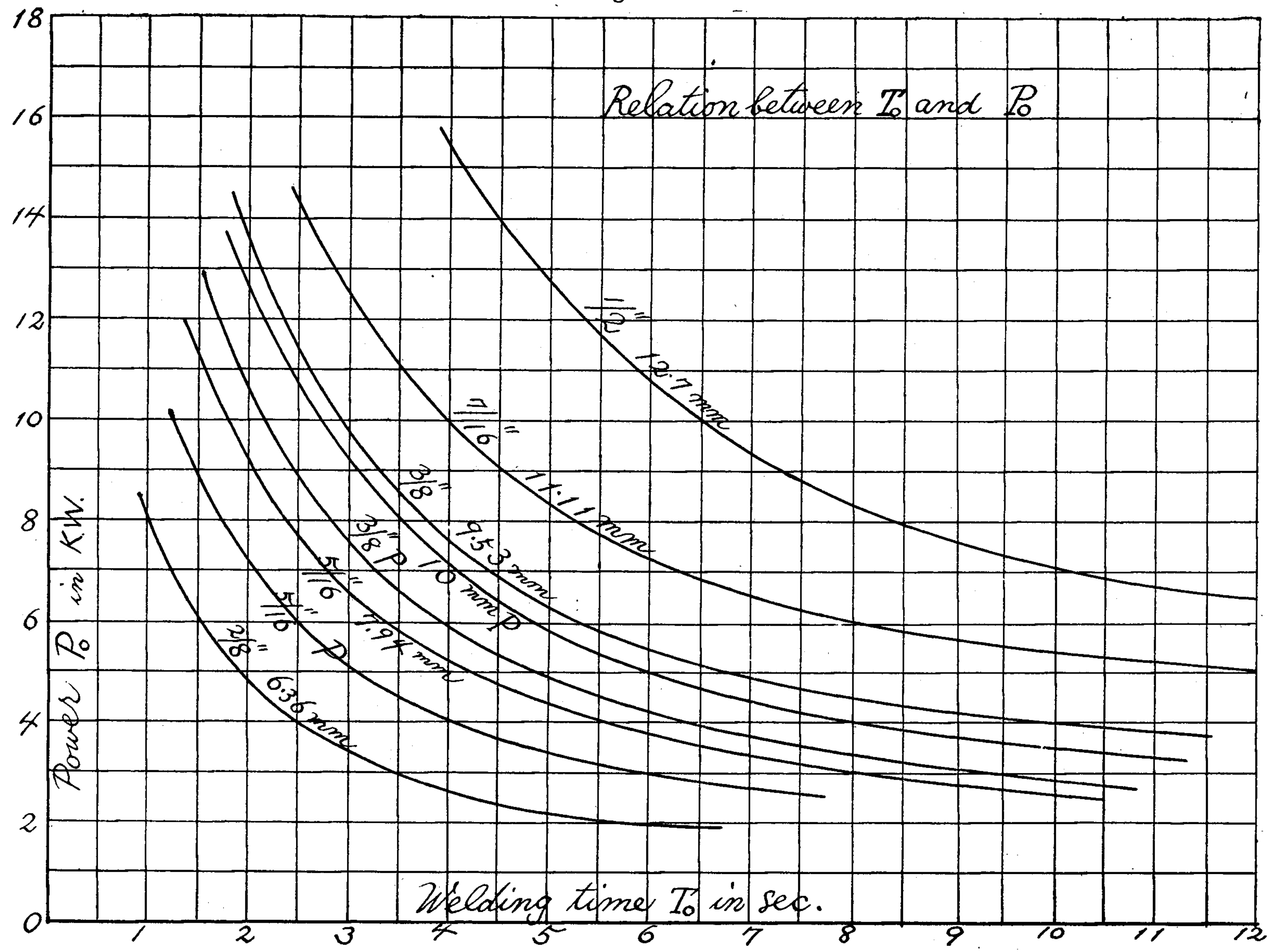
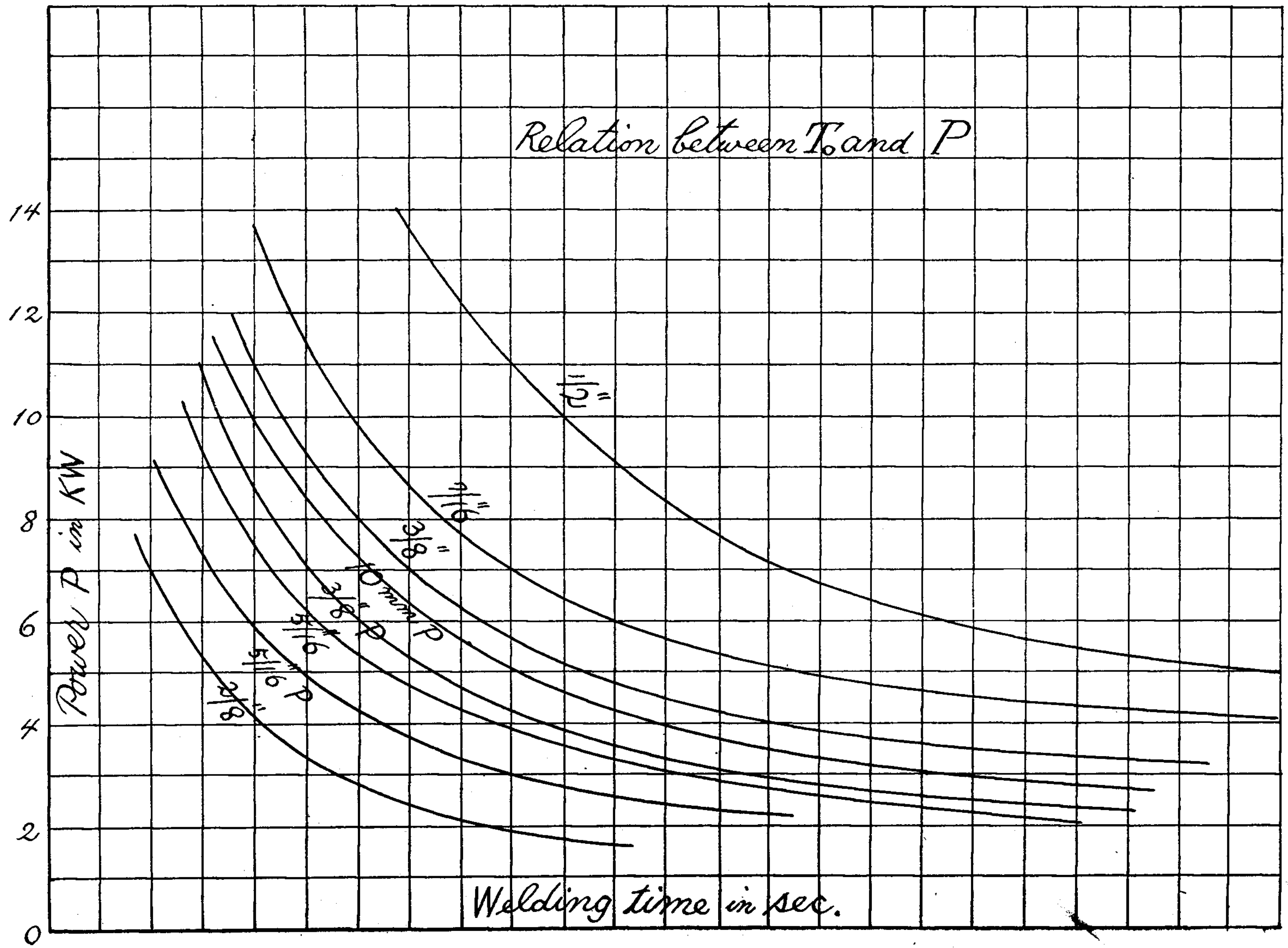

Relation between T_o and P_o
Power P_o in KW.
Welding time T_o in sec.
1/2" 12.7 mm
7/16" 11.11 mm
3/8" 9.53 mm
3/8" P 10 mm P
5/16" 7.94 mm
5/16" P
2/8" 6.36 mm
0
2
4
6
8
10
12
14
16
18
1
2
3
4
5
6
7
8
9
10
11
12

Fig. 17.


Relation between T_0 and P
Power P in KW
Welding time in sec.
0
2
4
6
8
10
12
14
1/2"
7/16"
3/8"
10mm P
3/8" P
5/16"
5/16" P
3/8"

welding time and a smaller power consumption.

Now we shall proceed to find the relation between the power consumption per sq. cm of the cross section of the bar and the welding time. The power consumption for various welding times were taken from Fig. 16 and divided by the cross sectional area *s*. They are tablated in the following table.

Table 6.

Dia.	$\frac{1}{2}''$	$\frac{7}{16}''$	$\frac{3}{8}''$	$\frac{5}{16}''$	$\frac{1}{4}''$	1 cm	$\frac{3}{8}''P$	$\frac{5}{16}''P$
				$T_0=2$				
s	1.27	0.971	0.711	0.495	0.318	0.785	0.711	0.495
P_0	—	—	13.4	9.0	4.65	12.4	10.4	7,05
P_0/s	—	—	18.9	18.2	14.6	15.8	14.6	14.2
				$T_0=3$				
P_0	—	12.4	9.65	6.45	3.3	9.05	7.45	5.05
P_0/s	—	12.8	13.6	13.0	10.4	11.5	10.5	10.2
				$T_0=4$				
P_0	15.2	9.85	7.53	5.1	2.6	7.1	5.85	3.95
P_0/s	12.0	10.1	10.6	10.3	8.2	9.05	8.23	7.98
				$T_0=5$				
P_0	12.5	8.2	6.2	4.2	2.2	5.8	4.85	3.35
P_0/s	9.85	8.45	8.72	8.7	6.92	7.4	6.83	6.77
				$T_0=6$				
P_0	10.6	7.2	5.4	3.75	2.0	4.95	4.15	3.0
P_0/s	8.35	7.42	7.6	7.58	6.3	6.3	5.84	6.06
				$T_0=7$				
P_0	9.2	6.5	4.9	3.3	—	4.4	3.7	2.7
P_0/s	7.25	6.7	6.9	6.67	—	5.6	5.2	5.46
				$T_0=8$				
P_0	8.2	6.0	4.45	3.0	—	3.95	3.3	—
P_0/s	6.45	6.18	6.27	6.07	—	5.03	4.64	—
				$T_0=9$				
P_0	7.55	5.65	4.2	2.75	—	3.6	3.05	—
P_0/s	5.95	5.82	5.9	5.56	—	4.58	4.29	—

From the above table it is seen that the value of the power consumption per unit area has a tendency to increase with the diameter of the bar. This is perhaps due to the fact that the power loss which takes place between the bar and the clamping block increases in proportion to the square of the welding current as the contact resistance between them is almost constant irrespective of the diameter of the bar.

The welding transformer used in our experiment was of a capacity of 7.5 k.w. and, from the point of view of the capacity and the efficiency, it is suitable for welding bars of the diameters of 7/8″, 3/8″ or 5/16″. This can also be justified by the fact that in the above table the values P_0/s for these diameters are nearer to each other than to those for the larger or the smaller diameters. The same can be said for the polished bars of the diameters of 1 cm, 3/8″ or 5/16″. We have therefore calculated the mean values of the power consumption per unit area for these two groups and also the ratio of the value of the polished to that of the ordinary bar and tabulated them as follows:

Table 7.

T_0	ordinary	polished	ratio in %
2	18.6	14.9	80.2
3	13.1	10.7	81.7
4	10.3	8.42	81.8
5	8.62	7.00	81.3
6	7.52	6.07	80.8
7	6.76	5.42	80 3
8	6.17	4.84	78.5
9	5.76	4.44	77.2

Fig. 18 shows the curves expressing these relations. We find that there is a difference of about 20% in the power consumption for the bars with ordinary and those with polished outer surfaces.

§ 2. RELATION BETWEEN THE WELDING TIME AND THE ENERGY CONSUMED.

As we have already stated, the heat loss due to the conduction along the bar or the transmission into the surrounding air increases with the welding time and accordingly the energy consumed for the welding must increase as much as the energy loss increases. We now proceed to

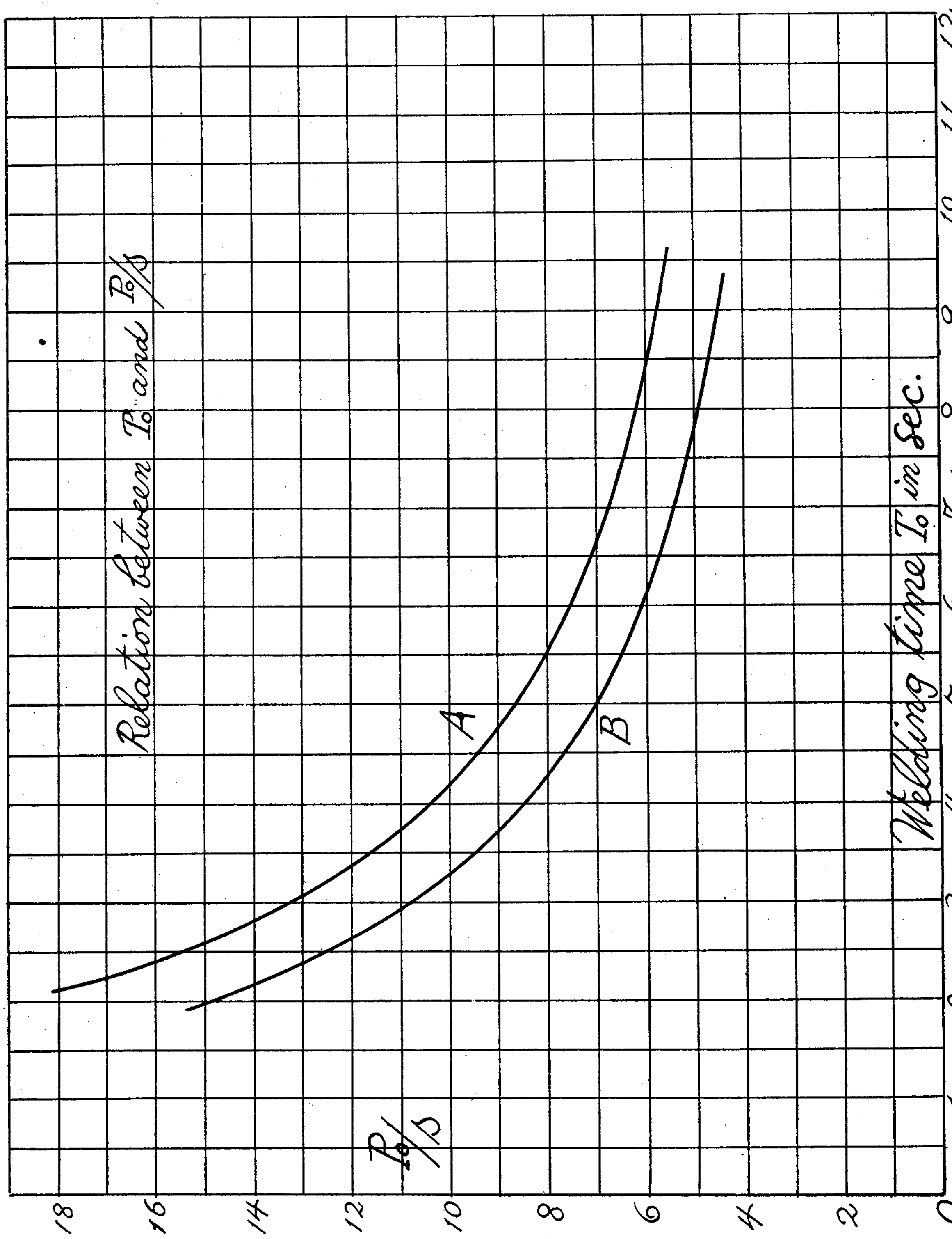
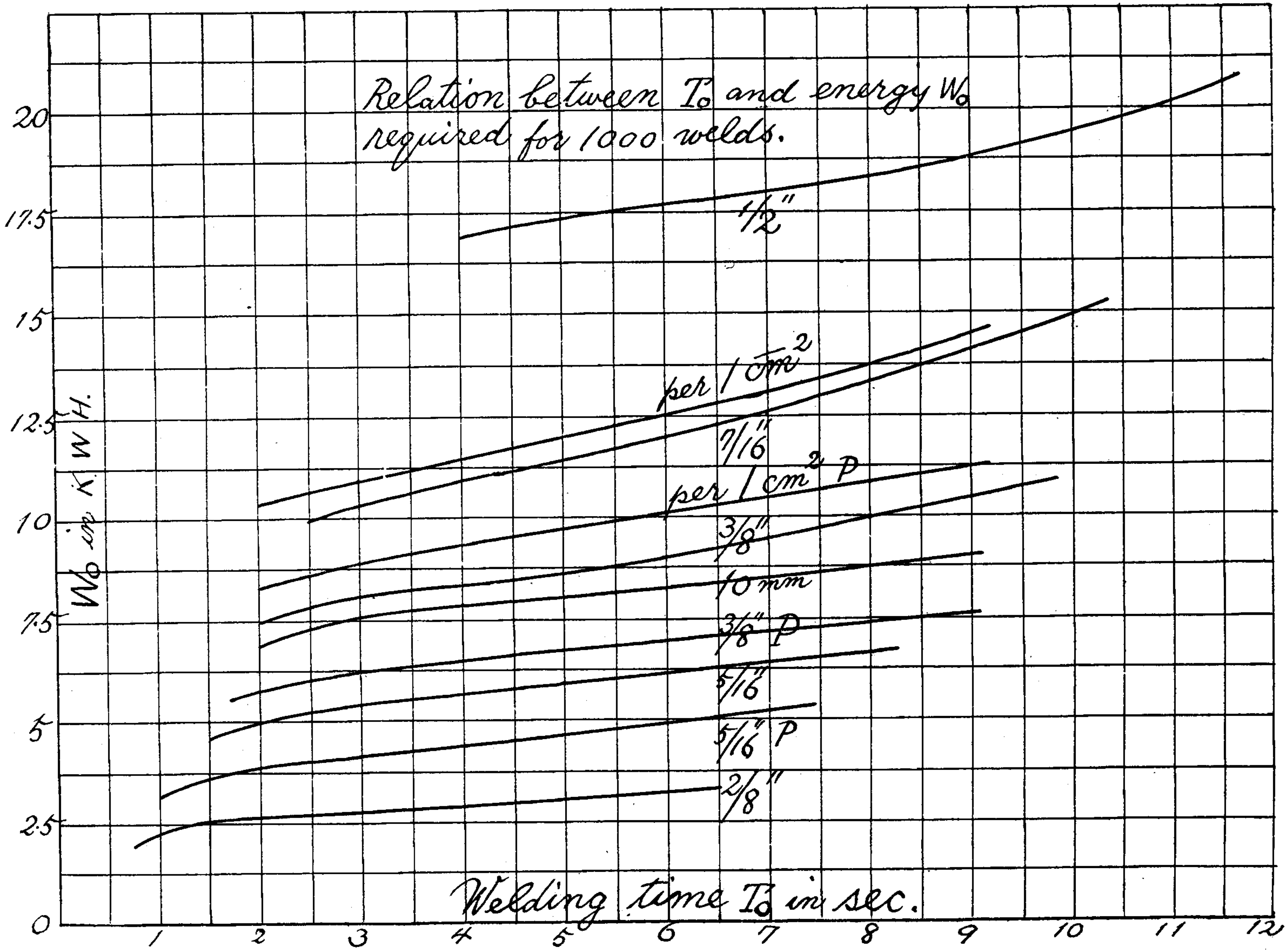

Relation between P_0 and P_0/S
Welding time T_0 in Sec.
A
B
P_0/S
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12

Fig. 18.

Fig. 19.


Relation between T_0 and energy W_0 required for 1000 welds.
W_0 in K.W.H.
Welding time T_0 in sec.
1/2"
per 1 cm²
7/16"
per 1 cm² P
3/8"
10 mm
3/8" P
5/16"
5/16" P
2/8"
0
2.5
5
7.5
10
12.5
15
17.5
20
1
2
3
4
5
6
7
8
9
10
11
12

find the relation between the welding time and the energy consumed for 1000 welds. Let T_0, P_0 and W_0 denote the welding time, the power input and the energy consumed in KWH respectively. Then we have

$$W_0 = \frac{T_0 \times P_0}{3600} \times 1000$$

From Fig. 16 we have taken the values of T_0 and P_0 for various diameters and calculated the values of W_0 and expressed the results with curves as shown in Fig. 19, taking T_0 in abscissa and W_0 in ordinate. In this figure the curves denoted by per 1 cm^2 or per 1 cm^2 P are calculated from Fig. 18 and hence correspond to the energy consumption per unit area of the cross section of the bar.

Chapter VII. EFFECT OF VARIOUS WELDING CONDITIONS ON THE TENSILE STRENGTH OF THE WELDS.

§ 1. EFFECT OF THE SPRING PRESSURE ON THE WELDING TIME AND THE TENSILE STRENGTH.

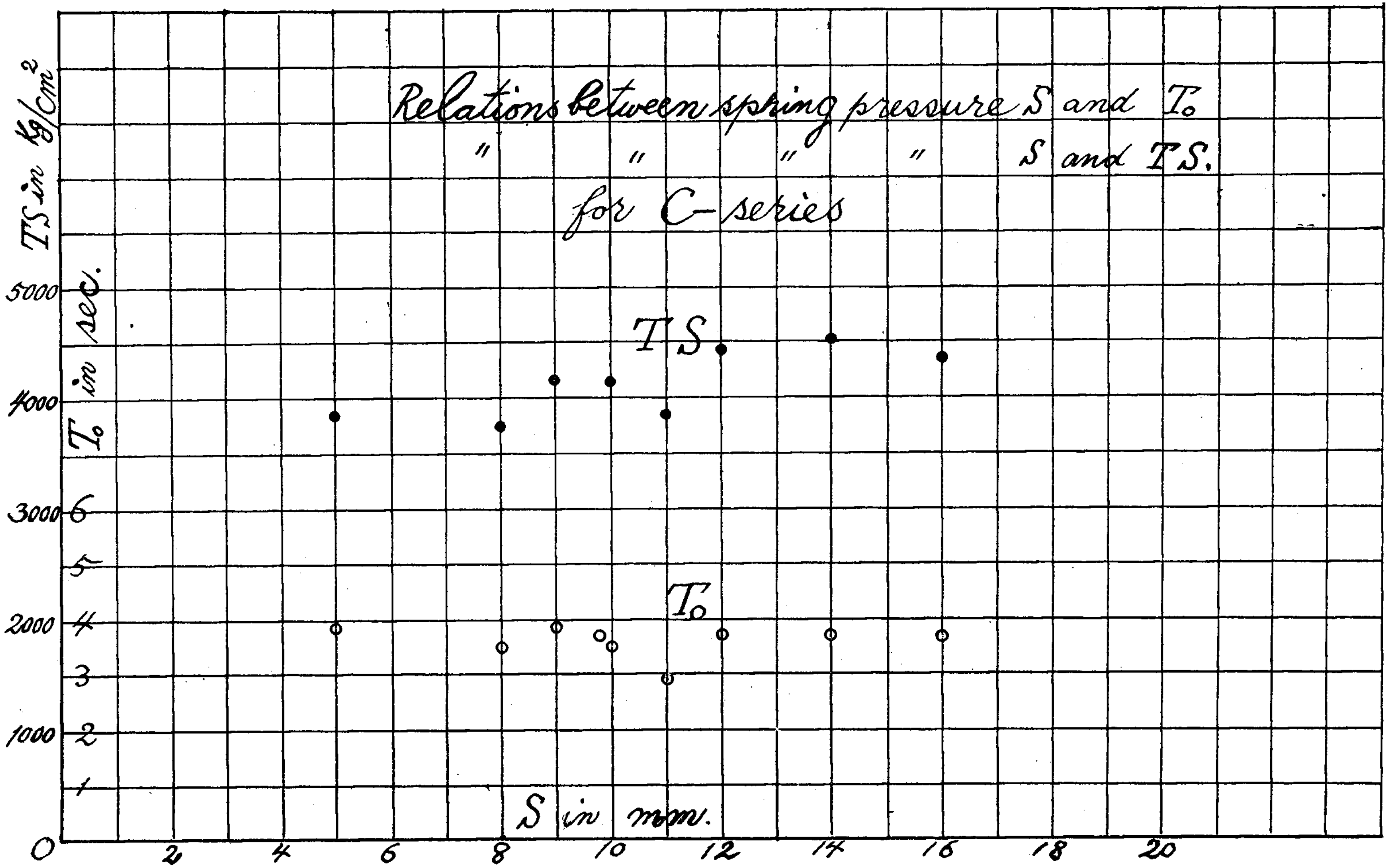
In the first place we measured the normal tensile strength and the elongation of the bars to be welded. The diameters of the bars tested were 5/16″ and 7/16″ for the ordinary and 3/8″ for the polished hard drawn bars, and the number of the test pieces was 15 each for the former and 10 for the latter.

The mean values of the tensile strength in kilograms per sq. cm and the elongation in percentage are as follows:

Diameter	5/16″	7/16″	3/8″ P
Tensile strength	4460	4100	5500
Elongation in %	28.1	30.1	12.8

Fig. 20 shows the relation between the spring pressure and the tensile strength as well as the welding time of the welds for the *C*—series, the spring pressure S in mm being taken in abscissa, the tensile strength

Fig. 20.


Relations between spring pressure S and T_0
" " " " S and TS.
for C-series
TS in kg/cm²
T_0 in sec.
TS
T_0
S in mm.
5000
4000
3000
2000
1000
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20

TS in kilograms per square cm and the welding time in seconds in ordinate.

Each of the dots in the graph represents the mean value of several test results.

The value of the welding time seems to have a tendency to decrease very slightly for the larger values of the spring pressure, but it remains in this case almost constant throughout all the spring pressures. The amount and the manner of changing of the voltage drop across two · butt surfaces in the oscillograms shown in the preceding chapter is the same and independent of the spring pressure, and therefore the rate of heat generation and also the temperature rise are not influenced by it. Hence the phenomenon that the welding time is scarcely influenced by the spring pressure is perhaps due to the fact that it requires a certain time interval for the metal to soften or melt and in this case the welding time of about 3.5 seconds corresponds to this time interval.

But the tendency of the welding time to decrease slightly with the increasing pressure becomes somewhat evident when the welding time is made longer, as we will show in the following figures.

The mean values of the tensile strengths and the welding times for the *C*—series are as follows:

S	p/s	T_0	TS
5	34.9	3.84	3850
8	55.8	3.48	3750
9	62.7	3.86	4200
10	69.7	3.54	4180
11	76.7	2.87	3880
12	83.7	3.74	4420
14	97.6	3.67	4550
16	111.0	3.71	4370

In the above table p/s denotes the spring pressure in kilograms per square cm of the cross sectional area of the bar.

The tensile strength has a tendency to increase with the increasing spring gressure. This phenomenon can easily by explained if we compare the microphotographs of the *B*— and the *C*—series in Fig. 14, the welded joint with the smaller spring pressure containing a larger quantity of oxides and other mixtures, and also if we compare the hardness in the neighborhood of the joint for both cases as is shown in § 2 Chapter IV.

We have found the same relation with regard to the *K*(I)—series, in which 3/8″ hard drawn bars were welded with a definite plug position *Pl* = 5 and with varying spring pressure. In finding the mean values we have picked out as many of the test results belonging to the other series as possible, which were welded with the same conditions as in this series, and got the following results.

S	p/s	T_0	TS
8	38.9	4.17	4060
9	43.7	3.72	4140
10	48.6	3.68	4100
12.5	60.7	3.40	4150
15	72.8	3.88	4190
17.5	85.0	3.74	4570

This result is shown in Fig. 21, in which the welding time remains almost constant as before except that corresponding to the spring pressure 8 mm, and the tensile strength has the same tendency to increase with the increasing spring pressure.

Fig. 22 shows the same relation with regard to the *K*(II)—series, in which 3/8″ hard drawn bars were welded with *Pl* = 6 and with varying spring pressure. The mean values calculated in the same way as in the above series are as follews:

S	p/s	T_0	TS
8	38.9	6.53	3540
9	43.7	6.10	4430
10	48.6	6.15	4480
12.5	60.7	6.40	4430
15	72.8	6.21	4390
17.5	85.0	6.15	4610

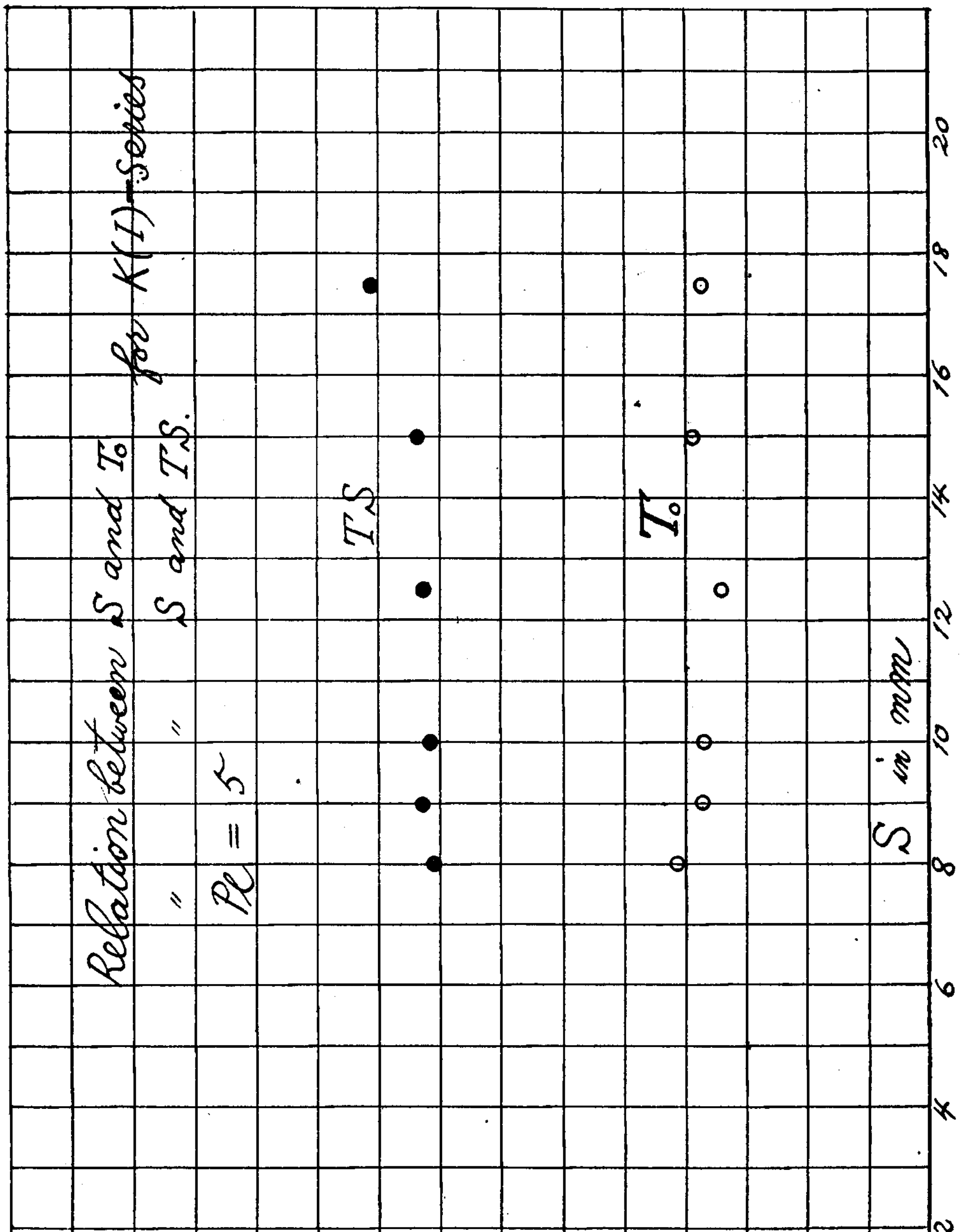
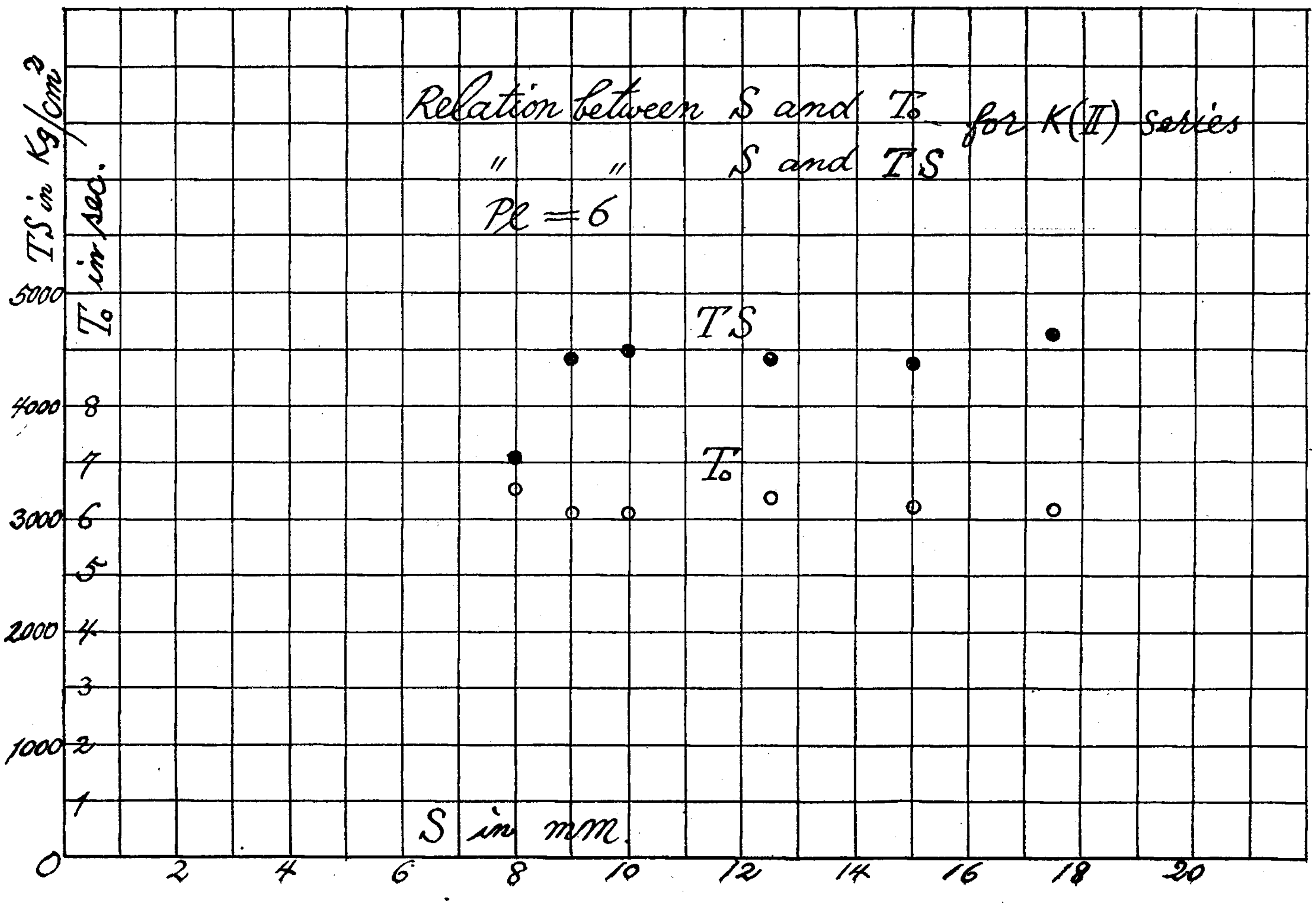

Relation between S and T_0 for K(I)-series
" " S and TS.
Pc = 5
TS
T_0
S in mm
T_0 in sec
TS in kg/cm^2
0
2
4
6
8
10
12
14
16
18
20
1
2
3
4
5
6
1000
2000
3000
4000
5000

Fig. 21.

Fig. 22.


Relation between S and T_0 for K(II) series
" " S and TS
Pl = 6
TS in Kg/cm²
T_0 in sec.
TS
T_0
S in mm.
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
2
4
6
8
10
12
14
16
18
20

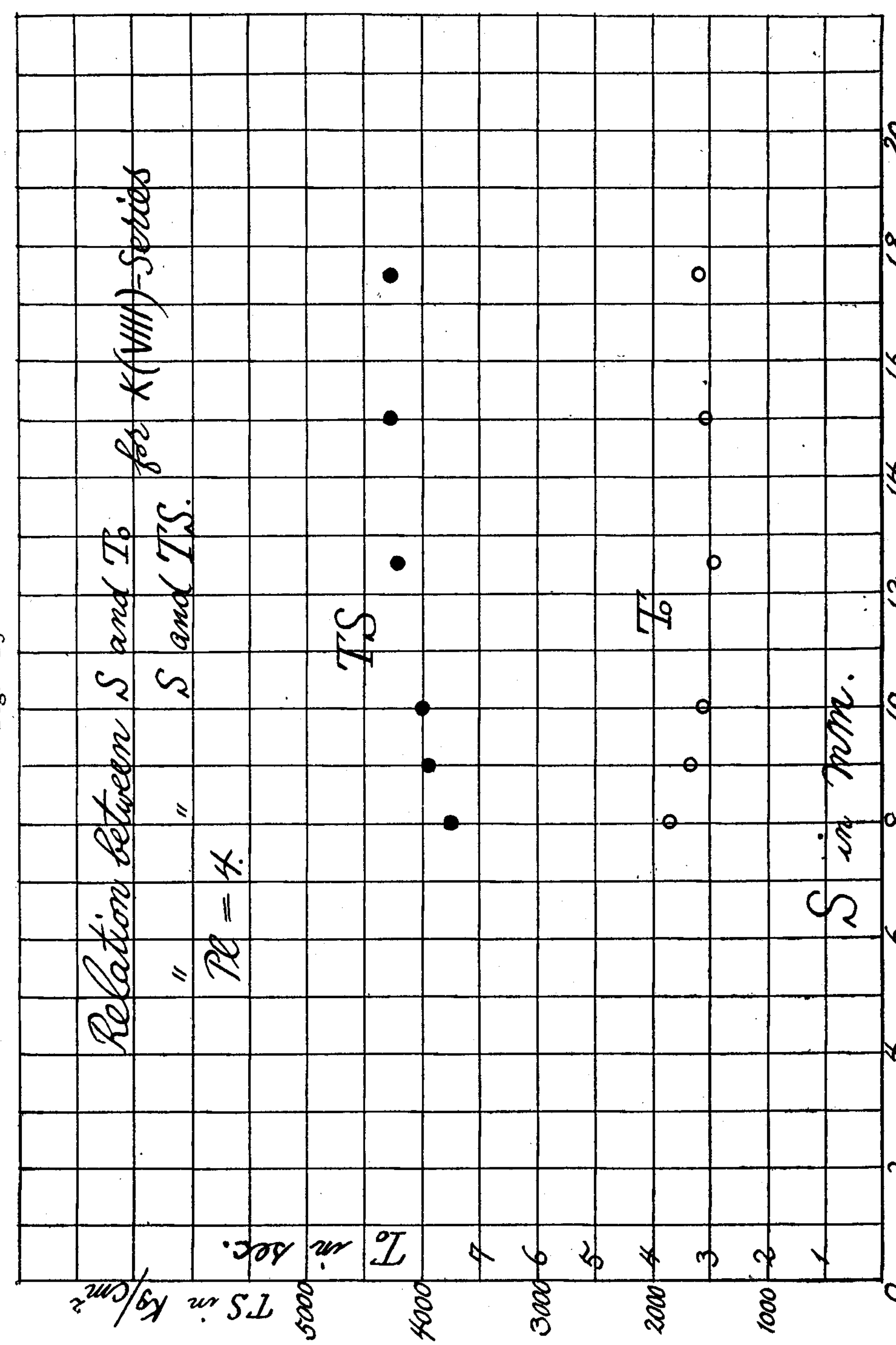

Relation between S and T0 for K(VIII)-Series
" " S and TS.
Pc = 4.
TS
T0
S in mm.
T0 in sec.
TS in kg/cm²

Fig. 23

In this graph it can be recognized that the welding time seems to decrease a little when the spring pressure increases. This is owing, as we have mentioned before, to the longer welding time.

Fig. 23 shows the same relation with regard to the K(VIII)—series, in which the same bars were welded with $Pl = 4$ and varying spring pressure. The calculated mean values are as follows:

S	p/s	T_0	TS
8	38.9	3.71	3780
9	43.7	3.36	3950
10	48.6	3.17	4000
12.5	60.7	2.96	4220
15	72.8	3.07	4290
17.5	85.0	3.20	4300

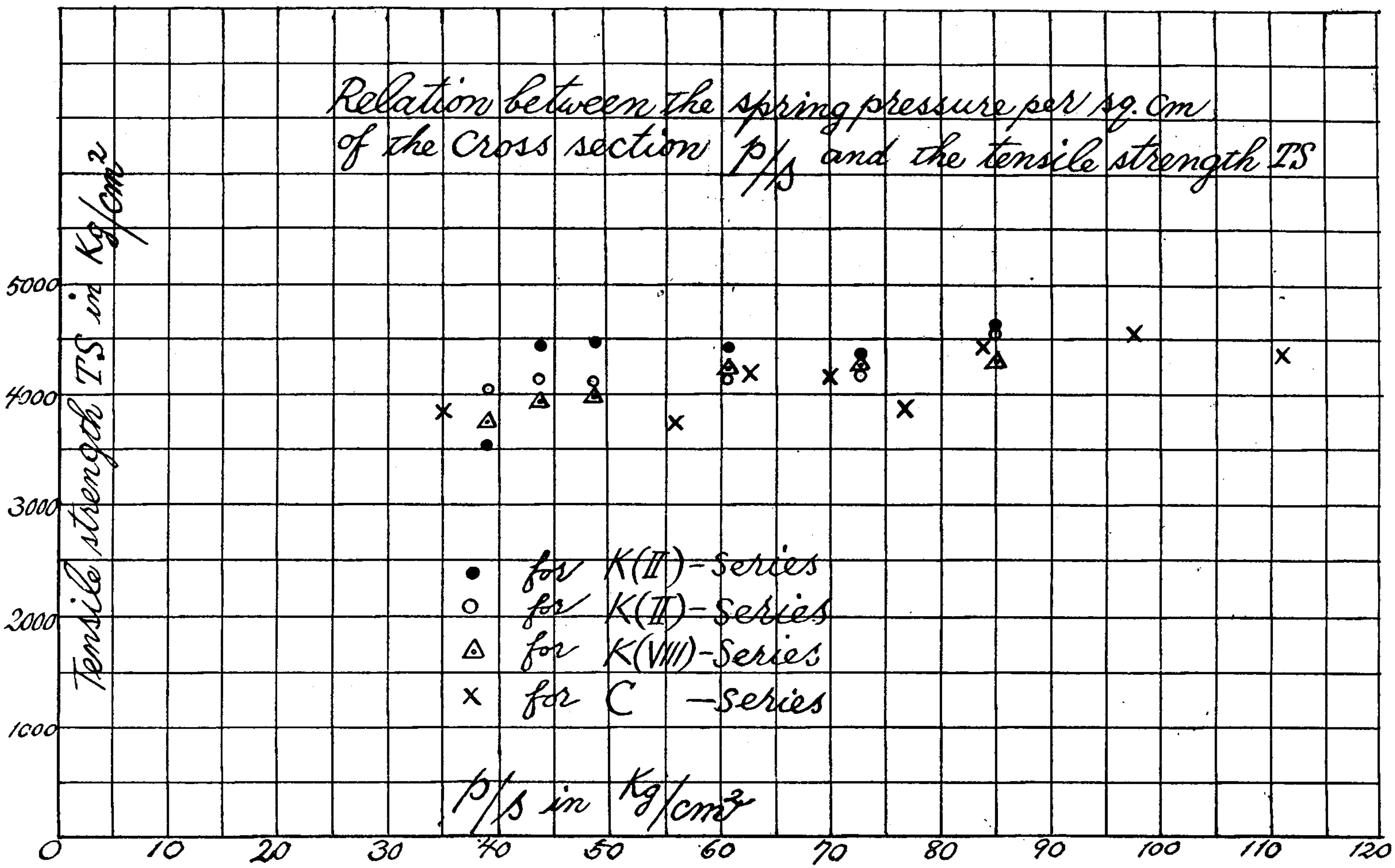
In Fig. 24 we have plotted these relations between the tensile strength and the spring pressure at the same time, taking the spring pressure per unit area of the cross section p/s in kg/cm^2 in abscissa and the tensile strength in ordinate in order to make clear the above mentioned tendency of the tensile strength.

§ 2. EFFECT OF THE TRAVEL ON THE TENSILE STRENGTH.

One of the bars to be welded is pressed against the other by the spring pressure and it is thus shifted towards the other by a distance called the travel at the end of the process, cutting out automatically the supply of the primary current at the same instant. We have made a series of experiments, in which all the bars were welded under the same conditions except the amount of the travel in order to see its effect on the tensile strength.

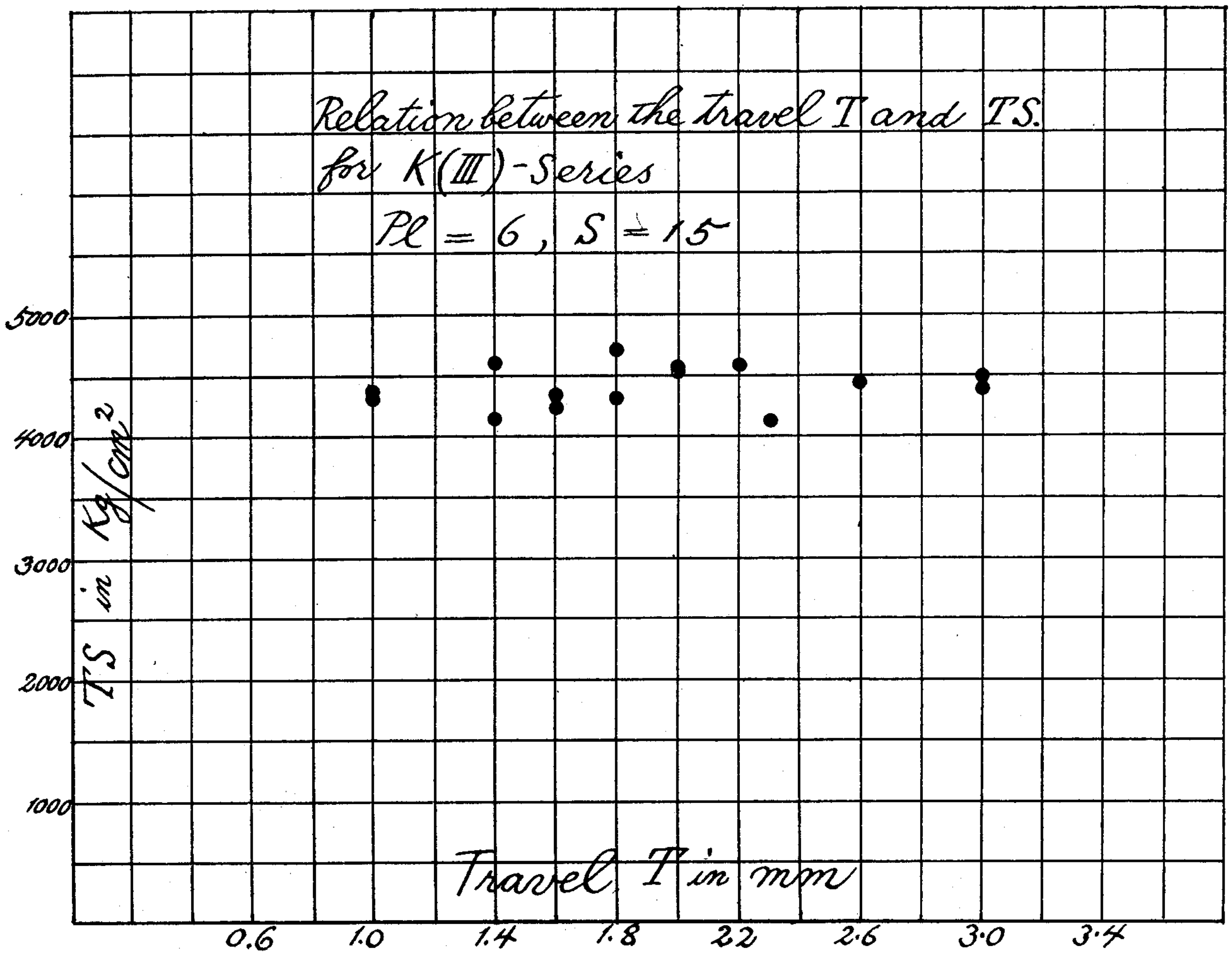
Fig. 25 shows this with regard to the K(III)—series, in which 3/8″ hard drawn bars were welded with $Pl = 6$ and $S = 15$ m. The amount of the travel was varied between 1 to 3 mm, but we can not find any appreciable effect of the travel on the tensile strength.

Fig. 24.



Relation between the spring pressure per sq. cm
of the Cross section p/s and the tensile strength TS
Tensile strength TS in Kg/cm²
5000
4000
3000
2000
1000
for K(II)-Series
for K(II)-Series
for K(VIII)-Series
for C -Series
p/s in Kg/cm²
0
10
20
30
40
50
60
70
80
90
100
110
120

Fig. 25.


Relation between the travel T and TS.
for K(III)-Series
Pl = 6, S = 15
TS in Kg/cm²
5000
4000
3000
2000
1000
0.6
1.0
1.4
1.8
2.2
2.6
3.0
3.4
Travel T in mm

§ 3. EFFECT OF THE WELDING TIME ON THE TENSILE STRENGTH.

In the next place we proceeded to find the relation between the welding time and the tensile strength of welded bars of various diameters by chang:ng the pos:tion of the plug for the welding and thus changing the weld'ng time. Although the test results are more or less affected by the diameter of the bar and also by the spring pressure, the general tendency is that the tensile strength of the welds becomes less and also irregular when the welding time is made longer. This is ow'ng to the fact that the peripheral part of the butt surfaces of the bars welded is oxidized when the welding time becomes longer except when the spring pressure is sufficiently strong. Thus the bars welded with the longer welding time are for the most part broken at the jo:nt in the tensile strength test and the layer of oxides is clearly seen round the broken surfaces.

Fig. 26 shows graphically this effect of the welding t'me with regard to the *B*—series, taking the welding time is abscissa and the tensile s rength in ordinate. The dots within small circles are of those welds which were broken at some distance outs'de the joint at the test and the thick horizontal line indicates the normal tensile strength of the bar.

The elongation of the test pieces varies between the maximum and the minimum values of 25.8% and 22.5% respectively for the welds which were broken at the outside of the joint, and 16.2% and 1.9% respectively for those which were broken at the joint.

Fig. 27 shows the same relation with regard to the *D*—series, in which bars of a small diameter (2/8″) were welded with the spring pressure $S=$ about 6, and the above-mentioned tendency is very clearly seen. The maximum and the minimum elongations are 29.2% and 23.4% respectively for the welded bars broken outside the joint, and 16.9% and 7.1% for those broken at the joint in the test.

Fig. 28 is the graph for the *E*—series, in which 7/16″ bars were welded with the spring pressure $S=$ about 15, and it can easily be seen that the tensile strength is not only reduced but also irregular with the

Fig. 26.

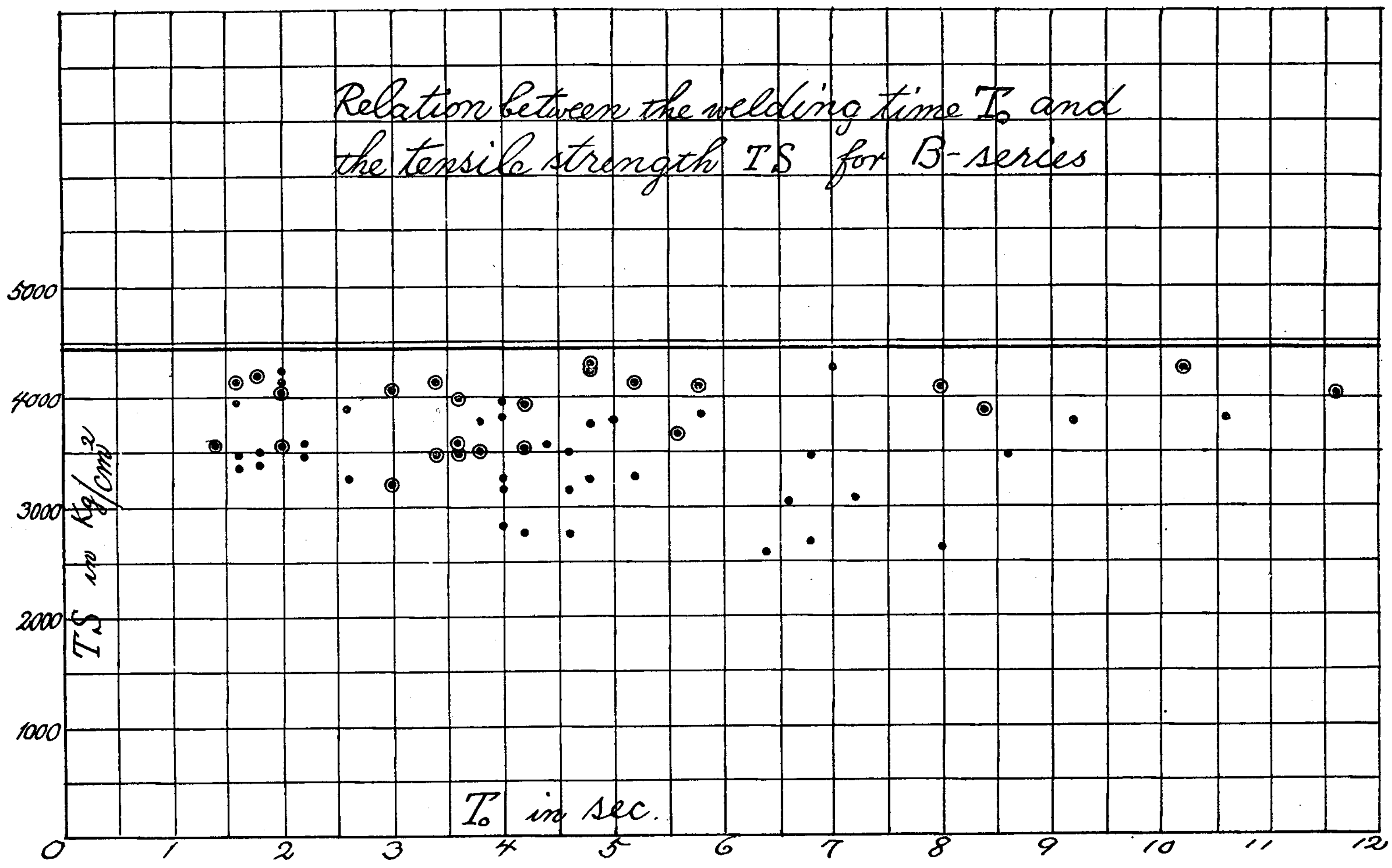

Relation between the welding time T₀ and
the tensile strength TS for B-series
TS in Kg/cm²
T₀ in sec.
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
11
12

Fig. 27.

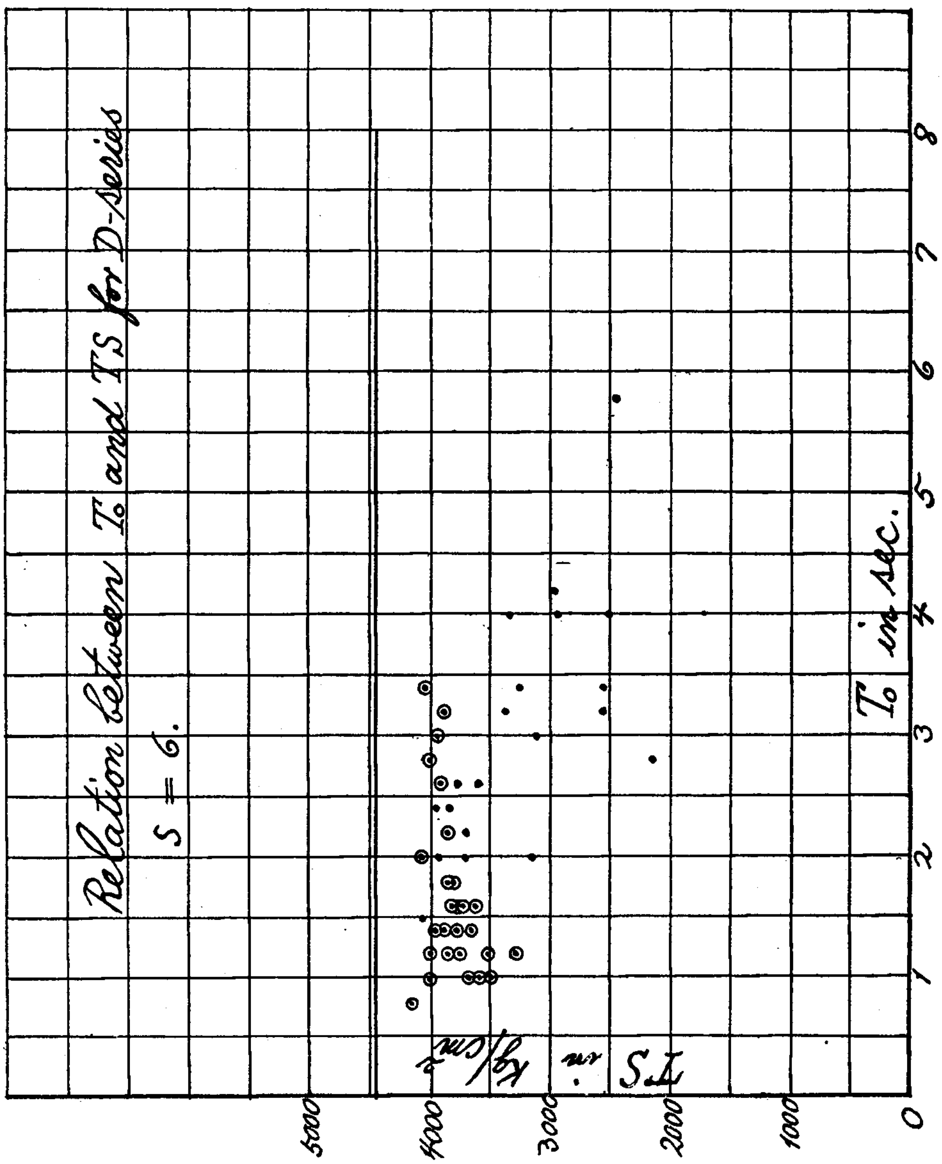
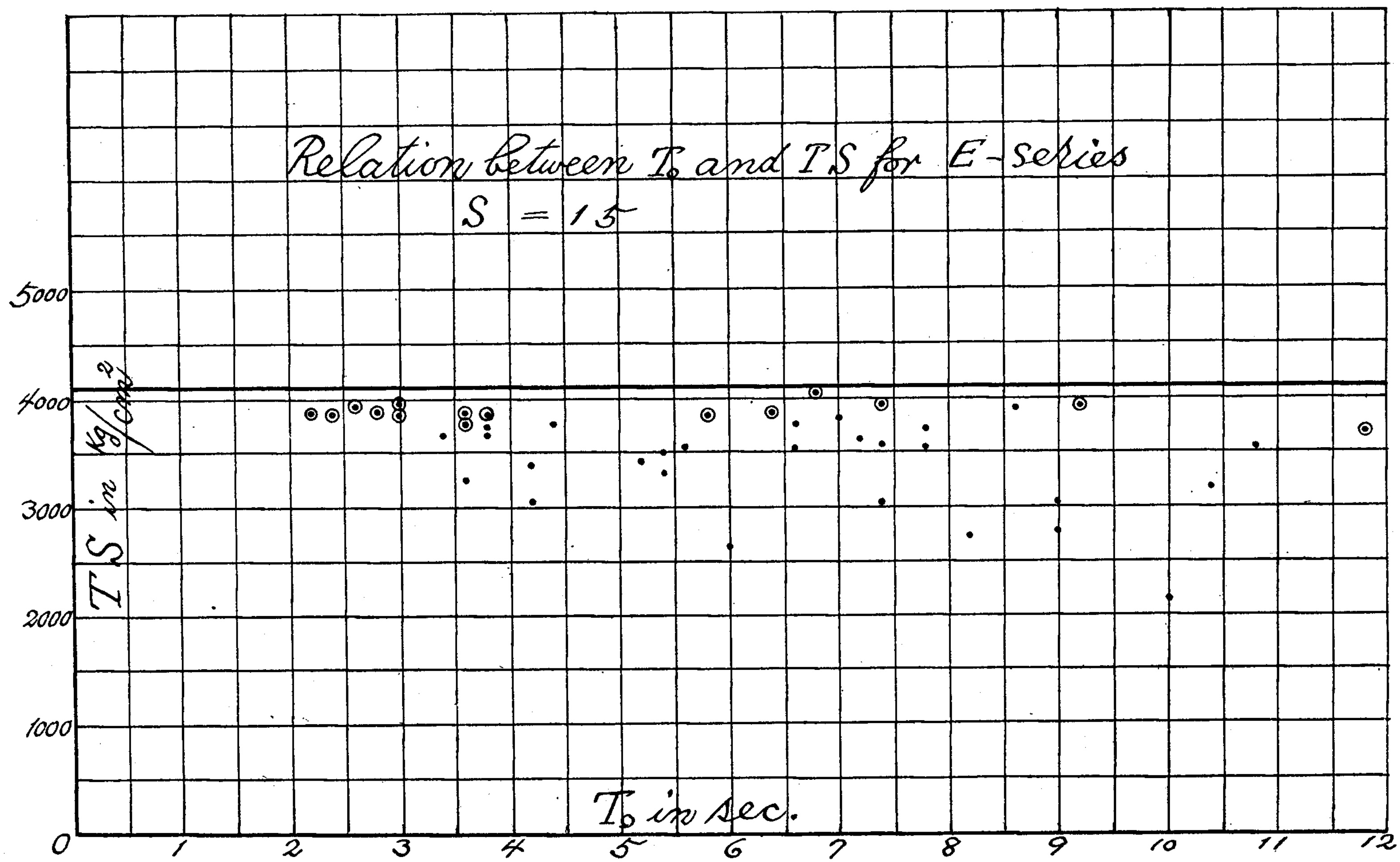

Relation between T_0 and TS for D-series
S = 6.
T_0 in sec.
TS in Kg/cm²
0
1
2
3
4
5
6
7
8
1000
2000
3000
4000
5000

Fig. 28.


Relation between T_0 and TS for E-series
S = 15
TS in Kg/cm²
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
11
12
T_0 in sec.

longer welding times. The elongation varies between 25.9% and 23.6% for the welds broken outside and between 20.2% and 1.1% for those broken at the joint.

Fig. 29 shows the graph for the *F*—series, in which bars of a comparatively large diameter i.e. 1/2″ were welded with the spring pressure $S =$ about 16. The strength of the welds is not so much reduced as in the other series with the longer welding times. This is due to the fact that the oxidized peripheral part of the joint comes to occupy a less percentage of the whole cross sectional area, the larger the diameter becomes. We can easily understand this circumstance if we just compare the graph with that in Fig. 27. The elongation varies between 26.5% and 20.6% for the welds broken outside, and 18.6% and 2% for those broken at the joint.

Fig. 30 shows the graph for the *G*— and the *J*—series, in which bars of the diameter of 1 cm were welded, the spring pressure being kept at $S =$ about 10 and 15 respectively. In the *G*—series the spring pressure is a little smaller than necessary for the diameter and accordingly the decreasing tendency of the strength is clearly noticeable. The elongation varies between 22.5% and 17.5% for the welds broken outside and 16.3% and 0% for those broken at the joint. In the *J*—series, on the contrary, the spring pressure is strong enough and this tendency is scarcely seen. The points marked × and ⊗ are for the *J*—series.

Fig. 31 shows the graph for the *H*—series, in which hard drawn bars of 5/16″ diameter were welded with the spring pressure $S =$ about 10. As the normal tensile strength of hard drawn bars is large, amounting to 5500, the welds break when tested always either at the joint or at the annealed and somewhat softened part, several millimeters from the joint. This is always the case for bars which are mechanically treated and more or less hardened. The elongation varies between 13.4% and 10.2% for the welds broken outside the joint, and 10.4% and 1.9% for those broken at the joint.

Fig. 32 shows the test result of the *I*—series, in which 3/8″ bars were welded with the spring pressure $S =$ about 12. Because the spring

Fig. 29.

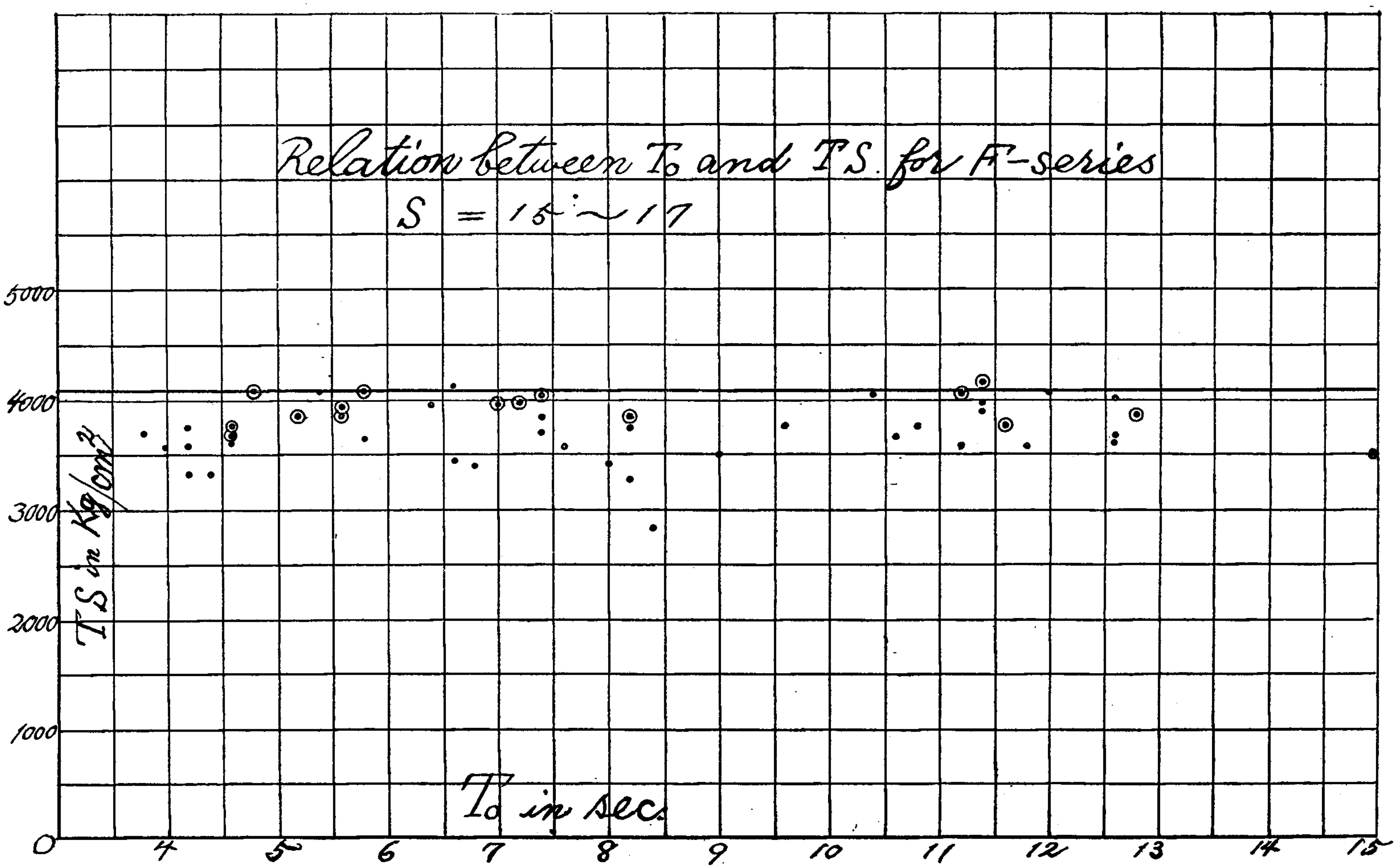

Relation between T_0 and T.S. for F-series
S = 15 ~ 17
TS in Kg/cm²
T_0 in sec.
5000
4000
3000
2000
1000
0
4
5
6
7
8
9
10
11
12
13
14
15

Fig. 30.

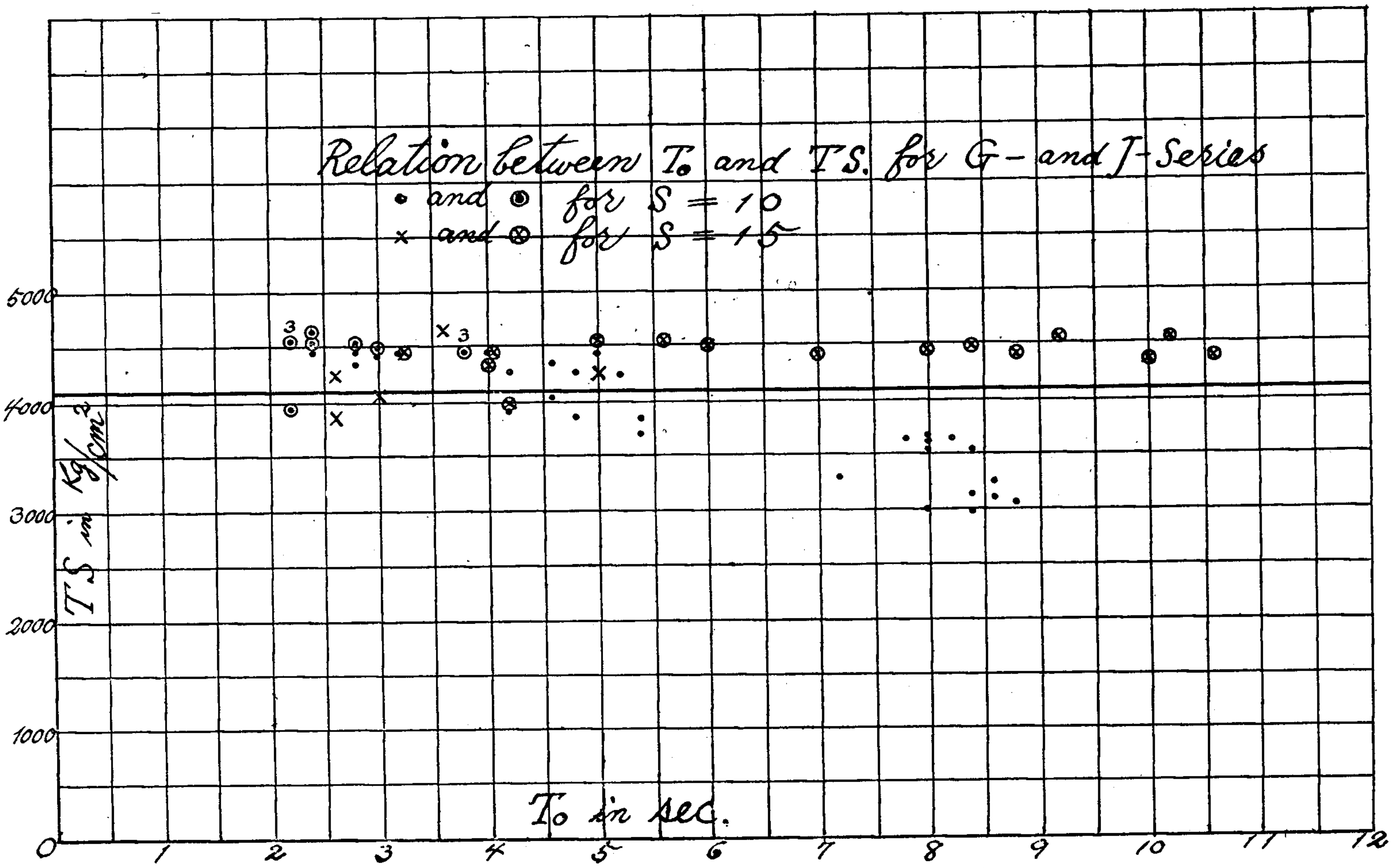
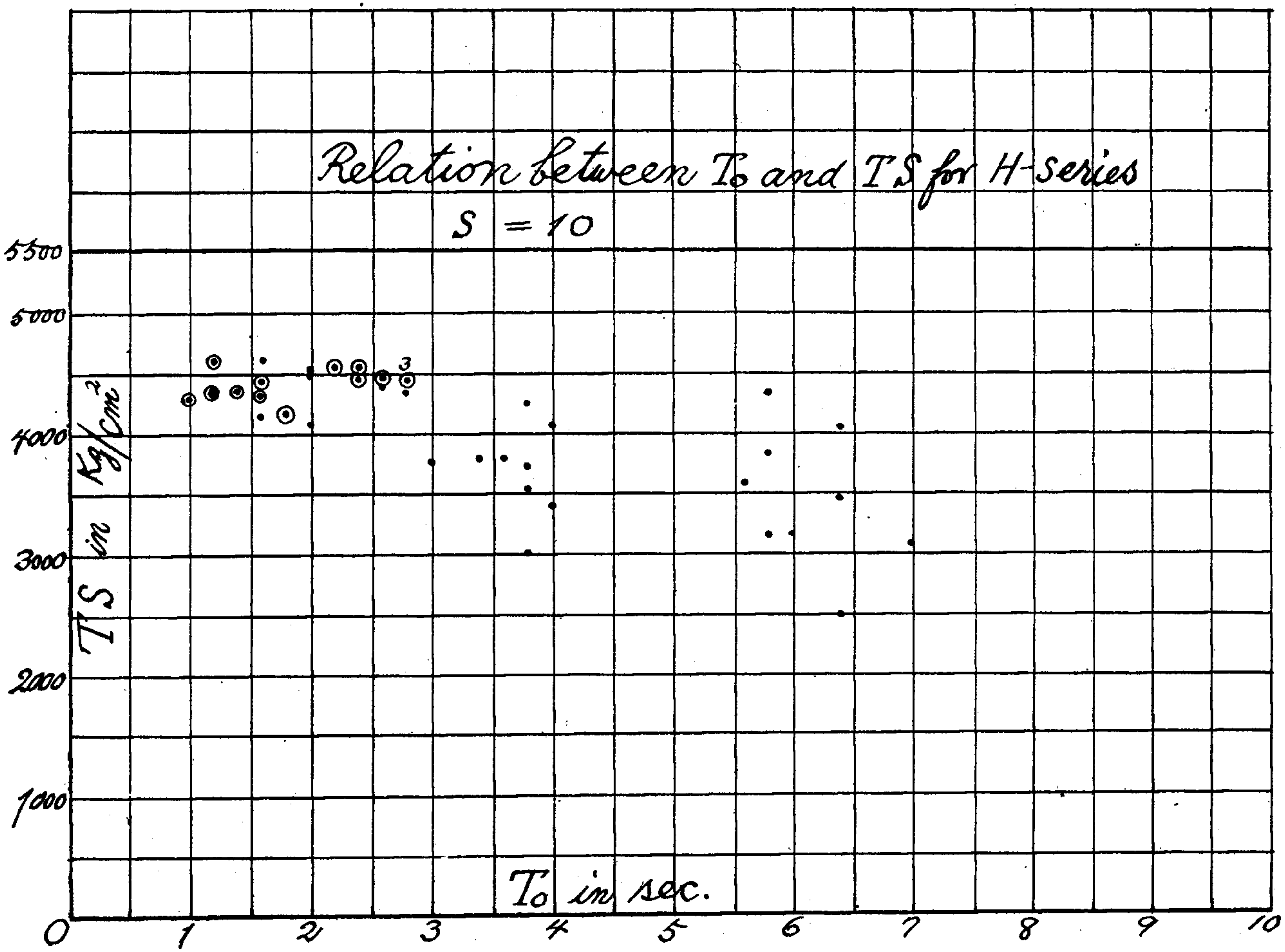

Relation between T_0 and T.S. for G- and J-Series
• and ⊙ for S = 10
× and ⊗ for S = 15
T.S. in Kg/cm²
To in sec.
0
1
2
3
4
5
6
7
8
9
10
11
12
1000
2000
3000
4000
5000

Fig. 31.


Relation between T₀ and T.S for H-series
S = 10
5500
5000
4000
3000
2000
1000
T S in Kg/cm²
0
1
2
3
4
5
6
7
8
9
10
T₀ in sec.

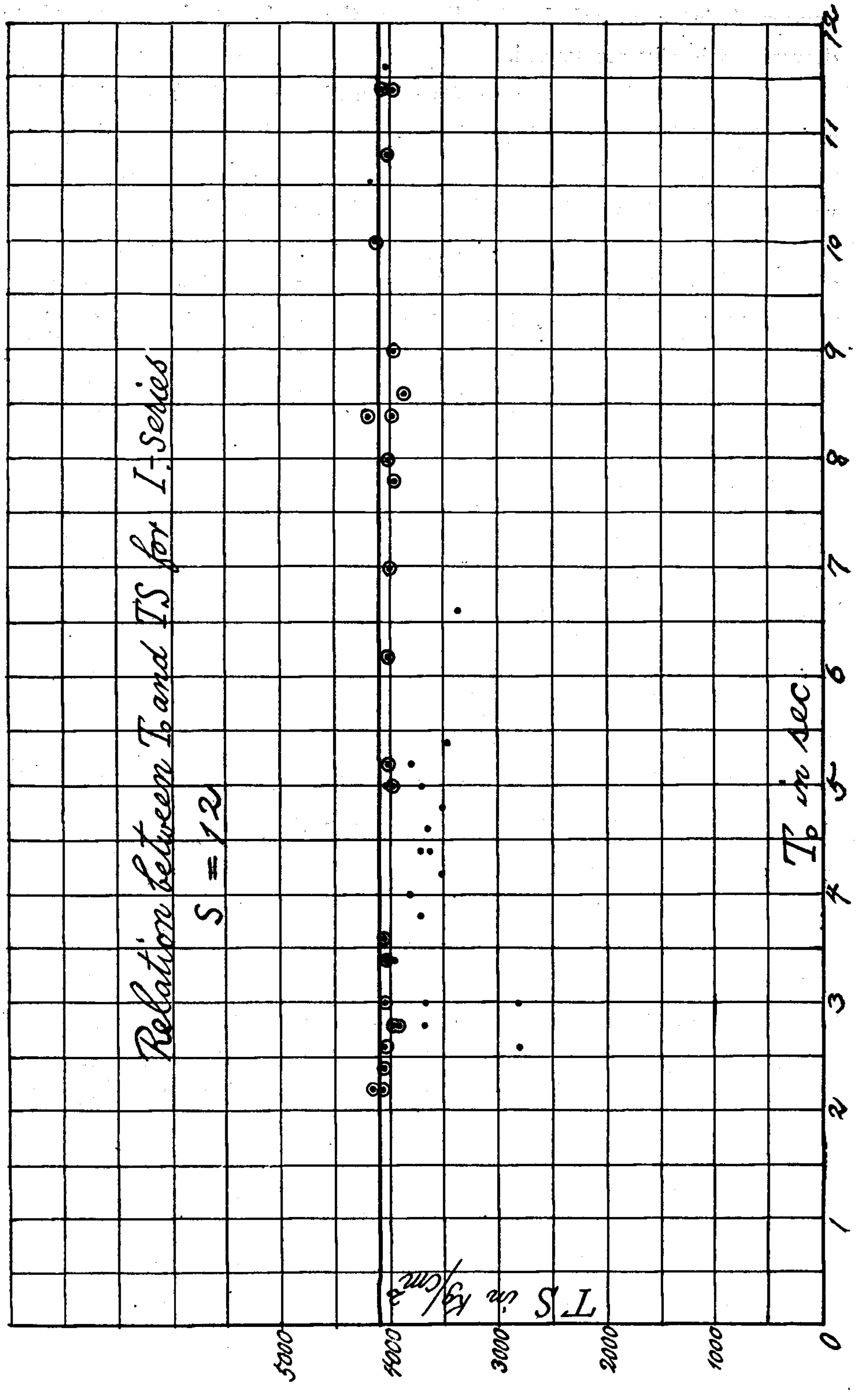

Relation between T0 and TS for I-Series
S = 12
T0 in sec
TS in kg/cm2
0
1
2
3
4
5
6
7
8
9
10
11
12
5000
4000
3000
2000
1000
0

Fig. 32.

pressure is large enough for the diameter, the tendency of the strength to decrease is hardly recognized.

Fig. 33 shows the test results of the K(IV)—, K(V)— and K(X)—series, in which 3/8″ hard drawn bars were welded with the spring pressures $S = 17.5$ for K(IV), and $S = 8.0$ for K(V) and K(X). This latter was welded with the butt surfaces closely surrounded and coated with borax paste. In this graph it is very clearly shown that the tendency of t' e strength to decrease is greatly influenced by the spring pressure. The bars welded with the smaller spring pressure are broken at the joint without exception and the strength decreases fairly rapidly with the increasing welding time. This tendency is not much improved even if we make use of the borax paste as is shown in the graph by the K(X)—series. As this result shows, the borax paste is not so effective as we expected. This is due to the fact that it is violently scattered when the temperature near the joint rises abruptly. The elongation varies b.tween 11.8% and 10.5% for the welds broken outside and 7.9% and 1.3% for those broken at the joint with regard to the K(IV)—series, and 6.6% and 1.3% with regard to the K(V)—series.

Fig. 34 is the graph for the K(IX)—series, in which 3/8″ hard drawn bars were welded with the spring pressure $S = 12.5$ and welds the were tested without lathing and removing of the swell at the joint. The test result shows that the break takes place at the joint more than at other points and as to the tensile strength, no appreciable difference can be seen.

Fig. 35 shows the graph for the K(VI)—series, in which 3/8″ hard drawn bars were welded with the spring pressure $S = 12.5$ as in the K(IX)—series, and the welds were annealed at the temperature of 840°C before the test. We see that the strength is much smaller than that of the K(IX)—series. This is owing to the oxidization of the peripheral area of the cross section of the joint. The elongation varies between 9.2% anc 7.7%.

§4. FORMS OF THE JOINTS.

Fig, 36 shows the typical forms of the welded joints and also the

Fig. 33.

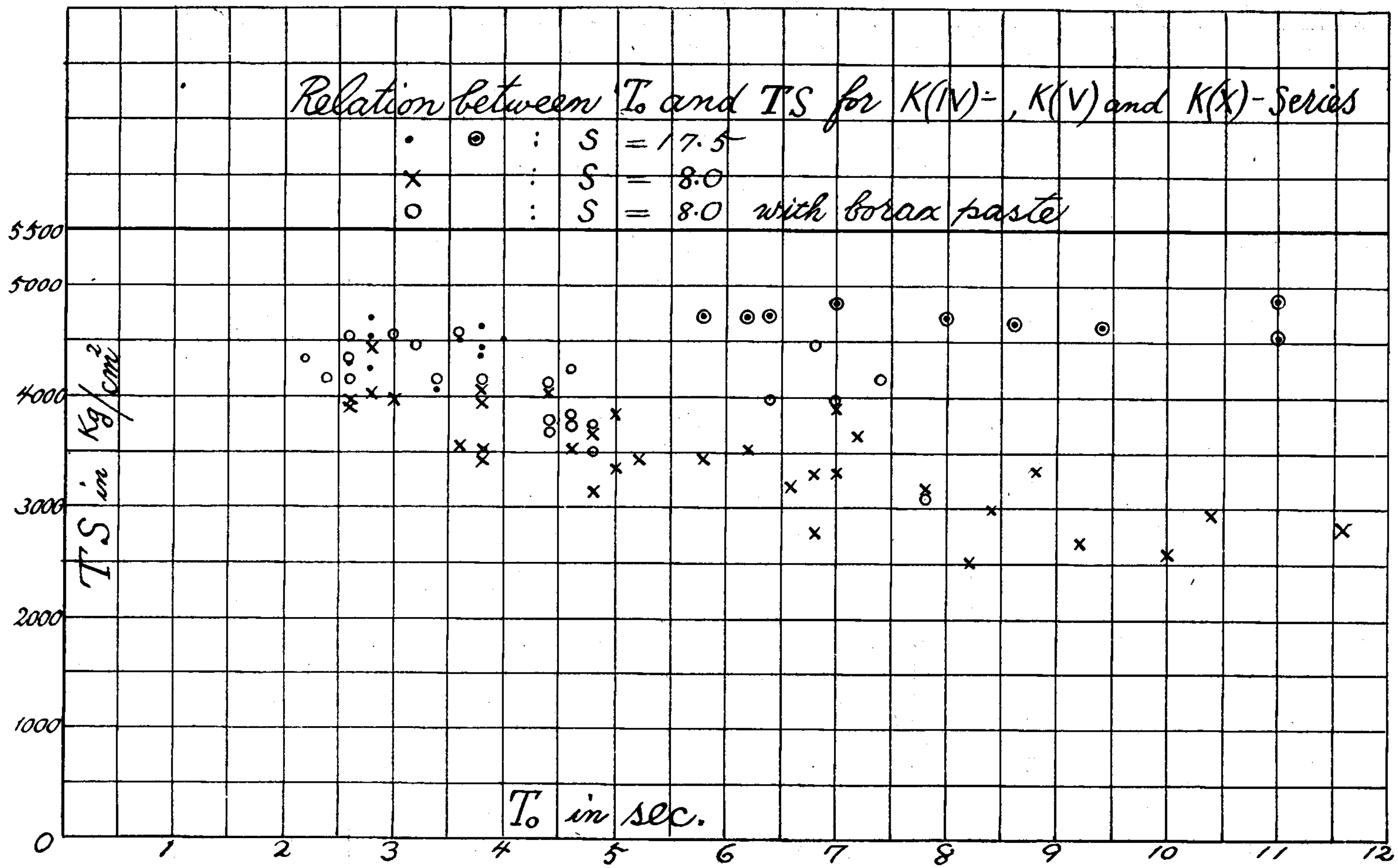

Relation between T_o and TS for K(IV)-, K(V) and K(X)-Series
• ⊙ : S = 17.5
× : S = 8.0
○ : S = 8.0 with borax paste
TS in Kg/cm²
5500
5000
4000
3000
2000
1000
0
T_o in sec.
1
2
3
4
5
6
7
8
9
10
11
12

Fig. 34.

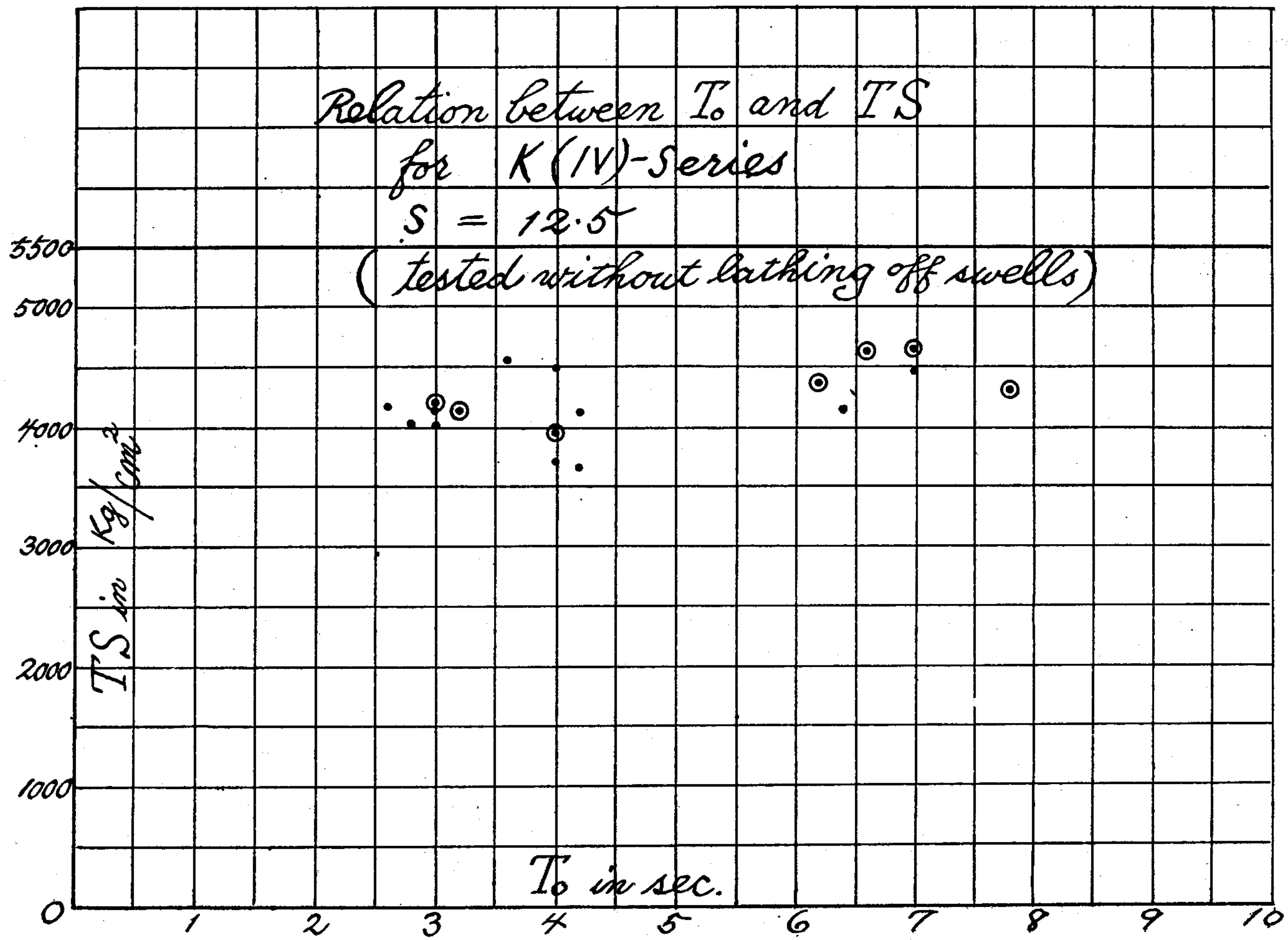

Relation between T_0 and TS
for K(IV)-Series
S = 12·5
(tested without lathing off swells)
TS in Kg/cm²
T_0 in sec.
5500
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10

Fig. 35.

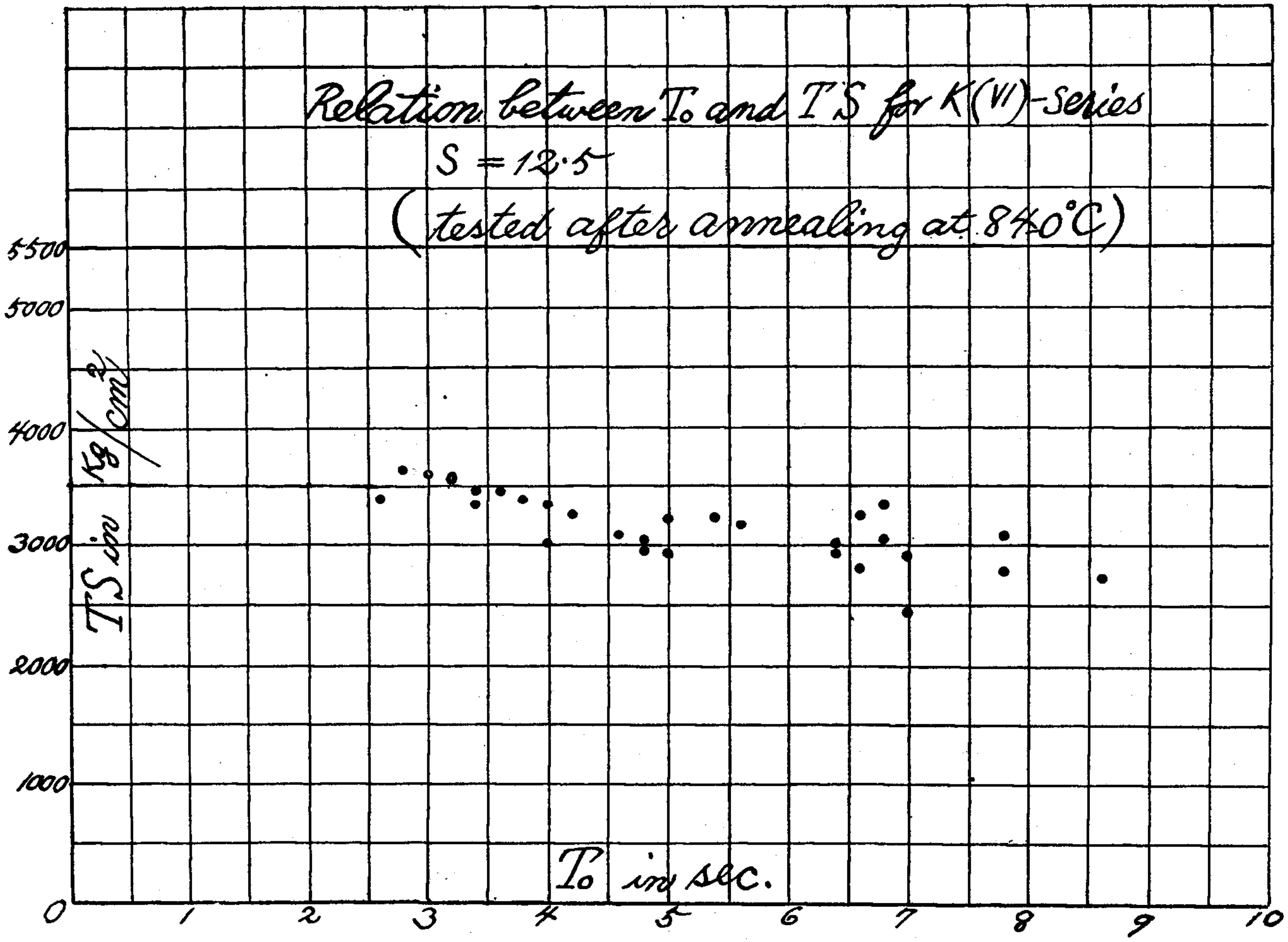
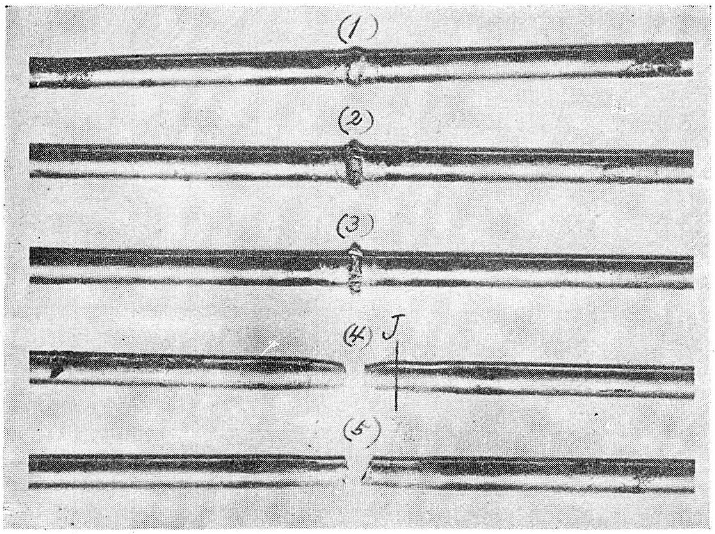

Relation between T₀ and TS for K(VI)-series
S = 12·5
(tested after annealing at 840°C)
TS in Kg/cm²
T₀ in sec.
5500
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10

Fig. 36.



contraction of the cross section which takes place at a distance of several millimeters from the joint at the tensile test.

The forms of the joints can be classified into two kinds. One of them is the so-called "swell" and is free from any cracks or formation of oxides as the photograph (1) shows, and the other is the so-called "flash" as (3) shows, which is formed by the violent pushing out of the molten metal around the periphery of the joint at the end of the welding and has more or less cracks and is for the most part oxidized. The photograph (2) shows a form intermediate between the two.

The swell is formed generally when the spring pressure is sufficiently-large and the tensile strength for such a joint is always larger than that for the other form. If, however, the spring pressure is large and at the same time the welding time is sufficiently short, the joint may often appear as a flash, but the tensile strength is in such a case larger than that of the ordinary flash.

When the spring pressure is small, the joint always appears as a flash and in such a joint the oxidization has penetrated even into the effective cross sectional area of the joint.

The photograph (4) shows the contraction and the breaking of the cross section at the tensile test at a distance of several millimeters from the joint such as we often observed in the *H*— and the *K*—series. Photograph (5) shows an ideal example of a joint which has broken not in a plane, but in an irregular breaking surface.

Chapter VIII. BUTT WELDING OF COPPER BAR.

§ 1. INTRODUCTION.

Copper is one of the metals difficult to be welded by this butt welding. This is due to the fact that the electric resistivity and its temperature coefficient of copper are much smaller and the thermal conductivity is on the contrary much larger than those of steel, and moreover it is liable to oxidization at high temperatures.

We have welded B.S. No. 4 copper wires under various conditions and tested the welds by the testing machine. The welds have broken at the joints or in their immediate neighborhood and the tensile strength can not be larger than that for the normal annealed wire.

We have welded a series of copper wires with a coating of borax paste, but the result was as little affected as in the case of the soft steel welding. The tensile strength is made remarkably larger if we give the welded bar mechanical treatment, for example, hammering on the joint and its neighborhood after the operation of welding, but it can scarcely be made larger than that for the normal annealed wire. The welded wire can, however, be bent 180 degrees at the joint.

We have also welded copper wires by inserting a thin plate of silver solder or brass of the thickness of 0.8 mm between the two butt surfaces, as is often practised, but the test pieces thus welded have always broken at the joints, revealing a thin layer of molten silver solder or brass on the broken butt surfaces and the tensile strength of such a weld is not large, although the oxidization or the microstructural change about the joint can be made much smaller, the melting points of these alloys being lower.

§ 2. WELDING CURRENT, VOLTAGE AND POWER.

Notwithstanding the much larger current density than that for steel the rate of the heat generation is small, because the voltage drop across two butt surfaces is far smaller than that in the case of steel and at the same time the electric resistivity and its temperature ceefficient are also small. Since the comparatively small quantity of the heat thus generated between and near the butt surfaces is quickly conducted away along the wire in both directions, it becomes somewhat difficult to concentrate and keep the heat around the joint and raise the temperature quickly.

Let us take the example given by oscillograph (4) in Fig. 5, in which the power input is 6.65 KW, the energy cansumed is 8.7 watt-hours and the welding time is 1.0 second. The calculation from these data shows that the power input per sq. cm. of the cross sectional area of the wire is 31.3 KW and the current density in amp. per sq. cm. is 22700. These are far larger than in the case of steel welding.

Another example given by oscillograph (11) in Fig. 5 shows similar results. In this example, B.S. No. 3 copper wires were welded with the welding time 1.6 second and the calculation shows that the current density is 16100 amp. per sq. cm and the power input and the energy consumption per sq. cm. are 23.6 KW and 10.5 watt-hours respectively.

§ 3. WELDING TIME, SPRING PRESSURE AND TRAVEL.

Although the welding time must be more or less varied according to the dimensions of the metals to be welded, it is especially necessary in the case of copper welding that the time be made as short as possible in order to avoid the bad effect of the oxidization and the change in the mechanical properties due to the unnecessary heating and also to save the energy consumption.

The spring pressure exerted on one of the wires was varied between 5 and 12 in our experiment as is shown in the next table, but the tensile strength showed no tendency to increase with the increasing of the pressure, contrary to that in the case of steel. In the welding of B.S. No. 4

copper wires we have found by experience that the spring pressure $S = 8$ is proper.

The travel was also varied between 0.8 and 3.0 mm in our experiment and the test pieces welded with the smaller pressure showed the better results, as we see in the next table, this being quite contrary to the tendency in the case of steel welding.

§4. CHANGE IN THE ELECTRIC RESISTANCE AT THE JOINT.

We welded a series of copper wires under various conditions and measured the electric resistance before the tensile strength test in order to see whether the resistance might have undergone any change owing to the oxidization and the microstructural change at and near the joint, but we could not find any appreciable difference between normal and welded wires, as is shown in the following table.

The resistance was measured by means of Kelvin's double bridge and the length of the test piece was 5 cm. The resistance of normal copper wire at the room temperature of 22°C is as follows:

test piece	resistance in ohms	test piece	resistance in ohms
1	40.5×10^{-6}	4	40.5 ,,
2	40.6 ,,	5	40.5 ,,
3	40.5 ,,	Mean value	40.5 ,,

The fact that the hammering of the welded wires improves the mechanical properties, as we have already stated, is evident if we look at the test results of No. 71, 72, 73, 87 and 88 in the table. The copper wires were welded as a general rule with the borax powder held all round the butt surfaces by a specially devised supporter in order to avoid the oxidization of the joint. In the table the same symbols are used as in Table 5, and r denotes the measured electric resistance of the welded wires. The tensile strength of the normal wire is as follows:

Test piece	ST	$E\%$	d
1	4450	5.76	4.5
2	4520	,,	4.0
3	4460	,,	4.1
4	4360	4.80	3.9
Mean value	4450	5.52	4.1

Table 8.

No.	T	T_0	S	Pl	W_0	TS	$E\%$	r	Remarks
1	2.0	1.2	5	6	2.0	1510	9.40		
2	2.5	1.2	,,	,,	2.0	1435	5.05		
3	,,	1.2	,,	,,	2.0	1590	3.85		
4	,,	1.2	7	,,	1.9	1130	4.57	40.8×10^{-6}	
5	,,	1.2	,,	,,	1.8	1870	9.60	40.6	
6	,,	1.0	,,	,,	1.9	1740	10.1	40.5	
7	2.0	1.0	,,	,,	1.9	1735	9.15	40.7	
8	,,	1.2	,,	,,	1.9	1560	8.20	41.0	
9	,,	1.0	9	,,	1.9	1360	7.00	40.5	
10	,,	1.0	,,	,,	1.8	1550	7.70	40.5	
11	,,	1.0	,,	,,	1.8	1580	4.08	40.5	
12	,,	1.0	,,	,,	1.7	1785	8.20		
13	,,	1.0	,,	,,	1.9	1820	8.20		
14	,,	1.0	,,	,,	1.9	790	3.38		
15	,,	1.0	,,	,,	1.7	900	1.92	40.5	without borax
16	,,	1.2	,,	,,	1.9	1710	9.15	40.3	,,
17	,,	1.2	,,	,,	1.8	1440	8.20	40.5	,,
18	,,	1.2	,,	,,	1.8	1690	8.90		,,
19	,,	1.2	,,	,,	1.9	1825	11.1		,,
20	,,	1.0	,,	5	1.9	1400	7.23	40.5	
21	,,	0.8	,,	,,	1.9	1845	10.6	40.3	
22	,,	0.8	,,	,,	1.9	2160	13.0	40.3	
23	,,	0.8	,,	,,	1.7	1910	10.6		
24	,,	1.0	,,	,,	1.7	1640	9.40		
25	,,	0.6	7	,,	1.8	1950	10.3		
26	,,	0.8	11	,,	1.9	1940	11.3	40.7	
27	,,	0.8	,,	,,	1.8	2100	13.5	41.0	
28	3.0	0.8	,,	,,	1.8	1370	7.21	41.0	
29	,,	0.8	,,	,,	1.8	1230	3.37	41.0	
30	,,	0.8	,,	,,	1.8	1200	5.77	40.9	
31	,,	0.8	,,	,,	1.9	1370	6.25	41.0	

No.	T	T_0	S	Pl	W_0	TS	$E\%$	r	Remarks
32	3.0	1.0	11	5	1.9	1560	6.75	41.0	without borax
33	”	0.8	”	”	1 8	1250	5.05	40.6	”
34	”	0.8	”	”	1.8	1410	5.30	41.0	”
35	”	0.8	”	”	1.8	1580	7.45	41.0	”
36	”	0.8	”	”	1.7	1940	8.66	41.0	”
37	”	0.8	”	”	1.8	1380	5.30	41.0	”
38	“	0.6	13	”	1.8	1850	10.1		
39	”	0.8	”	”	1.8	1830	9.15		
40	”	0.8	”	”	1.9	2140	13.2		
41	”	0.6	”	”	1.6	1770	6.75		
42	”	0.8	”	”	1.7	1620	7.45		
43	”	0.8	”	”	1.8	no cracks when bent 180 degrees			
44	”	0.6	”	”	1.8	1460	6.75		without borax
45	”	0.6	”	”	1.7	1540	6.50		”
46	”	0.8	”	”	1.8	1350	5.30		”
47	”	0.8	”	”	1.8	1640	9.15		”
48	”	0.8	”	”	1.8	1180	4.57		”
49	”	0.8	”	”	1.8	1870	9.86		”
50	”	1.0	11	6	1.7	620	4.10	41.0	
51	”	0.8	”	”	1.8	740	2.64	41.0	
52	”	1.0	”	”	1.7	640	3.36	41.0	
53	2.5	1.0	”	”	1.7	1010	5.30	41.0	
54	”	1.0	”	”	1.8	1050	3.85	40.8	
55	”	1.0	”	”	1.8	1610	8.18		
56	2.0	1.0	”	”	1.7	1520	4.81		
57	3.0	1.0	13	”	1.8	750	2.65		
58	”	1.0	”	”	1.6	1010	3.36		
59	”	1.0	”	”	1.8	1190	2.88		
60	”	1.0	”	”	1.7	1230	4.81		
61	”	0.8	”	”	1.7	1150	4.34		
62	”	1.0	”	”	1.8	905	3.85		
63	”	1.0	”	”	1.8	630	4.33		without borax
64	2.5	1.0	”	”	1.7	915	4.10		”
65	”	1.0	”	”	1.7	1520	7.22		”
66	”	1.0	”	”	1.7	1500	5.78		”
67	”	1.0	”	”	1.7	1240	4.80		”
68	”	0.8	”	4	1.7	1950	10.6		
69	1.0	1.0	8	6	1.9	broken when bent about 60 degrees after cooling.			
70	”	1.2	”	”	1.8	no cracks when bent 180 degrees after cooling.			
71	”	1.2	”	”	1.9	2210	5.77		hammered
72	”	1.0	”	”	1.9	2360	4.82		”

No.	T	T_0	S	Pl	W_0	TS	$E\%$	r	Remarks
73	1.0	1.2	8	6	1.9	2080	5.05		hammered
74	„	1.0	„	„	1.8	1300	4.82		
75	„	1.2	„	„	1.9	—	—		
76	„	1.2	„	„	1.8	1670	4.82		
77	„	1.2	„	„	1.9	715	—		
78	„	1.4	„	„	1.9	1660	6.25		
79	„	1.2	„	„	1.9	1510	4.57		
80	„	1.0	„	„	1.9	1295	3.37		
81	„	1.0	„	„	1.8	1320	5.77		
82	„	1.2	„	„	1.7	1235	5.77		
83	„	1.2	„	„	1.7	1260	3.37		
84	0.8	1.0	„	„	1.8	1570	5.77		
85	„	1.2	„	„	1.7	1415	5.77		
86	„	1.0	„	„	1.8	1570	5.77		
87	1.4	1.2	„	„	1.8	2600	20.2		hammered
88	„	1.0	„	„	1.8	2530	19.5		„
89	„	1.2	„	„	1.7	1510	4.33		
90	„	1.0	„	„	1.8	1220	3.85		
91	„	1.0	„	„	1.7	1440	5.05		
92	1.2	1.2	„	„	1.9	1440	5.77		
93	„	1.0	„	„	1.8	1190	3.13		
94	„	1.0	10	„	1.7	1520	6.25		
95	„	1.2	„	„	1.8	1620	5.30		
96	„	1.0	„	„	1.7	1570	5.77		
97	„	1.2	„	„	1.6	1500	4.82		
98	1.0	1.0	„	„	1.7	1520	5.05		
99	„	1.0	„	„	1.7	1640	6.97		
100	„	1.0	„	„	1.8	1570	5.53		
101	1.2	1.0	8	„	for the metallographical study.				
102	„	1.0	9	„			„		
103	0.6	0.6	6	„	1.0	709	plate of silver solder inserted		
104	„	0.6	„	„	0.9	755	„		
105	„	0.6	„	„	0.9	755	„		
106	„	0.6	5	„	1.0	1035	„		
107	„	0.6	„	„	1.0	1273	„		
108	„	0.6	„	„	1.0	755	„		
109	0.4	0.6	„	„	0.9	890	„		
110	0.6	1.0	6	„	1.5	945	plate of brass inserted.		
111	„	0.8	„	„	1.5	1510	„		
112	„	0.8	„	„	1.4	565	„		
113	0.8	0.8	„	„	1.3	709	„		

Chapter IX. BUTT WELDING OF BRASS WIRE.

The butt welding of brass wire is accomplished more easily and always with a better result than that of copper. This is due to the lower melting point, the smaller thermal conductivity and the larger electric resistivity than those of the latter and it is easy to concentrate and keep the heat near the joint.

We welded a series of brass wires, B. S. No. 4, of the same diameter as the copper wire. The welding time for plug position 6 was about 1.0 second in the case of the copper, but it is much smaller, 0.5 to 0.8 second, in this case. The energy consumption is also much smaller and amounts only to 0.9 or 1.0 watt-honr, which is about the half of that for copper, which is about 1.8 watt-hour.

We welded a series of brass wires under various conditions and tested the tensile strength, which is for the most part almost equal to that of the original wire especially when mechanically treated by hammering as will be clearly seen by the test pieces No. 9, 10, 11, 22, 23, 24, and 25 in Table 9.

The breaking of the welded wires at the tensile test takes place at a distance of several millimeters from the joint, that is, at one of the contractions of the cross section, which often appeared when welded hard drawn steel bars were tested.

The travel was varied between 1.0 and 1.6 mm, but it was found to have no beaing at all on the tensile strength of the welds just as was the case in the steel welding.

It will be found from the table that the spring pressure need not be kept large and it suffices in our case if it is kept at S=about 8.

The oscillogram (6) in Fig. 5 shows that the voltage drop across the two butt surfaces is much larger than that in copper wires and its initial value is 0.27 volt. The welding time is 0.65 second, the power input is 5.5 *KW*, the current is 3750 amp. and the energy consumption is 1.0 watt-hour, whence it is calculated that the current density is 17700 amp. per sq. cm. and the power input and the energy consumption per sq. cm of the cross section are 25.9 *KW* and 4.7 watt-hours respectively. These are far smaller than those for copper wires.

Table 9 shows the records and results of the testing of brass wire welding. The normal tensile strength is as follows:

No.	*TS*	*E%*	*d*	
1	4660	—	2.9	The test pieces broke outside the gauge length except No. 5.
2	4700	—	3.6	
3	4700	—	3.0	
4	4700	—	3.2	
5	4660	24.3	2.9	
Mean value	4680	—	3.1	

Table 9.

No.	T	T_0	S	Pl	W_0	TS	PB	$E\%$	d	Remarks.
1	1.0	0.6	8	6	1.0	2740	J	17.8		
2	"	0.6	"	"	1.0	3680	C	29.3	2.8	
3	"	0.8	"	"	1.0	3680	"	30.4	2.9	
4	"	0.6	"	"	0.9	3680	"	30.6	2.7	
5	"	0.8	"	"	1.0	4000	J	11.3		hammered
6	1.4	0.6	"	"	0.9	3730	C	32.2	2.6	
7	"	0.8	"	"	1.0	3730	"	28.6	2.5	
8	"	0.6	"	"	0.9	3960	J	11.3		hammered
9	"	0.6	"	"	1.0	4170	C	17.8	3.2	"
10	"	0.6	"	"	0.9	4300	"	13.7	2.9	"
11	1.6	0.6	"	"	1.0	4160	"	19.2	3.1	"
12	"	0.6	"	"	0.9	3680	"	29.8	2.9	
13	"	0.6	"	"	1.0	3630	J	21.4		
14	"	0.6	"	"	1.0	3730	C	29.8	2.8	
15	"	0.6	"	"	1.0	4150	"	17.8	2.9	hammered
16	"	0.6	"	"	0.9	3680	J	22.0		without borax
17	"	0.6	"	"	0.9	3380	"	17.3		"
18	"	0.6	"	"	0.9	3420	"	19.5		"
19	"	0.6	"	"	0.9	4070	C	19.7	2.8	"
20	"	0.6	"	"	0.9	4120	"	18.7	3.2	hammered
21	1.4	0.6	"	"	1.0	3730	"	19.2	3.2	"
22	"	0.6	"	"	1.0	4150	"	15.9	3.0	"
23	"	0.6	"	"	1.0	4460	"	15.4	2.8	"
24	"	0.6	"	"	1.0	4660	21*			"
25	"	0.6	"	"	0.9	4600	19*			"

No.	T	T_0	S	Pl	W_0	TS	PB	$E\%$	d	Remarks
26	1.4	0.6	10	6	1.0	3040	J	10.6		
27	,,	0.6	,,	,,	0,9	2650	,,	8.2		
28	,,	0.6	,,	,,	0.9	3630	,,	22.0		
29	,,	0.6	,,	,,	0.9	3680	C	27.4	3.0	
30	,,	0.6	,,	,,	0.9	3430	J	15.4		
31	,,	0.6	12	,,	1.0	2500	,,	5.7		
32	,,	0.6	,,	,,	0.9	2800	,,			
33	,,	0.6	,,	,,	0.9	3080	,,			
34	,,	0.4	,,	,,	0.9	3140	,,			
35	,,	0.4	,,	,,	0.9	4220	,,			hammered.
36	,,	0.6	8	,,	for the metallographical study.					
37	,,	0.6	9	,,	,,					