"DEVELOPMENT OF A NEW ALUMINIUM ALLOY CONDUCTOR"

Prof. Dr. A.A. NASSER(1), Dr. A. R.EL-DESOUKY(2)&Dr.S.M.SERAG(3)
(Faculty of Eng. & Technology, Menoufia University)

ABSTRACT:

It is highly desirable to obtain high strength and high conductivity aluminium alloy conductor with excellent formability, that is, with the capacity of taking many reverse plastic bends and manipulations without cracking. Also to obtain this wire at a reasonable cost.

The foregoing is particularly important in communication wire. In this application, high conductivity is important, however, electrical grade (EC grade) aluminium having high conductivity often has low strength or is susceptible to elevated temperature strength degradation and room temperature creep and relaxation. This naturally has an adverse effect on mechanical electrical contacts. The higher strength alloys which overcome the foregoing strength deficiences are generally deficient with respect to electrical conductivity.

Accordingly, it is a principal object of the present work to provide improved aluminium alloy base conductor which are characterised by a combination of high strength (min. tensile strength in the hard drawn condition 170 Nmm^{-2}) and high conducitivity (over 61% IACS in the hard drawn condition) with a suitable degree of thermal stability and are obtainable at a reasonable cost.

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(1) ABDEL-HADY ABDEL-BARY NASSER: Prof. Dr. Production Eng. & Machine Design, Head of Production Eng. & Machine Design Department.

(2) AHMED REFFAT EL-DESOUKY EL-SISSI: Dr. Eng., Lecturer of Production Eng. & Machine Design Department.

(3) SOAD MOHAMED SERAG: Ph.D., Lecturer of Production Engineering and Machine Design Department.

INTRODUCTION:

In view of the scanty resources of copper and mounting engineering demands for the transmission of electricity, copper is being replaced by aluminium. Al has a relative good electrical conductivity (about 60% that of Cu), smaller specific weight than Cu and appropriate corrosion resistance. In addition, Al is non-magnetic and a favorable profiles for electric cable can be made by several forming proceses, for example by extrusion, due to its higher formability. Joining of Al is possible under a protective gas or with the Aluthermic-process. Lastly, the lower price of Al is of special importance.

Several attempts have been made to develop an Al-alloy with a higher mechanical and electrical properties. The results of such attempts have been protected as patents. Table 1 summarises the results of the most important patents in this field.

The common methods of strengthing Al-alloys are: a) cold working, b) formation of solid solution; and (c) dispension hardening by a constituent may either saluble (as in age hardenable alloys) or relatively insoluble at elevated temperatures. Let us consider these briefly with regard to electrical conductivity and thermal stability ...a) cold working decreased the conductivity and high temperature strength and should be avoided. b) Solid solution strengthing is effective for strength but unfortunatly, conductivity decreases sharply; c) As far as dispersion hardening is concerned, serious loss in strength occurs at high temperatures when the dispersed phase is soluble in the matrix. Thus for an elevated temperature service, producing a dispersions of insoluble constituent in the alloy is the most useful method for attaining high strength and good structural stability.

Because of the lower solid solubility of iron in Al, the electrical conductivity of the latter has been little affected by Fe addition only when it was found in a precipitated form. Soluble iron increased the electrical resistivity of Al with 2.56 $\mu\Omega$cm/weight %, while iron in the precipitated form results in an increase of resistivity with 0.058 $\mu\Omega$ cm/weight % (1).

In the present work 0.9% iron was added to the highly pure Al.

EXPERIMENTAL PROCEDURE:

The alloys were prepared in an electric furnace from the highly pure metals:
Aluminium, iron and silicon. The chemical composition was shown in Table 2.

To investigate the effect of the rate of solidification on the mechanical and electrical propoerties, three different moulds were used: 1- Water - cooled copper mould (50 ∅ 450 mm height), the water temperature was 7 °C. 2- Cast - iron mould 3 - Flat copper mould (50 x 150 x 500 mm) heated before casting to a temperature of 200 °C.

The progress of solidification was determined by Ni-N_iC_r-thermocouples fixed at different points from mould wall. The time for a temperature decrease from 660 to 460°C during solidification was measured and the cooling rate for each mould was determined. This was as follows:
1. 4.45 (Fast solidification : FS); 2. 2.1 (Ms) &3. 0.65°CS^{-1}(SS)

The specimens were hot rolled to bars with 16 mm ∅, at a starting rolling temperature of 450°C. This gave a total deformation ε_t = 89%.

The bars were then given the first cold drawing to wires of 10 mm ∅. ($\varepsilon = 60\%$) at a drawing rate of 17.5 m/min.

Three different heat treatments were applied to clarify their effect on mechanical and electrical properties:

a) Recrystallisation anneal (550°C, 1 hr - Water quenching), which aimed to accomplish recrystallisation in a saturated matrix; i.e to delay precipitation that can first take place during the second cold drawing in a finely dispersed form.

b) Homogenisation anneal (550°C, 20 hr - Water quenching)

c) Heterogenisation anneal (300°C, 20 hr - furnace cooling).

The specimens were then given a final cold drawing ($\varepsilon = 93.75\%$) to reach a wire with 2.5 mm ∅ . The wires were annealed isochronally in an air circulating furnace at 100, 150, 200, 250, 300, 350 and 400°C, each for one hour.

The mechanical properties (ultimate tensile strength σ, yield strength σ_y and elongation % (for 100 mm wire length)) were determined on a "Zwick-testing machine" at a cross-head displacement rate of 50 mm/min.

For the determination of electrical conductivity of wire, the compensation technique of 4- points-method was applied(2).

EXPERIMENTAL RESULTS AND DISCUSSION:

The effect of cooling rate and chemical composition on the mechanical properties in the as cast condition (shown in Table 3) can be summarised as follows:

Addition of 0.9% iron increased σ- and σ_y - values and the maximum increase was found for alloy B. These two values were also affected by F_e/S_i - ratio. S_i- addition decreased σ- values which may be attributed to the decrease in solid solubility of F_e in Al and the coarsening of the ternary F_e- S_i-Al-phases.

The quantitative effect of grain size D on σ_y can be expressed by Hall-Petch relationship for alloy B at three different cooling rates.

$$\sigma_y = \sigma_i + KD^{-\frac{1}{2}}$$

where σ_i is the friction stress needed to move a dislocation through the lattice, K_y the grain-boundary locking term.

σ_i had a value of 38.9 N mm^{-2} and K equal to 1.96 $Nmm^{-3/2}$. These values were given for a high strength Al-alloys (3).

Fig. (1) shows the microstructures of the samples in the as cast condition. The effect of cooling rate on the highly pure Al (A) was not observed, while for alloy B, the effect of the rate of cooling in refining the grains was noticed. Relating to the Al-Fe phase diagrams; the white area represents α-solid solution and at grain boundaries Al_3F_e- Phase coexist .

A literature survey of phases precipitating in Al-F_e- and Al-F_e-S_i- alloys gave different formulas. For example, Miki and warlimont (4) have founded the following phases in Al-F_e- alloys with 0.04% Fe and varying amounts of S_i up to 0.68%: Al_3Fe, $Al_{12}\ Fe_3\ Si$, $Al_9Fe_2\ Si_2$. However, Sickels and Bush (5) observed the precipitation of $FeAl_6$ from a highly worked 0.05% Fe alloy at 370°C. Blank (6) reported the observation of three prominant phases (but not Fe Al_6) during precipitation from high iron splat-quenched material.

In Al-Fe casting, the identity of the second phase is dependent upon the solidification rate; the equilibrium phase Al_3Fe is present after slow salidification, whereas in rapidly solidified materials the metastable $FeAL_6$ phase predominates (7). Jacobi et al (8) have found the existance of $Al_{12}\ Fe_3\ S_i$-phase in aluminium (99% purity) when was rapidly solidified .

The grain boundary of alloy Fs(C) was relatively thicker than FS(B), which may be attributed to Si-addition that decreased the solubility of iron in solid solution and attained a higher FeSi-precipitation at the grain boundaries. As a result, silicon counteracts the effect of rapid solidification on the mechanical properties.

Examination of the microstructures leads to the conclusion that the condition of solidification not only affects the grain size, but also the form, size and distribution of the precipitating phase.

The effect of rapid solidification on mechanical properties can be attributed to the following factors:

1. Grain refining action, i.e a large grain boundary area per unit volume (Hall-Petch).

   The effect of grain size (2000, 120 and 83 μm) in aluminium 99.99 and 99.5 on the mechanical properties was also confirmed in literature (9).

2. Supersaturation of soluble alloying elements (solid solution hardening).

3. Higher concentration of frozen vacancies. The number of vacancies increases sharply with temperature, at about the melting temperature of aluminium a concentration of about 10^{-4} to 10^{-3} was reached (10).

The concentration of frozen vacanicies depends not only on the casting temperature but also on the rate of solidification. The higher the freezing rate, the larger the concentration of vacancies.

After (11), the concentration of vacancies increased with the amount of iron in solid solution (temperature 660°C).

4. The grain boundaries were little loaded with foreign atoms.

Regarding the softening processes, the following points were deduced:

After heterogeneous anneal and finally cold drawned, the softening took place in two-steps (Figs. 4 and 5). A flat step (recorevy) followed by a sharp drop (recoystallisation). Recrystallisation in this condition and especially with a higher degree of deformation ($\varepsilon = 93.75\%$) was able to occur at a lower temperature of anneal.

An opposite course showed the homogeniously annealed specimen. Recrystallisation was highly retarded. Electron microscopic examinations proved the occurence of precipitation (also as in recrystallisation annealed specimens) during the second cold drawing. Softening was essentially affected by precipitation. The finely dispersed precipitcites hinder the dislocation motion much more than when coarse and widely spaced.

A very slow rate of softening was attained for recrystallisation annealed wire. Not only the dislocation motion for recovery process was hindered, but also the motion of secrystallisation front was highly retarded so that recrystallisation took place only at high temperature.

Figure (9 and 10) show the effect of isochronal annealing on the electrical conductivity which can be described as follows:

Only a little change of $\mathcal{H}$ was found from room temperature to 150°C. The increase of $\mathcal{H}$ -values from 150 till about 250°C can be attributed to the disappearance of point defects. Electrical conductivity increased in the temperature range 250 400°C due to the softening andprecipitation processes.

As expected, the hetergenous annealed wires have the highst $\mathcal{H}$ -values.

During the isochronal annealing, there was no decrease of $\mathcal{X}$-values due to the solid solubility of precipitates. A study of Al - Fe and Al-Si phase-diagrams show that ab 450°C the above effect occurs.

A comparison between Fig. (9) and (11) shows that alloy C has a lower $\mathcal{X}$ - values because of the higher S_i-Content.

CONCLUSSIONS:

1. The harmful effect of silicon on electrical conductivity and mechanical properties can be kept minimum through the application of rapid solidification technique, high iron addition, appropriate heat treatment program and finally extensive cold working.

2. The results of the present work show that the recrystallisation heat treatment (550°C, 1 hr) before the final cold drawing gave a wire with a higher thermal stability. For a practical heat treatment of Al-Fe alloys, the alloy can be soft-annealed quickly by the above heat treatment where recrystallisation is not impeded by precipitation. The start of the precipitation is delayed very much due to the high activation energy of iron in aluminium. In this state, the work hardened condition can be preserved up to about 200°C for a very long periods of times. Relative to other transition elements, iron is a desirable alloy addition for this application because of its low cost and minimal reduction in conductivity caused by Al-Fe- second phase.

3. The interplay between composition, casting condition and thermal treatment is important in controlling a large numbers of possible effects of casting, mechanical working and annealing.

4. The conductor developed in our work (alloy B, fast solidified, recrystallisation annealed) may be readily employed in industrial conductor sizes including transmission, communication and building wire where a good combination of strength, ductivity, thermal stability and higher conductivity is required.

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Table 1
Aluminium Alloys Conductors

Patent	Chemical Composition (as given)	Properties	Reference (Inventors)
."Triple E" US-Patent 3,512,221	Fe 0.6 Si 0.05 Mg 0.002Mn 0.002 Cu 0.004	30% higher tensile strength, three time of elongation percent $\varkappa$=61%IACS(35.4 m/Ω mm^2)	Al 50 (1974)11, 737 Metallurgical research Lab.,Southwire Co, Carrellton,(USA).
.Super T alloy	F_e 0.5 Co 0.75	σ= 253 N/mm^2(hard) & 134 (soft), $\varkappa$ 61%IACS	Al 48(1972)7,477
.X 8076 US-Patent 3,697,260	Fe 0.6-0.9 M_g 0.08-0.22 S_i max. 0.1	$\varkappa$=61.2% IACS σ:290 to 110 N/mm^2	Wire Journal 6(1973) 10,91: Aloca Lab. (USA)
.US-Patent 3,830,635	N_i 0.2-0.6 Co 0.3-1.3	Min $\varkappa$ 33.2 m/Ω mm^2 (57% IACS) higher thermal stability	Southwire company Carrellton, (USA)
.US-Patent 3,763,686	Fe 0.04-1 Si 0.02-0.2 Cu 0.1 - 1	σ 185-175 N/mm^2 δ 7-19%, $\varkappa$ 61.7-62.1	Olin Corporation, New Haven, Conn.(USA)
.NML-PM2 Electric grade Al alloy		$\varkappa$>61.2%IACS, higher σ	National Metallurgical Laboratory, Jamshedpur, India.
.US-Patent 3,827,917	Fe 1.7%	σ:158-127, δ 17.5-20 $\varkappa$ 59.6-60.1	Al 52(1976) 2,123
.Canada-Patent 967 405	Co	$\varkappa$ > 50 %IACS	Light Metal Age, 34 (1976) 3/4, 31: Southwire comp. Carrolton Georgia (USA).
. Hungary 33-E	Mg 0.0-1.2 Si 0.2-0.5 Fe 0.2-0.5	$\varkappa$ 32.6-33 δ:17 σ 280-130	Metallurgical Research Institute: Panenské Brezàny, ČSSR
.Italy Almhoflex	Fe 0.3-1 Si 0.2-0.5	$\varkappa$> 61.5 %IACS σ>130 N/mm^2	Metals Abstracts 7607 46 0067

Table (2) Chemical analysis of the examined alloys, Wt-%

Alloy	Cu	Fe	Si	ppm Mn	PPmT_i	PPm C_r	PPm Z_n	PPm V
A	0.0008	0.061	0.003	< 10	< 10	< 5	< 20	< 10
B	0.0025	0.92	0.07	< 10	< 10	< 5	< 20	< 10
C	0.0035	0.91	0.15	< 10	< 10	< 5	< 20	< 10

Table (3) The σ- and σ_y- values in the as-cast condition ($N\ mm^{-2}$)

cooling rate °C/S \ alloy		A	B	C
4.6	σ	46.7	97.3	92.7
	σ_y	30.5	50.2	44.4
2.1	σ	45.3	92.6	86.0
	σ_y	29.3	46.4	42.6
0.7	σ	45.0	89.3	84.0
	σ_y	29.1	42.5	41.0

Table(4): The σ , σ_y - and δ %-values after the first cold drawing ($\varepsilon = 60\%$) and heat treatment

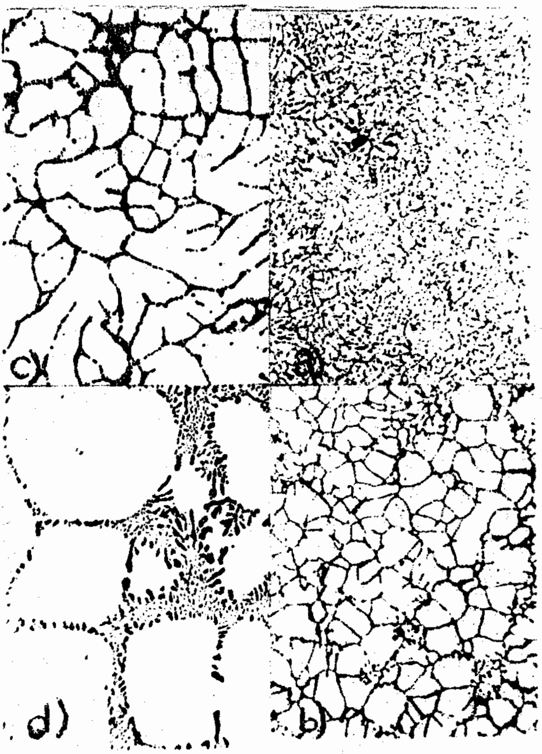
H.T.1 550°C,hr H.T.2 550°C, 20 hr H.T.3 300°C, 20 hr

Alloy		AFS	BFS	BMS	CFS	CMS	CSS
W.H.T	σ	112	160	152	149.8	148	142
	σ_y	100	141.7	137.0	134.2	133.4	129.2
	δ	25	18	15	16	15	14.1
H.T.1	σ	45.5	98.6	94.0	91	86.6	83.4
	σ_y	26.5	42.1	38.4	40.0	38.3	36.1
	δ	36.7	55	46	44	44	40
H.T.2	σ	43.8	90.4	85.7	79.5	76.2	72.1
	σ_y	42.7	40.2	39.0	36.8	37	33.8
	δ	38.0	50	44	47.7	43	39
H.T.3	σ	50.8	84.6	80.1	80.8	78.6	75.5
	σ_y	27.9	40.7	38.6	38	36.4	34
	δ	54.3	49	47.2	51	49	51.5

FS:Fast Solidification MS Medium Solidification SS Slow solidification

Fig. 1)

Microstructure of alloy B
in the as-cast condition:
a) FS-100X b) MS-100X
c) SS-100X d) SS-500X



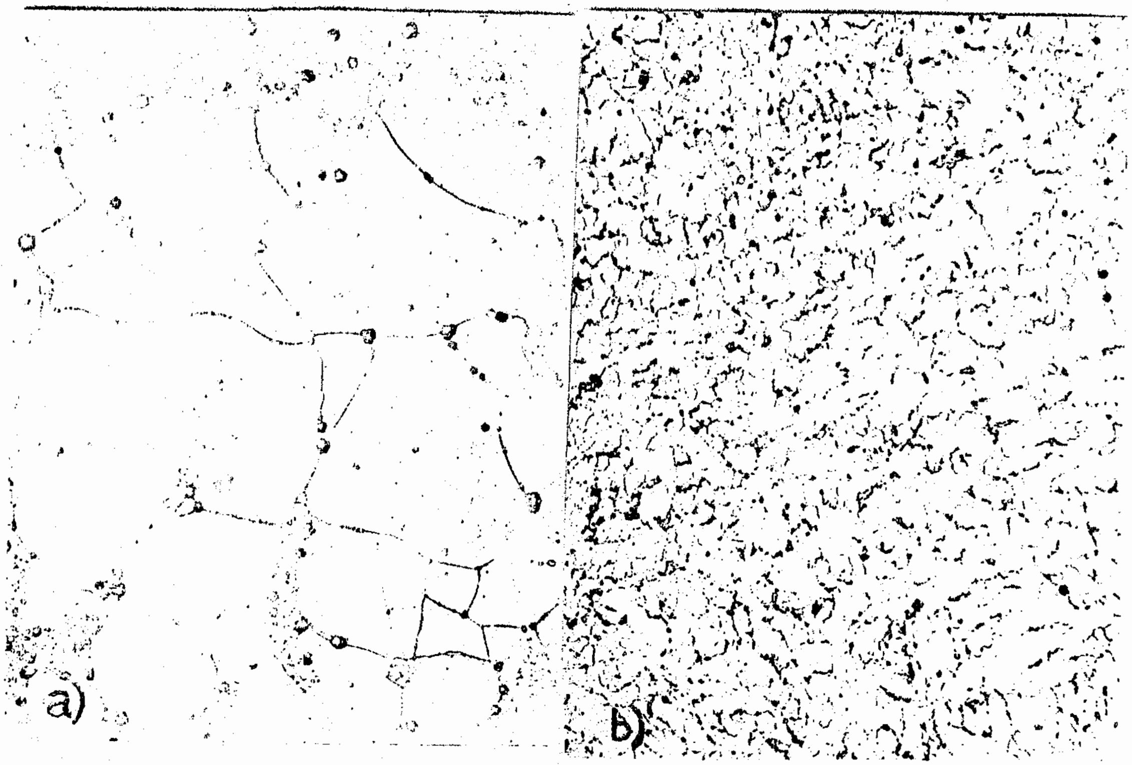


Fig. 2)

Microstructures after hot rod rolling(rolling temperature 450°C, ε = 89%), 500X of a)alloy A and b)alloy B.

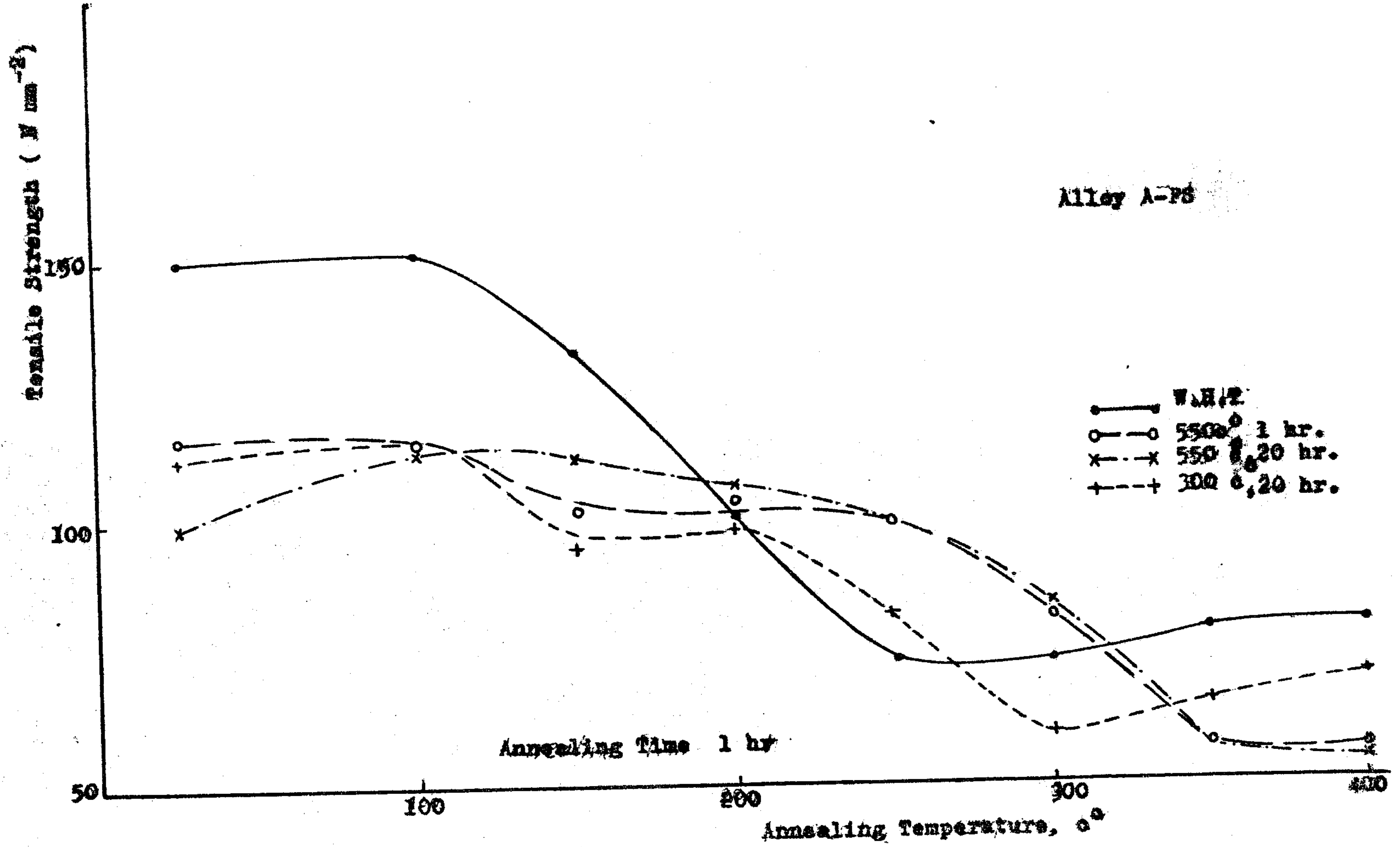

Tensile Strength (N mm^{-2})
150
100
50
Alloy A-P5
W.H.T.
550C° 1 hr.
550 C°,20 hr.
300 C,20 hr.
Annealing Time 1 hr
100
200
300
400
Annealing Temperature, c°

Fig. 3

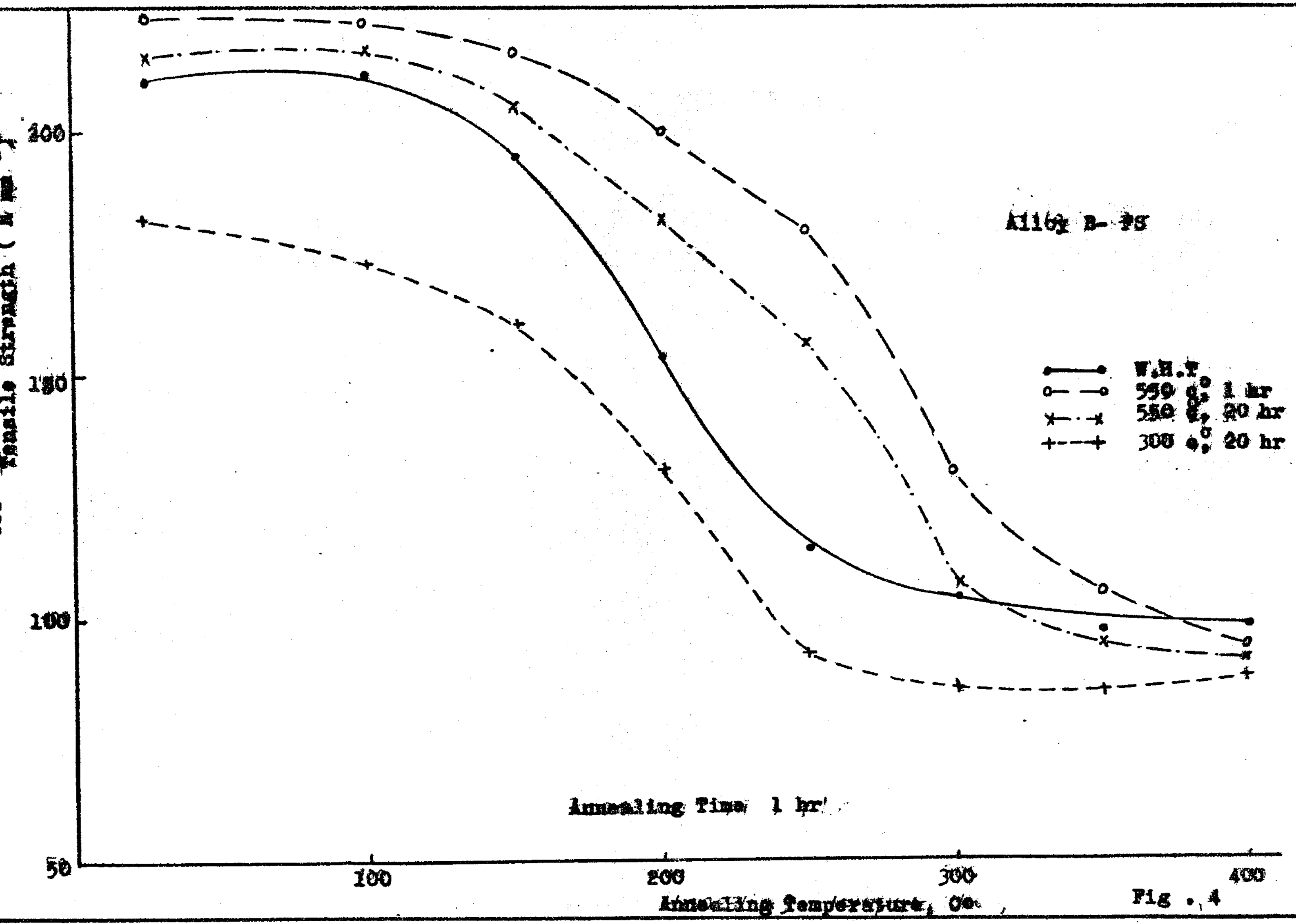

Tensile Strength (N mm^{-2})
200
150
100
50
100
200
300
400
Annealing Temperature, °C
Annealing Time 1 hr
Alloy B- PS
W.H.T
550 °C, 1 hr
550 °C, 20 hr
300 °C, 20 hr

Fig . 4

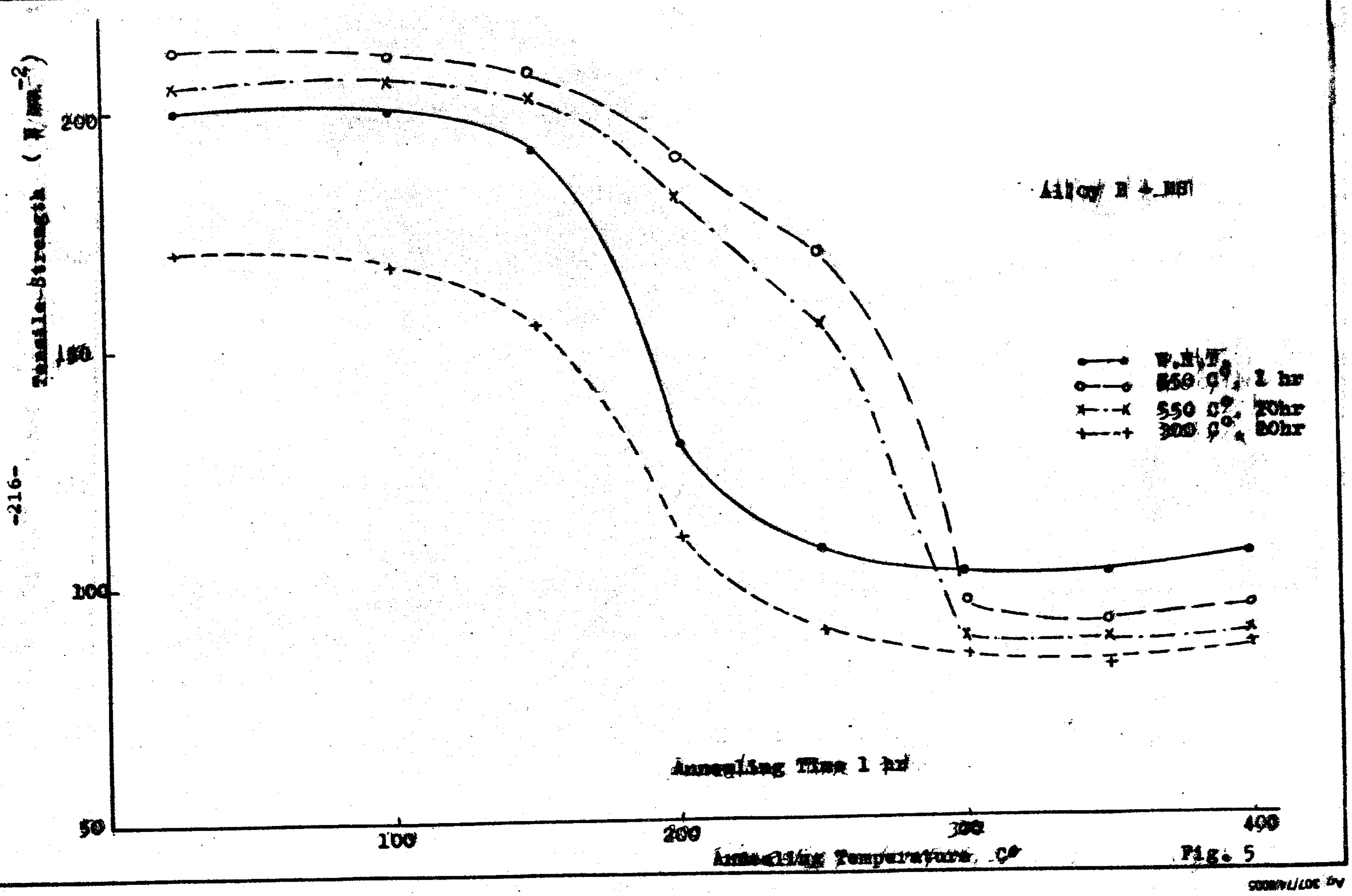

Tensile-Strength (N mm^{-2})
200
150
100
50
100
200
300
400
Annealing Temperature, C°
Annealing Time 1 hr
Alloy E + MM
W.H.T.
550 C°, 1 hr
550 C°, 70hr
300 C°, 80hr

Fig. 5

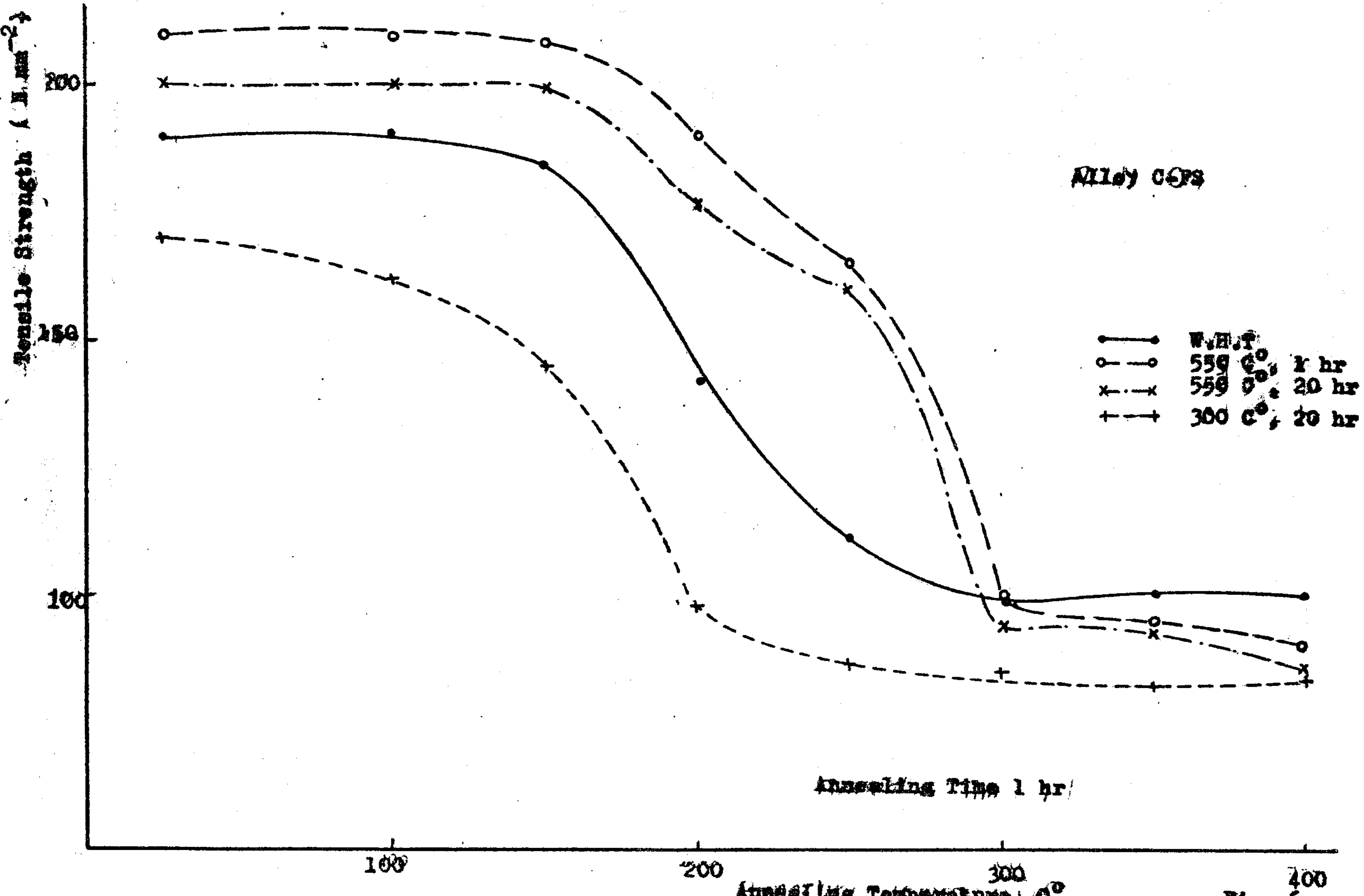

Tensile Strength (N mm^{-2})
200
150
100
Alloy C4FS
W.H.T
550 C°, 1 hr
550 C°, 20 hr
300 C°, 20 hr
Annealing Time 1 hr
100
200
300
400
Annealing Temperature, C°

Fig. 6

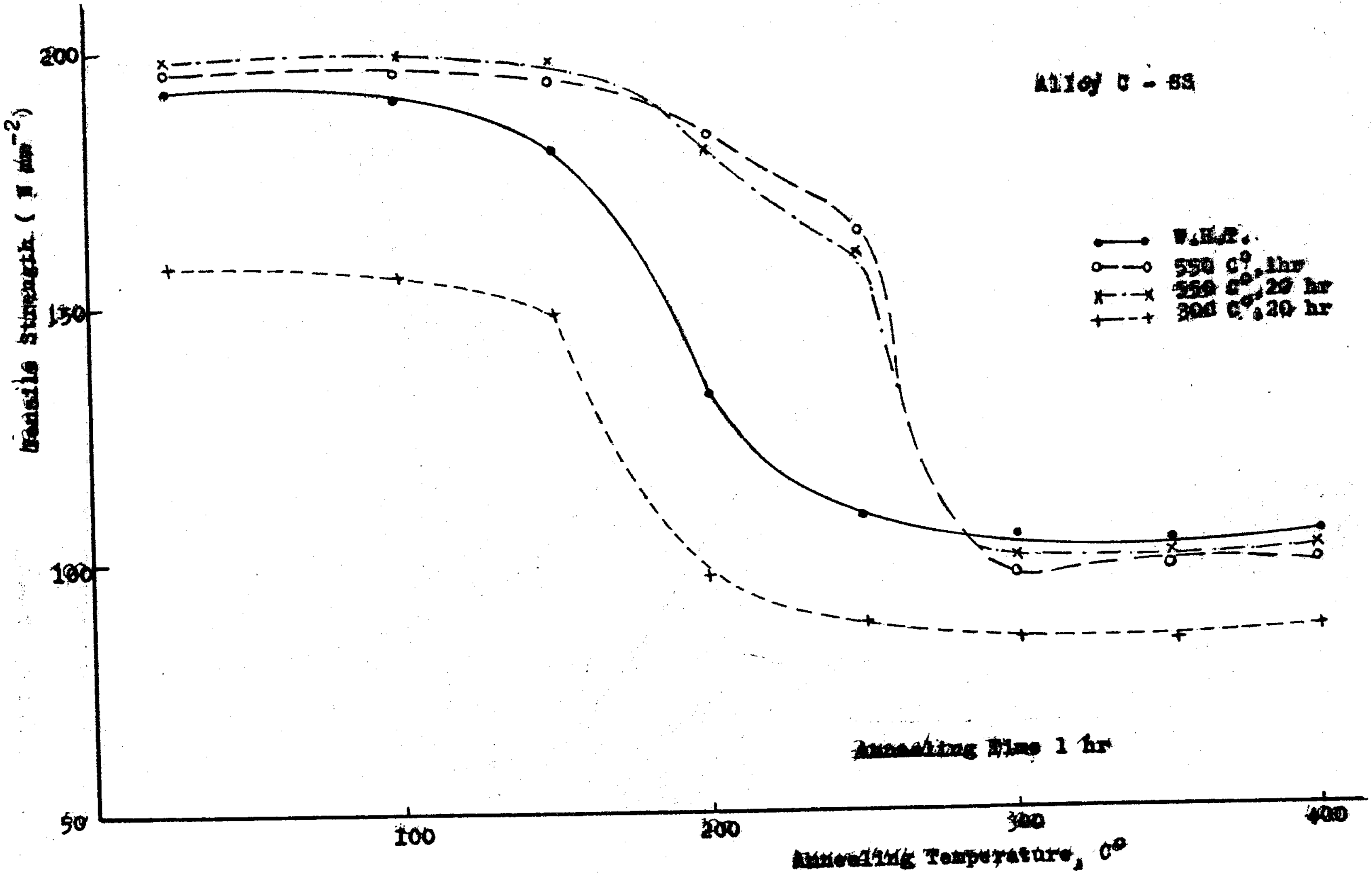

Tensile Strength (N mm^{-2})
200
150
100
50
100
200
300
400
Annealing Temperature, C°
Alloy C - 83
W.H.R.
550 C°, 1hr
550 C°, 20 hr
300 C°, 20 hr
Annealing Time 1 hr

Fig. 7

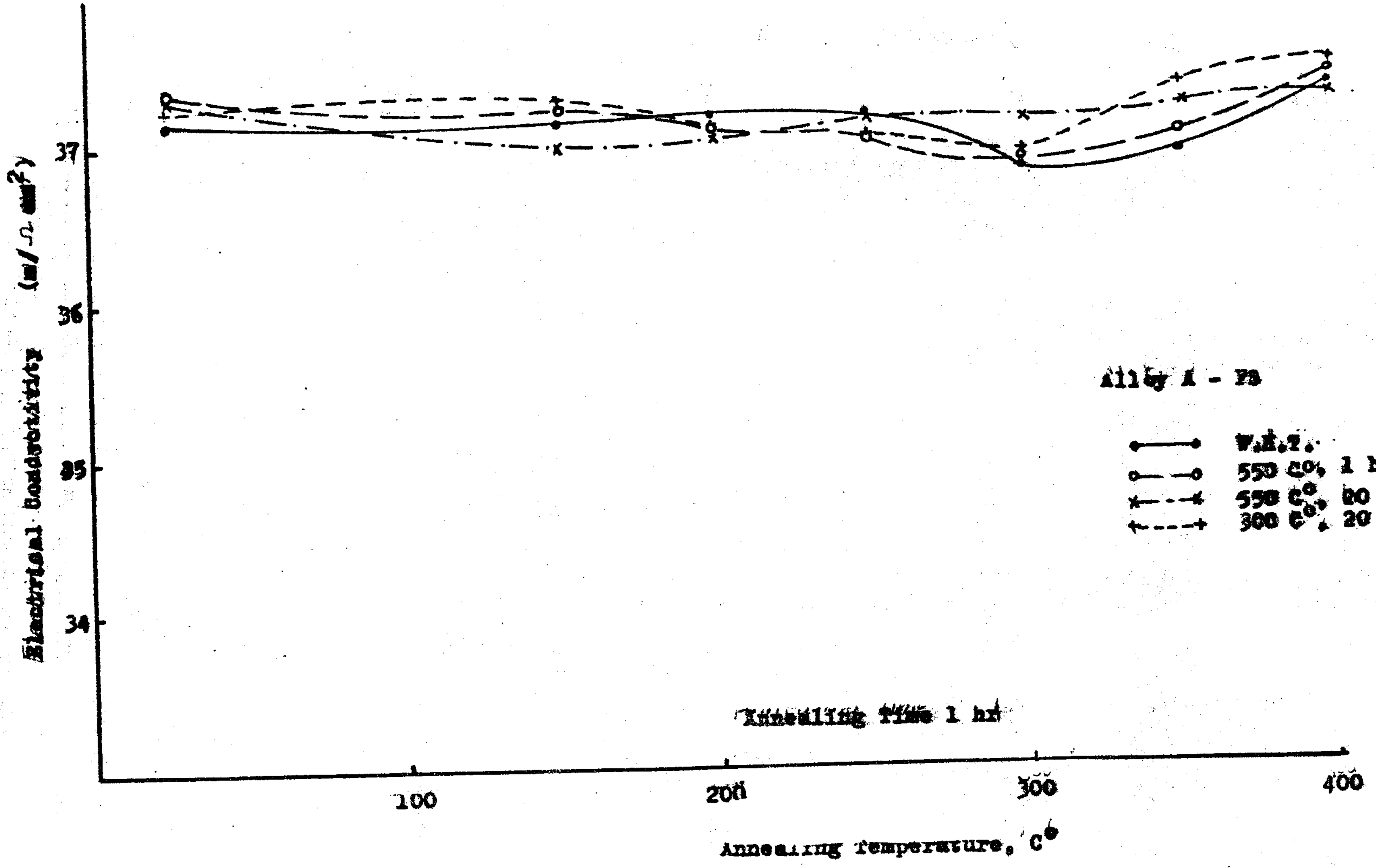

Electrical Conductivity (m/Ω mm²)
37
36
35
34
Alloy A - F3
W.Q.T.
550 C°, 1 hr
550 C°, 20 hr
300 C°, 20 hr
Annealing time 1 hr
100
200
300
400
Annealing temperature, C°

Fig. 3

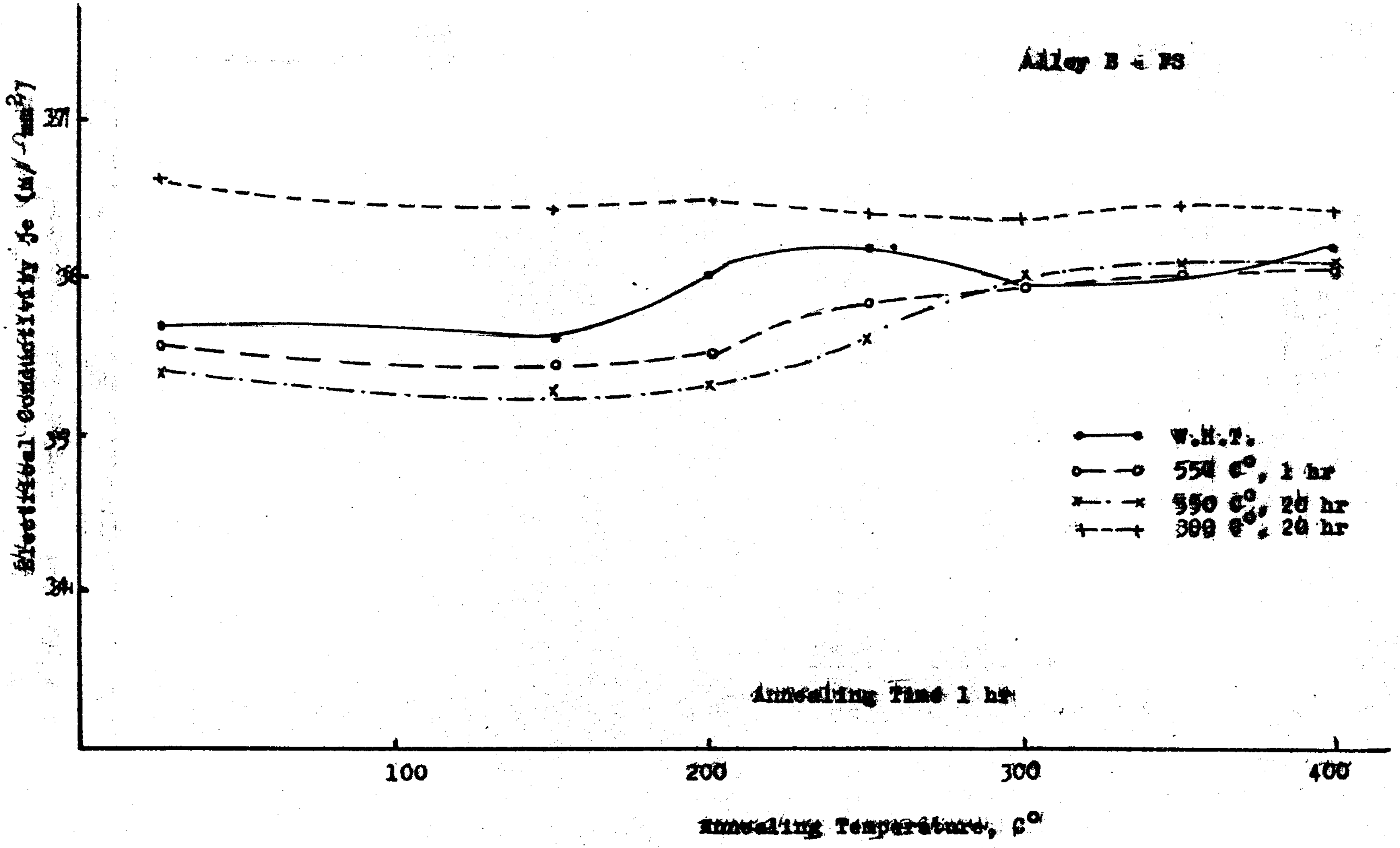

Alloy B + PS
Electrical Conductivity ϳe (m/Ω mm²)
37
36
35
34
W.H.T.
550 C°, 1 hr
550 C°, 20 hr
300 C°, 20 hr
Annealing Time 1 hr
100
200
300
400
Annealing Temperature, C°

Fig. 9

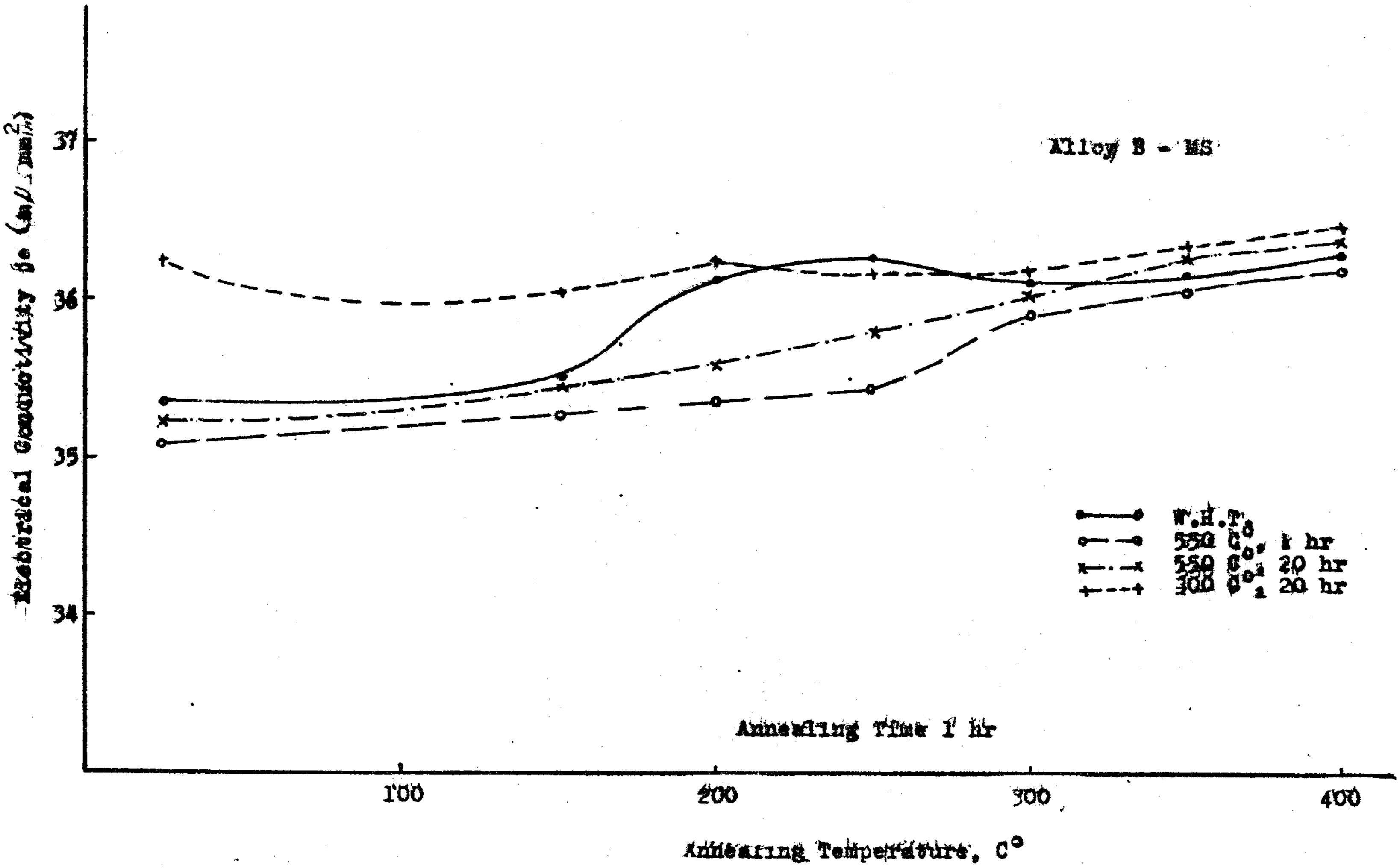

Electrical Conductivity σe (m/Ω mm²)
34
35
36
37
Alloy B - MS
W.H.T.
550 C°, 1 hr
550 C°, 20 hr
300 C°, 20 hr
Annealing Time 1 hr
100
200
300
400
Annealing Temperature, C°

Fig. 1Q

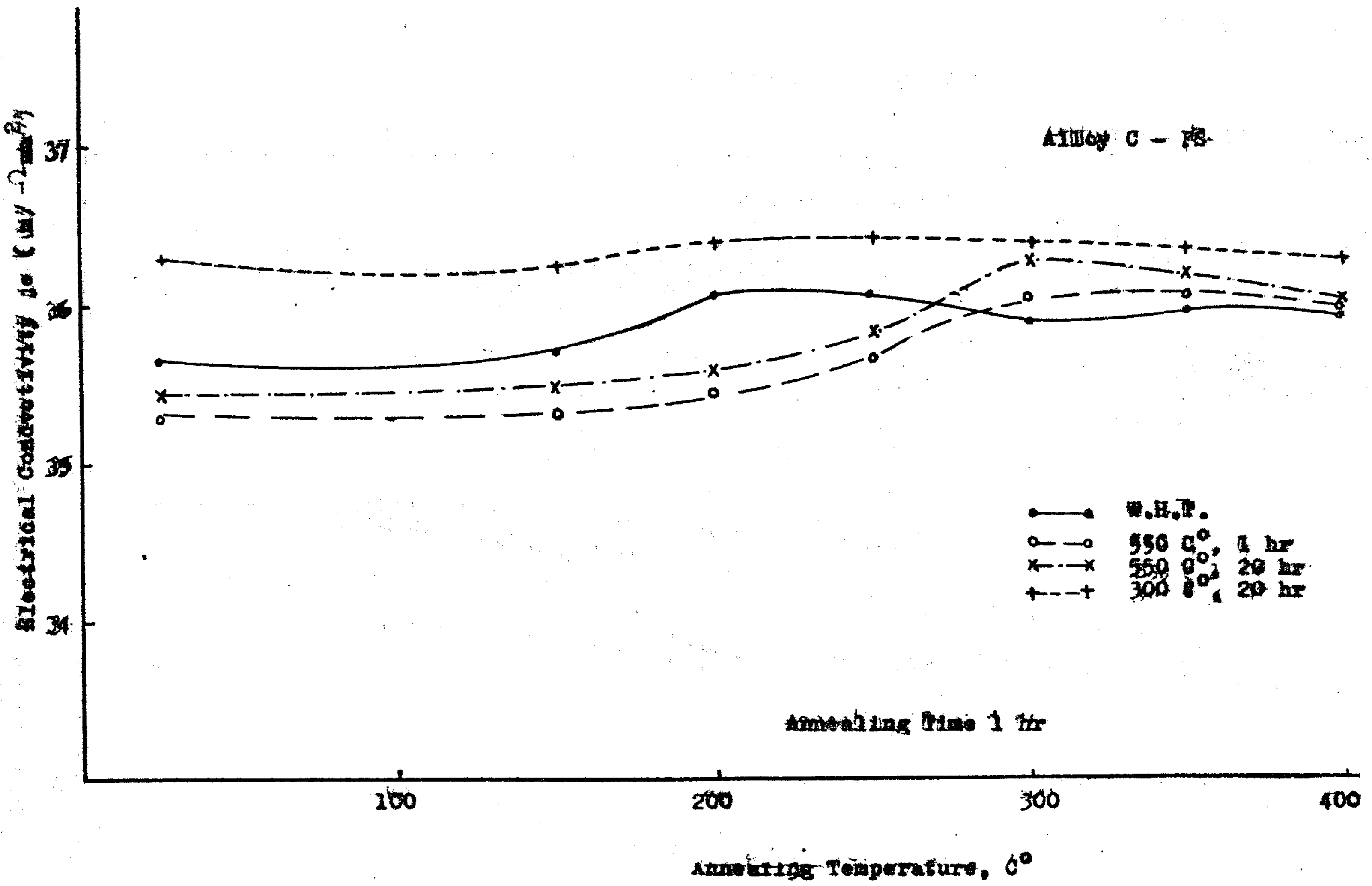

Electrical Conductivity in (m/ Ω mm²)
34
35
36
37
Alloy C – PB
W.H.T.
550 C°, 1 hr
550 C°, 20 hr
300 C°, 20 hr
Annealing Time 1 hr
100
200
300
400
Annealing Temperature, C°

Fig. 11

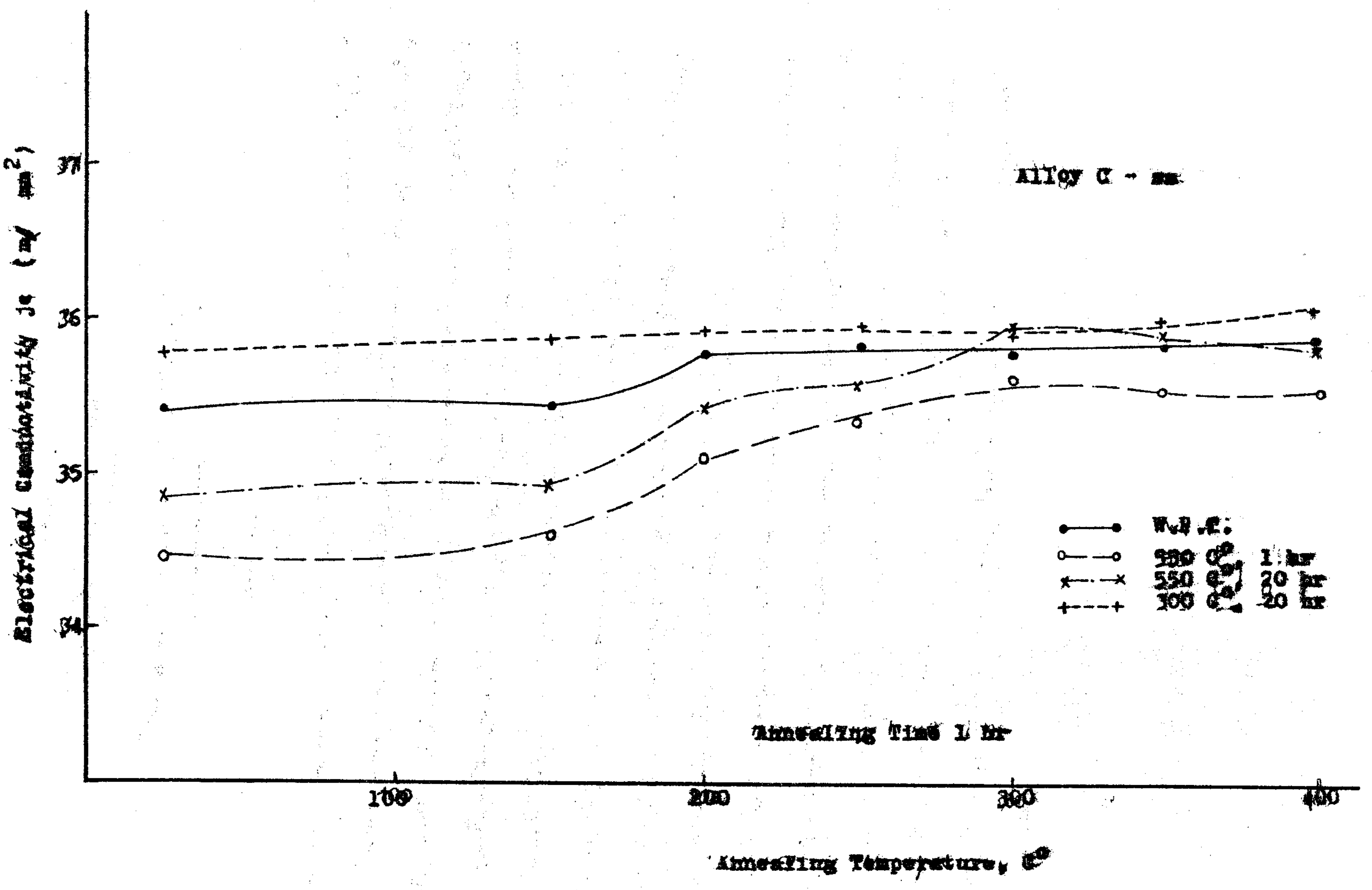

Electrical Conductivity je (m/ mm^2)
37
36
35
34
Alloy C - mm
W.Q.C.
980 C° 1 hr
550 C° 20 hr
300 C° 20 hr
Annealing Time 1 hr
100
200
300
400
Annealing Temperature, C°

Fig. 12

" بسم الله الرحمن الرحيم "

" تطوير موصل جديد من سبائك الالمنيوم "

ملخص

يلعب الحد من استهلاك المواد الاستراتيجية دورا أساسيا فى اقتصاديات الدول ٠٠ وهذا التوفير يمكن تحقيقه فى المصنع من خلال حركة اقتصاديات المواد ومن خلال الاحلال بمواد بديلة متوفرة ورخيصة نسبيا لتحقيق هذا الهدف ٠٠٠ و هذا الطريق الأخير يتطلب المزيد من الأبحاث ٠٠ و لقد أجريت الدراسة فى هذا البحث لامكانية انتاج أسلاك المنيوم ذات درجة عالية من التوصيل الكهربى لا تقل عن ٦١ % (IACS) وقوة تحمل أكبر من ١٧٠ ميجا بسكال / م^{٢} مع مقاومة عالية للزحف ودرجة مناسبة للاستقرار الحرارى ٠٠ وذلك نظرا للحاجة الماسة فى الصناعات الكهربية لهذا النوع من الموصلات وحتى يمكن أن تحل محل النحاس الغالى الثمن ٠

والمعروف أن الحديد يؤثر قليلا على درجة توصيل الالمنيوم للكهرباء بسبب قابليته الضئيلة للذوبان فيه ٠٠ لكن بترسيبه على صورة جزيئات صغيرة الحجم ومفروشة فى الالمنيوم يزيد من مقاومة الأخير للزحف ويعطى ثباتا لخواصه الميكانيكية مع الاحتفاظ بدرجة جيدة للتوصيل الكهربائى ٠٠ لذا فقد أضيف الحديد بنسبة تصل الى ٩ر % للالمنيوم وأستخدم معدل سريع للتصلب مع اجراء المعالجة الحرارية: ٥٠٠°م – ساعة ٠٠