NACA TN No. 1415

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

TECHNICAL NOTE

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THE EFFECT OF PREHEATING AND POSTHEATING ON THE QUALITY

OF SPOT WELDS IN ALUMINUM ALLOYS

By W. F. Hess, R. A. Wyant, and F. J. Winsor

Rensselaer Polytechnic Institute

Washington
November 1947

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SUMMARY

This report is the result of further work in the course of studies
to improve the quality of spot welds in aluminum alloys. The present
investigation was performed to determine the effect of preheating and
postheating cycles on the quality and strength of spot welds in alumi-
num alloys. The welds for the preheating study were made by discharging
two banks of condensers in sequence through a condenser-discharge welding
machine, the first discharge serving to preheat the material and the
second to make the weld. Postheating of spot welds was accomplished in
an alternating-current welding machine by using a sequence timer to con-
trol the welding cycle, cool time, and postheat cycle.

The results of the investigation showed that the combination of a
slowly rising condenser-discharge preheat current with a rapidly rising
welding current afforded no more freedom from expulsion than was ob-
tained with the rapidly rising welding current alone. A double wave-
form combination of this type was in all cases inferior to a single,
slowly rising welding current. With 0.040-inch Alclad 24S-T, the addi-
tion of a slowly rising preheat current to a slowly rising welding cur-
rent produced some beneficial results with regard to decreasing expulsion,
but this combination was less effective with the bare 24S-T and 61S-T
alloys. In most cases, however, it is more practicable to decrease ex-
pulsion by raising the electrode force for welding, although with some
alloys this, too, has a definite limitation because of the introduction
of excessive sheet separation. Condenser-discharge preheating has no ap-
parent effect on the occurrence of cracks in the welds.

Postheating of spot welds in 0.040-inch Alclad 24S-T made with alter-
nating current had no effect on their shear strength until the magnitude
of postheating current was sufficient to cause remelting of the welds,
which greatly increased the weld diameter and the shear strength. Radio-
graphic examination, however, showed no increase in the magnitude of
cracks in those welds in which remelting occurred.

INTRODUCTION.

This report describes the results of an investigation to determine
the effects of preheating and postheating on the quality of spot welds
in aluminum alloys. The welds for the preheating study were made with
a condenser-discharge welder by discharging two banks of condensers in
sequence. The purpose of the first discharge was to preheat the stock
between the welding electrodes, and the second current pulse, which
was of higher magnitude, produced the weld. The welds for the study of
postheating were made with a conventional alternating-current welder
using a Thyratron control panel and a sequence timer. The current-time
program was such as to produce a 6-cycle weld with a 2-cycle cool time,
followed by a 30-cycle postheat.

A previous investigation in which condenser-discharge welding
equipment was used, indicated that a steep or rapidly rising welding
current was slightly superior to a shallow-wave-form current for welding
0.020-inch Alclad 24S-T. (See reference 1.) With the steep wave form
the weld strength was less affected by changes in the welding current.
Because of the flatness of the strength-current characteristic in this
case, somewhat more freedom could be allowed in setting a machine to pro-
duce sound welds of a given strength. Attempts which have been made to
incorporate this desirable feature into the welding of heavier gages of
Alclad 24S-T and also other aluminum alloys by using steep-wave-form
welding currents have been unsuccessful. This is due to the greater
tendency for expulsion and surface flashing when thicker or harder-
surface materials are welded with rapidly rising currents. The same
difficulty is encountered in welding alloys which are difficult to
treat chemically to produce low and consistent surface resistances.

The purpose of the investigation of condenser-discharge preheating,
therefore, was to determine whether the addition of a shallow-wave-form
preheat to a steep-wave-form welding current would permit a realization
of the benefits of the steep-wave-form current by eliminating its un-
desirable effects with regard to expulsion and surface flashing.

The material used for this phase of the investigation consisted of
Alclad 24S-T and 61S-T alloys in the 0.40-inch gage, and bare 24S-T in
the 0.040 and 0.064-inch gages. Alclad 24S-T may be chemically treated
in a hydrofluosilicic acid solution at room temperature to produce a low
consistent surface resistance. Because of its low surface resistance
and soft surface cladding, this alloy gives less trouble with regard to
expulsion than most aluminum alloys. (See reference 2.) It has been
observed that, when the other welding conditions are optimum, an in-
crease in the thickness of Alclad 24S-T requires a decrease in the rate
of current rise in order to produce maximum freedom from expulsion.
(See reference 3.) This would indicate that the expulsion tendency is

definitely related to the material thickness. The 61S-T and bare 24S-T alloys have relatively high surface hardnesses and are difficult to treat in hydrofluosilicic acid or other solutions operated at room temperature to produce low, consistent surface resistances. These two factors are believed to be largely responsible for the difficulty in obtaining freedom from expulsion when welding these alloys.

The second phase of this investigation dealt with the use of an alternating-current welding and postheating program for spot-welding 0.040-inch Alclad 24S-T. A previous study in which an alternating-current postheat was added to a condenser-discharge welding current failed to reveal any significant changes in the weld properties. (See reference 4.) This was believed to be due to the insufficient magnitude of postheat current. It was intended in the present investigation to continue that earlier limited study on the postheating of spot welds after modifying the electronic control circuit of the welding equipment. The results of additional work indicated, however, that an extensive re-design of the equipment would be required in order to synchronize properly the condenser-discharge wave with the alternating-current postheat cycle.

Because of the difficulties encountered in combining the alternating-current postheat with the condenser-discharge-welding current, this procedure was abandoned, and a brief study was made with an alternating-current program consisting of a 6-cycle weld with a 2-cycle cool time, followed by a 30-cycle postheat.

These investigations have been performed at the Rensselaer Polytechnic Institute under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

EQUIPMENT

The welding equipment for the condenser-discharge preheat studies consisted of a Federal condenser-discharge welding machine and a Raytheon flexible weld power control unit. The electronic control equipment was designed to permit the firing of two banks of condensers in sequence. The first discharge served to preheat the stock and the second actually to make the weld. The design permitted considerable flexibility in the selection of different transformer-turns ratios for preheating and welding. In order to simplify the circuit as much as possible, the preheat condenser bank was charged from the rectifier to the same voltage as the welding condenser bank. Therefore, as the voltage was raised to increase the welding current, the preheat current was also increased proportionally. The initiation of the preheat current was accomplished when a microswitch on the head of the welder energized a relay in the ignition circuit of the ignitron tube which passed the preheat current. At a preselected point

on the preheat wave the discharge of the welding condenser bank was
initiated.

The welding for the study of the effect of postheat on the strength
of alternating-current spot welds in Alclad 24S-T was performed with a
Thomson-Gibb, 200-kilovolt-ampere press-type spot welder, using a
General Electric Thyratron control panel and sequence timer. The welding
program consisted of a 6-cycle welding current, a 2-cycle cool time, and a
30-cycle postheat. The magnitude of the welding current was held constant
for all welds, and the magnitude of the postheat current was varied for
different series of welds by means of a phase-shift control on the se-
quence timer.

PROCEDURE AND RESULTS

Condenser-Discharge Preheating of Spot Welds

in 0.040-Inch Alclad 24S-T

The Alclad 24S-T used for this phase of the investigation was
chemically treated at room temperature in a solution of hydrofluosilicic
acid, $1\frac{1}{2}$ percent by volume, prior to spot welding. This treatment
produced a consistently low surface resistance. All welds were made
with a constant electrode force of 600 pounds, since it was desired to
determine whether the preheating would have any effect on the occur-
rence of cracks at this low value of electrode force. Normally, cracks
are best avoided by the application of a forging force of sufficient
magnitude and properly timed with respect to the peak welding current.
The use of a forging force might be resorted to for the prevention of
cracks in the event that preheating should not eliminate cracks and
yet should prove desirable for some other reason, such as decreasing
the expulsion. Electrode tips, of Elkaloy A or SMS-101 alloy having
a spherical radius of $2\frac{1}{2}$ inches were used for the welding. The weld-
ing conditions are listed in table I.

Figure 1, consisting of a series of strength-current characteristics
made with 0.040-inch Alclad 24S-T, gives a comparison of results ob-
tained with this material both with and without preheat. As the welding
current was increased to make larger welds, the preheat current was in-
creased proportionately, because of the manner in which the electronic
control equipment was designed.

The strength-current characteristic shown in figure 1(a) was ob-
tained without any preheat and with a welding current having a steep
wave form. The numbers above each point on the strength-current
characteristic refer to the number of welds which expelled, out of the

total of eight welds made at that point. This number gives a quantita-
tive indication of the expulsion tendency for the different types of
current wave form. This tendency toward expulsion is to be expected
with such a steep wave from in combination with the low electrode force.
Oscillographic measurements of the current wave form for figure 1(a),
together with corresponding measurements of the other types of wave
form for figures 1(b) to 1(d), are presented in table II.

Figure 1(b) shows the results obtained with a shallow wave form, or
a slowly rising welding current without any preheat. From this, it is
evident that the shallow wave form is to be preferred to the steep wave
form of figure 1(a) because of the larger welds which were made without
expulsion. The maximum shear strength of welds having freedom from ex-
pulsion was about 600 pounds for the shallow-current wave form as com-
pared with the value of less than 400 pounds for the steep-current wave
form. Both figures 1(a) and 1(b) show that cracks occurred in welds of
relatively small size in each case, owing to the low electrode force.
In a further comparison of figures 1(a) and 1(b) it may be seen that
the peak welding current required to produce a weld of the same size
is much lower for the shallow current wave form than for the steep wave
form. This is due to the longer available heating time before the
peak value of current is reached with the shallow wave form. A slightly
higher energy discharge from the condensers is also required to make a
weld of the same size with a steep current wave form than with a
shallow wave from.

The characteristic obtained with a shallow-wave-form preheat plus
a steep-wave-form welding current is shown in figure 1(c). In this case,
the peak current for preheating was approximately 47 percent of that
for welding, although the energy ($1/2$ CE^2, where C is the condenser
capacitance and E is the difference of potential) was only 20 percent
as great for preheating as for welding. Oscillographic measurements of
this current wave form are shown in table II. The curve of figure 1(c)
indicates that little or no improvement in results over those obtained
with the steep-wave-form welding current alone (fig. 1(a)) was effected
by the addition of the condenser-discharge preheat. These data would
indicate that the expulsion due to the steep wave form was so severe
that, even with the preheat that was used, the results were still worse
than with the shallow-wave-form welding current alone. Another strength-
current characteristic was made after the condenser capacitance for pre-
heating was raised from 150 to 300 microfarads. In this case, the
energy for preheating was 40 percent of that for welding. Up to the
point at which fusion began to occur from the high value of preheat,
however, the results were no better than those shown in figure 1(c).

The next wave-form combination tried was that of a shallow-wave-
form preheat plus a shallow-wave-form welding current. The results are
shown in figure 1(d). In this case the peak current for preheating

was 64 percent of that for welding, and the energy for preheating was
20 percent of that for welding. The oscillographic measurements of the
current wave form are presented in table II. The curve of figure 1(d)
shows a considerable improvement over any of the other results shown in
figure 1. With this wave form, the maximum-size welds which were ob-
tained without expulsion had an average shear strength of about 800
pounds as compared with a corresponding strength of 600 pounds obtained
with a shallow-wave-form welding current alone, as shown in figure 1(b).
Another series of welds was made in which the condenser capacitance for
preheating was raised from 150 to 300 microfarads, thus increasing the
preheating-to-welding energy ratio from 20 to 40 percent. No improve-
ment in results over those shown in figure 1(d) was obtained with this
wave form, however.

A comparison of all the curves in figure 1, shows that the pre-
heating had no effect on the occurrence of cracks in the welds.

The use of a shallow-wave-form preheat in combination with a
shallow-wave-form welding current effectively lengthens the total time
of current flow and produces the same effect with regard to decreasing
the expulsion, as would be expected from a single-current discharge
through a sufficiently high turns ratio to give the same total time of
current flow. Expulsion can also be decreased by increasing the elec-
trode force, although at the expense of increasing the sheet separation
somewhat. From the results of the work with condenser-discharge pre-
heating on Alclad 24S-T it would appear that the use of higher
transformer-turns ratios and higher electrode forces are a much more
effective and economical means of reducing expulsion than the use of
condenser-discharge preheating.

Condenser-Discharge Preheating of Spot Welds

in 0.040-Inch and 0.064-Inch Bare 24S-T

It was considered advisable to study the effects of preheating on
bare 24S-T because of its high tendency toward expulsion even when very-
shallow-current wave forms are used for welding. This tendency has been
attributed to the high surface hardness of the material and also to the
difficulty of obtaining a uniformly low surface resistance with room-
temperature etching solutions. (See reference 2.) It is known that the
expulsion can be minimized by using the highest available turns ratio
together with relatively high values of electrode force as compared with
those found to be adequate for alloys having soft surfaces. Even with
these considerations, expulsion is still very often the limiting de-
fect in the production of large welds in the hard materials and the use
of a preheat to decrease the expulsion further might prove advantageous.

Series of welds were made in 0.040-and 0.064-inch thicknesses of
this material similar to those made in the study using 0.040-inch Alclad
24S-T material. In the 0.040-inch bare 24S-T, however, no welds were
made with a steep wave form alone, since the results with Alclad 24S-T
showed such a procedure to be undesirable and the higher surface hard-
ness of the bare alloy would be expected to cause even further trouble
than was encountered with the clad material. The welding conditions
that were used are shown in table III. The various strength-current
characteristics obtained with 0.040-inch bare 24S-T treated in hydro-
fluosilicic acid are presented in figure 2. The electrode force was
600 pounds, and the radius of the dome tips was $2\frac{1}{2}$ inches for each
series of welds. The curve obtained for welds made with a shallow-wave-
form welding current without any preheat (fig. 2(a)) shows that ex-
pulsion occurred with welds having shear strengths greater than 500
pounds. Figure 2(b), for a shallow-wave-form preheat plus a steep-wave-
form welding current, shows these particular conditions to be worse than
a shallow-wave-form welding current alone, since expulsion occurred in
this case when the weld strength was greater than 400 pounds. The re-
sults for a shallow-wave-form preheat plus a shallow-wave-form welding
current, shown in figure 2(c), appear to be slightly inferior to those
of figure 2(a) for the shallow-wave-form welding current alone.

These data indicated that a condenser-discharge preheat was of no
benefit from the standpoint of decreasing expulsion in this material
with a welding force of only 600 pounds. It was believed that any
slight improvement which might have resulted from preheating was com-
pletely masked by the high expulsion tendency for the welds at such a
low welding force. The logical step was to continue the investigation,
using a higher electrode force for welding. The force selected was
1200 pounds. The new welding conditions are shown in table III. The
results, with this higher electrode force, for a shallow-wave-form
welding current and no preheat as compared with a shallow-wave-form
preheat plus a shallow-wave-form welding current, are shown in figure 3.
From this, it may be seen that slightly improved results are obtained
with the preheat. Without preheat, expulsion occurred in welds with
shear strengths slightly greater than 600 pounds. With the preheat,
the weld strengths approached 700 pounds before expulsion occurred.
This small improvement would economically hardly justify the use of a
double condenser-discharge wave form for welding this material, since
the same decrease in expulsion could be obtained by a slight increase
in weld force, which would be a much more practicable solution to the
problem.

A series of welds was also made in the 0.064-inch thickness of this
alloy, using a shallow-wave-form preheat plus a shallow-wave-form welding
current. This double wave form, however, produced a slight but hardly
significant improvement in results over those obtained with a shallow-
wave-form welding current alone, as shown in figure 4.

In comparing the occurrence of cracking in welds made with preheat
and without it in figures 2, 3, and 4, it may be seen that preheating
did not lessen the cracking tendency of spot welds in this alloy.

Effect of Condenser-Discharge Preheating on 0.40-Inch 61S-T

A limited study of the effects of condenser-discharge preheating
was also made with the 61S-T alloy in the 0.40-inch thickness. This
alloy, like bare 24S-T, has a relatively high surface hardness and does
not treat well in a room-temperature etching solution. (See reference 2.)
As with bare 24S-T, these factors combine to give 61S-T a rather high
expulsion tendency when spot-welded with low electrode forces.

The welding conditions used for this material are shown in table IV.
The results obtained in welding this alloy at an electrode force of
600 pounds, using various current wave forms, are very similar to those
obtained with the bare 24S-T alloy. Figure 5(a) is the strength-current
characteristic obtained with a shallow-wave-form welding current alone.
The maximum-size weld with freedom from expulsion had an average shear
strength of about 450 pounds in this case. Figure 5(b) shows the re-
sults of combining a shallow-wave-form preheat with a steep-wave-form
welding current. It is apparent that such a step is in the wrong direc-
tion, since expulsion occurred with welds having shear strengths greater
than 350 pounds. A shallow-wave-form preheat plus a shallow-wave-form
welding current (fig. 5(c)) give roughly the same results as a shallow-
wave-form welding current alone (fig. 5(a)). A previous investigation
(reference 2) has shown that a welding force of 1200 pounds will produce
much more freedom from expulsion than was obtained in these character-
istics with an electrode force of 600 pounds. As was the case for bare
24S-T, it may be concluded that an increase in the welding force is much
more effective in decreasing expulsion from welds in this alloy than is
the use of a condenser-discharge preheat. The preheat had no effect on
the occurrence of cracks, as was the case with the other alloys.

Alternating Current Welds with Postheat in 0.040-Inch Alclad 24S-T

The welding for this part of the investigation was performed with a
Thomson-Gibb, 200 kilovolt-ampere spot welder and a General Electric
Thyratron control panel and sequence timer. The material was chemically
treated in hydrofluosilicic acid solution, $1\frac{1}{2}$ percent by volume, at room
temperature. The welding was performed with 4-inch-radius dome tips, by
using a constant electrode force of 750 pounds and a transformer-turns
ratio of 36:1. The welding program consisted of a 6-cycle welding cur-
rent, a 2-cycle cool time, and a 30-cycle postheat. The magnitude of
the postheat current was varied for different series of welds by means
of a phase-shift control. The welding conditions are tabulated in
table V.

The welds of series 1 may be considered equivalent to welds made without any postheat, since the postheating time was only 2 cycles with a low phase setting. Series 7 represents about the maximum post-heating current output which can be obtained with the present equipment.

The results of the shear tests of the welds are presented in table VI. The data indicate that no improvement in shear strength was obtained by postheating until the phase was set at 100 percent, in which case re-melting occurred in some of the welds and effectively increased the weld diameter. The radiographic examination revealed that the welding con-ditions were such as to produce incipient cracking in the welds, some of the cracks being radiographically detectable. With this in mind it is of interest that the remelting of some of the welds in series 7, although it produced larger welds, did not result in any detectable in-crease in the extent of cracking.

CONCLUSIONS

As a result of the investigation of the effect of preheating and postheating on the quality of welds in aluminum alloys, it is concluded that:

1. A slight reduction in the tendency for expulsion with large welds in 0.040-inch Alclad 24S-T was obtained by using a double condenser-discharge wave form consisting of a slowly rising preheat current and a slowly rising welding current.

2. A double condenser-discharge wave form effectively increased the total time of current flow so that the heating and cooling was much more gradual than could have been obtained with a single condenser-discharge wave from, using the maximum transformer-turns ratio of the machine.

3. Steep-current wave forms increased the tendency toward expulsion in Alclad 24S-T, bare 24S-T, and 61S-T alloys, and this is probably also true of other aluminum alloys. Expulsion with steep-current wave forms was more pronounced in those alloys having high surface hardnesses and also in those which were difficult to treat chemically to produce a low, consistent surface resistance.

4. The combination of a shallow-wave-form preheating current plus a steep-wave-form welding current was inferior to a single shallow-wave-form welding-current discharge from the standpoint of expulsion.

5. Shallow-wave-form preheating and welding currents were ineffec-tive in decreasing the expulsion of welds in hard alloys, such as bare

24S-T and 61S-T, when the electrode force for welding was low. At
higher electrode forces the double wave form decreased the expulsion
slightly. Increasing the electrode force, however, is a much more
effective means of decreasing expulsion in these alloys.

6. Condenser-discharge preheating had no apparent effect on the
occurrence of cracks in welds in 0.040-inch Alclad 24S-T, 0.040- and
0.064-inch bare 24S-T, and 0.040-inch 61S-T.

7. Postheating of spot welds made with alternating current had
no effect on their shear strength until the magnitude of the postheating
current was sufficient to cause remelting of the welds which greatly
increased the weld diameter and the shear strength.

8. Radiographic examination showed no increase in the magnitude
of cracks in those welds in which remelting occurred because of a very
high postheating current, although the diameter and the strength of
the remelted welds were much greater than the others.

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    Rensselaer Polytechnic Institute
        Troy, N. Y., June 29, 1945

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TABLE I. — WELDING CONDITIONS FOR INVESTIGATION OF CONDENSER—
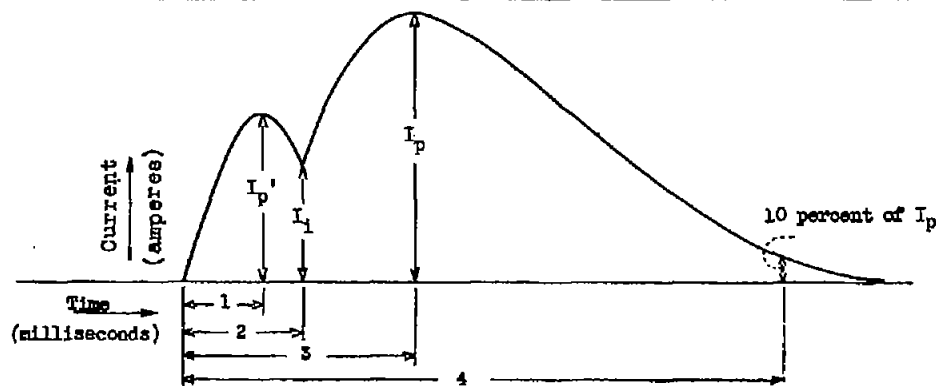
DISCHARGE PREHEAT ON 0.040-INCH ALCLAD 24S-T

[Electrode dome-tip radius, $2\frac{1}{5}$ in; electrode force, 600 lb ; material vapor degreased, treated 8 min at 75° F in hydroflusosilicic acid solution ($1\frac{1}{2}$ percent by volume); surface resistance, 5 to 10 microhms]

Type of wave form	Condenser voltage range (volts)	Preheat		Weld		Remarks
		Turns ratio	Condenser capacitance (microfarads)	Turns ratio	Condenser capacitance (microfarads)	
No preheat, steep-wave-form weld-ing current (rapid current rise)	1800-2300	– – –	– –	103:1	750	See fig. 1(a)
No preheat, shallow-wave-form welding current (slow current rise)	2000-2800	– – –	– –	398:1	750	See fig. 1(b)
Shallow-wave-form preheat, steep-wave-form welding current	1800-2400	398:1	150	103:1	750	See fig. 1(c)
Shallow-wave-form preheat, shallow-wave-form welding current	2000-2800	398:1	150	398:1	750	See fig. 1(d)

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TABLE II.— OSCILLOGRAPHIC MEASUREMENTS OF CURRENT WAVE FORMS FOR SPOT WELDING 0.040-INCH ALCLAD 24S-T

Type of wave form	Transformer-turns ratio		Condenser voltage (volts)	Condenser capacitance (microfarads)		Peak current (amperes)		I_p'/I_p	Time (milliseconds) to —			I_1/I_p' (× 100)	Total time of current flow to 10 percent I_p (milliseconds) (4)
	Preheat	Weld		Preheat	Weld	I_p'	I_p		I_p' (1)	I_1 (2)	I_p (3)		
No preheat, steep-wave-form welding current		103:1	1800 2000 2100 2200 2300		750		37,000 41,100 42,200 45,100 47,400				4.5 4.3 4.5 4.5 4.6		17.4 17.7 17.6 17.9 18.2
No preheat, shallow-wave-form welding current		398:1	2000 2200 2400 2600 2800		750		30,700 34,000 37,400 40,700 44,800				12.5 12.9 13.6 13.1 14.0		50.3 51.5 51.0 51.8 51.4
Shallow-wave-form preheat, steep-wave-form welding current	398:1	103:1	1800 2000 2200 2300 2400	150	750	16,700 18,900 20,000 21,500 22,600	35,200 40,000 43,700 44,800 47,400	0.474 .472 .458 .480 .477	6.8 6.8 6.8 6.6 6.6	13.2 12.4 13.0 12.9 12.5	16.5 16.5 17.0 16.7 16.5	60.0 62.7 61.1 62.1 62.3	30.3 29.4 30.9 30.4 29.7
Shallow-wave-form preheat, shallow-wave-form welding current	398:1	398:1	2000 2200 2400 2600 2800	150	750	20,000 21,500 23,000 24,800 27,400	30,800 33,700 35,500 38,500 42,900	0.651 .637 .646 .644 .638	6.8 7.1 6.9 7.0 6.9	11.6 11.3 11.7 11.9 11.6	21.7 21.8 21.9 22.2 21.9	70.4 72.8 69.4 67.2 67.6	57.8 58.0 60.0 59.3 60.0

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TABLE III. — WELDING CONDITIONS FOR INVESTIGATION OF CONDENSER-DISCHARGE PREHEAT ON BARE 24S-T

[Material vapor degreased, treated 8 min at 75° F in hydrofluosilicic acid solution (1½ percent by volume)]

Material thickness (in.)	Type of wave form	Condenser voltage range (volts)	Preheat		Weld		Electrode force (lb.)	Radius of dome tips (in.)
			Turns ratio	Condenser capacitance (microfarads)	Turns ratio	Condenser capacitance (microfarads)		
[a]0.040	No preheat, shallow-wave-form welding current	1400–1900	------	----	398:1	750		
0.040	Shallow-wave-form preheat, steep-wave-form welding current	1400–1800	398:1	150	103:1	750	[b]600	2½
0.040	Shallow-wave-form preheat, shallow-wave-form welding current	1400–2000	398:1	150	398:1	750		
0.040	No preheat, shallow-wave-form welding current	1800–2600	------	----	398:1	750	[c]1200	2½
0.040	Shallow-wave-form preheat, shallow-wave-form welding current	1800–2600	398:1	150	398:1	750		
[d]0.064	No preheat, shallow-wave-form welding current	1800–3000	------	----	398:1	1200	2000	4
	Shallow-wave-form preheat, shallow-wave-form welding current	1800–3000	398:1	450	398:1	1200		

[a]Surface resistance, 26 to 185 microhms.
[b]See figure 2.
[c]See figure 3.
[d]Surface resistance, 24 to 160 microhms.

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TABLE IV. — WELDING CONDITIONS FOR INVESTIGATION OF CONDENSER—

DISCHARGE PREHEAT ON 0.040-INCH 61S-T

[Electrode dome-tip radius, $2\frac{1}{5}$ in.; electrode force, 600 lb; material vapor degreased, treated 8 min at 75° F in hydrofluosilicic acid solution ($1\frac{1}{2}$ percent by volume); surface resistance, 75 to 1050 microhms]

Type of wave form	Condenser voltage range (volts)	Preheat		Weld		Remarks
		Turns ratio	Condenser capacitance (microfarads)	Turns ratio	Condenser capacitance (microfarads)	
No preheat, shallow-wave-form welding current	1400–2200	- - -	- -	398:1	750	See fig. 5(a)
Shallow wave-form preheat, steep-wave-form welding current	1400–2100	398:1	150	103:1	750	See fig. 5(b)
Shallow-wave-form preheat, shallow-wave-form welding current	1600–2400	398:1	150	398:1	750	See fig. 5(c)

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TABLE V. — WELDING CONDITIONS FOR STUDY OF EFFECT OF POSTHEATING

ON ALTERNATING-CURRENT WELDS IN 0.040-INCH ALCLAD 24S-T

[Turns ratio, 36:1; electrode force, 750 lb; electrode dome-tip radius, 4 in.; surface resistance, 5 microhms (1½ percent by volume H_2SiF_6, room temperature)]

Weld series	Generator terminal voltage (volts)	Weld		Cool time (cycles)	Postheat	
		Time (cycles)	Phase (percent)		Time (cycles)	Phase (percent)
1	575	6	92.5	2	2	22.5
2	575	6	92.5	2	30	50
3	575	6	92.5	2	30	70
4	575	6	92.5	2	30	80
5	575	6	92.5	2	30	90
6	575	6	92.5	2	30	95
7	575	6	92.5	2	30	100

TABLE VI.— RESULTS OF SHEAR TESTS OF POSTHEATED SPOT WELDS

IN 0.040-INCH ALCLAD 24S-T

Weld	Postheat		Shear strength (lb)
	Time (cycles)	Phase (percent)	
1a	2	22.5	505
b			455
c			445
			Av. 468
2a	30	50	455
b			450
c			480
			Av. 462
3a	30	70	485
b			425
c			470
			Av. 460
4a	30	80	430
b			455
c			440
			Av. 442
5a	30	90	445
b			465
c			525
			Av. 478
7a	30	100	485
b			455
			Av. 470
c			[a]1105
d			[a]1045
			Av. 1075

[a]Remelted.

(a) No preheat; welding current, steep wave form.

(b) No preheat; welding current, shallow wave form.

(c) Preheating current, shallow wave form; welding current, steep wave form.

(d) Preheating current, shallow wave form; welding current, shallow wave form.
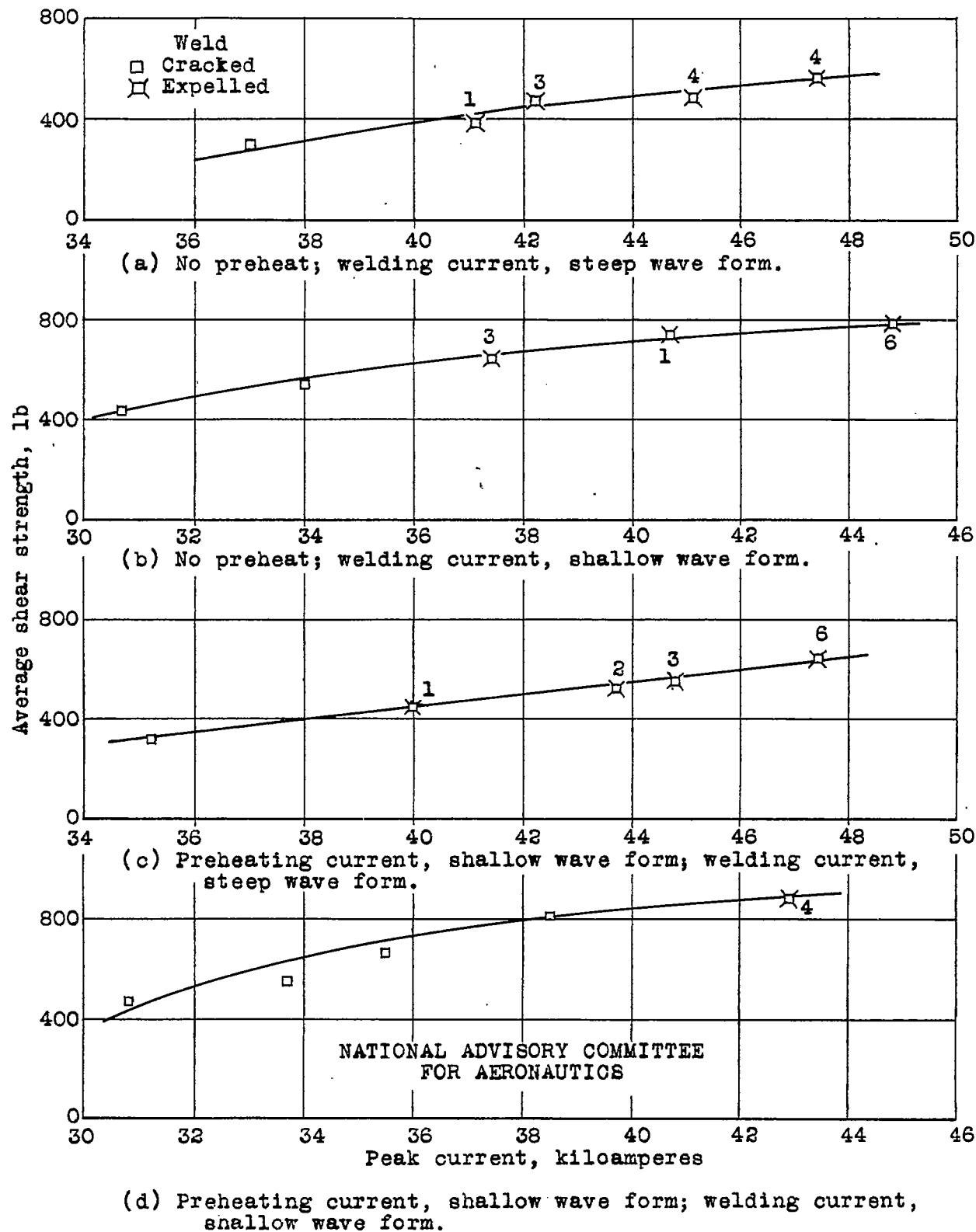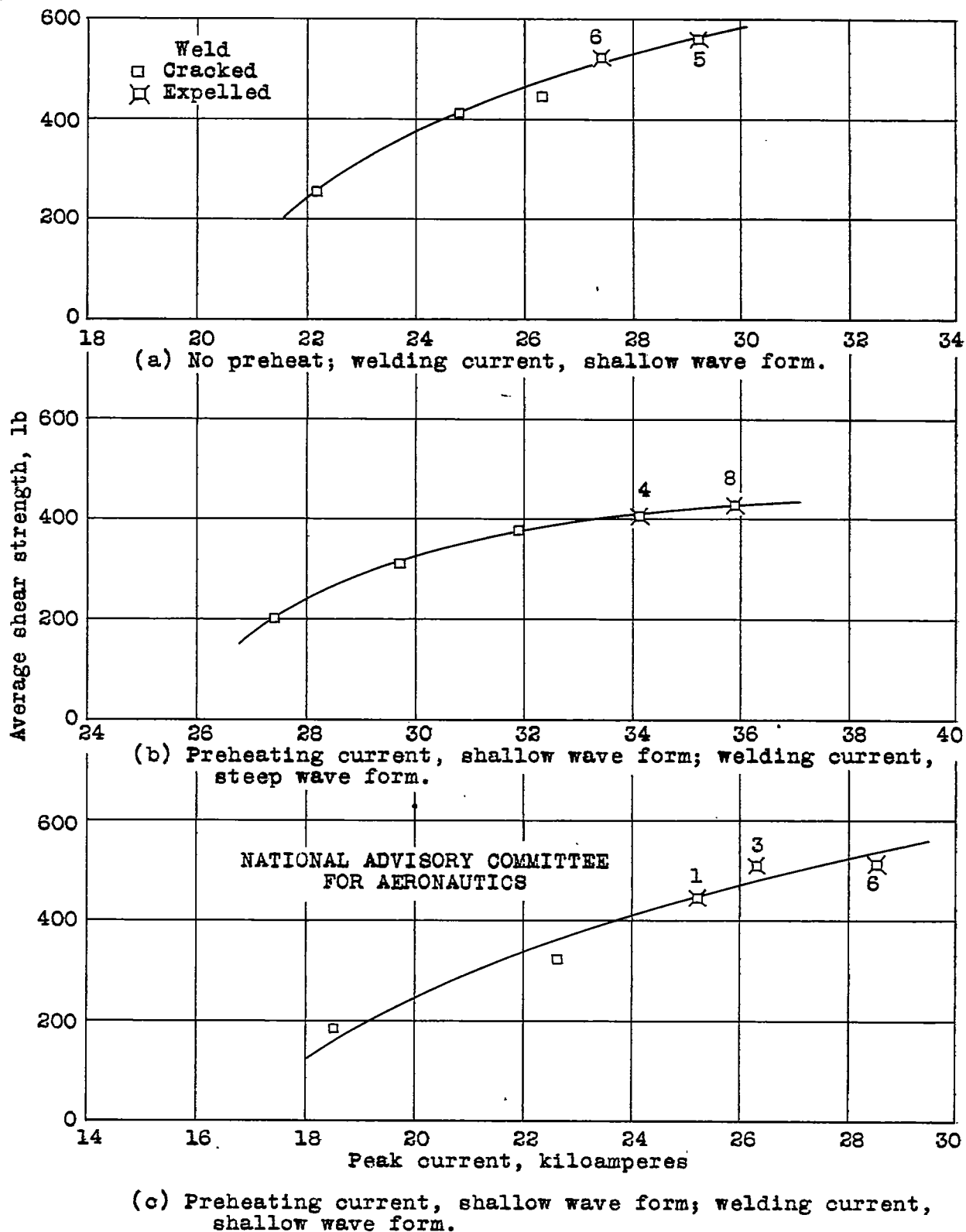
Figure 1.- Strength-current characteristic of Alclad 24S-T. Thickness, 0.040 inch; electrode dome-tip radius, 2-1/2 inches; electrode force, 600 pounds; chemically treated.

(a) No preheat; welding current, shallow wave form.

(b) Preheating current, shallow wave form; welding current, steep wave form.

(c) Preheating current, shallow wave form; welding current, shallow wave form.

Figuer 2.- Strength-current characteristic of bare 24S-T. Thickness, 0.040 inch; electrode dome-tip radius, 2-1/2 inches; electrode force, 600 pounds; chemically treated.
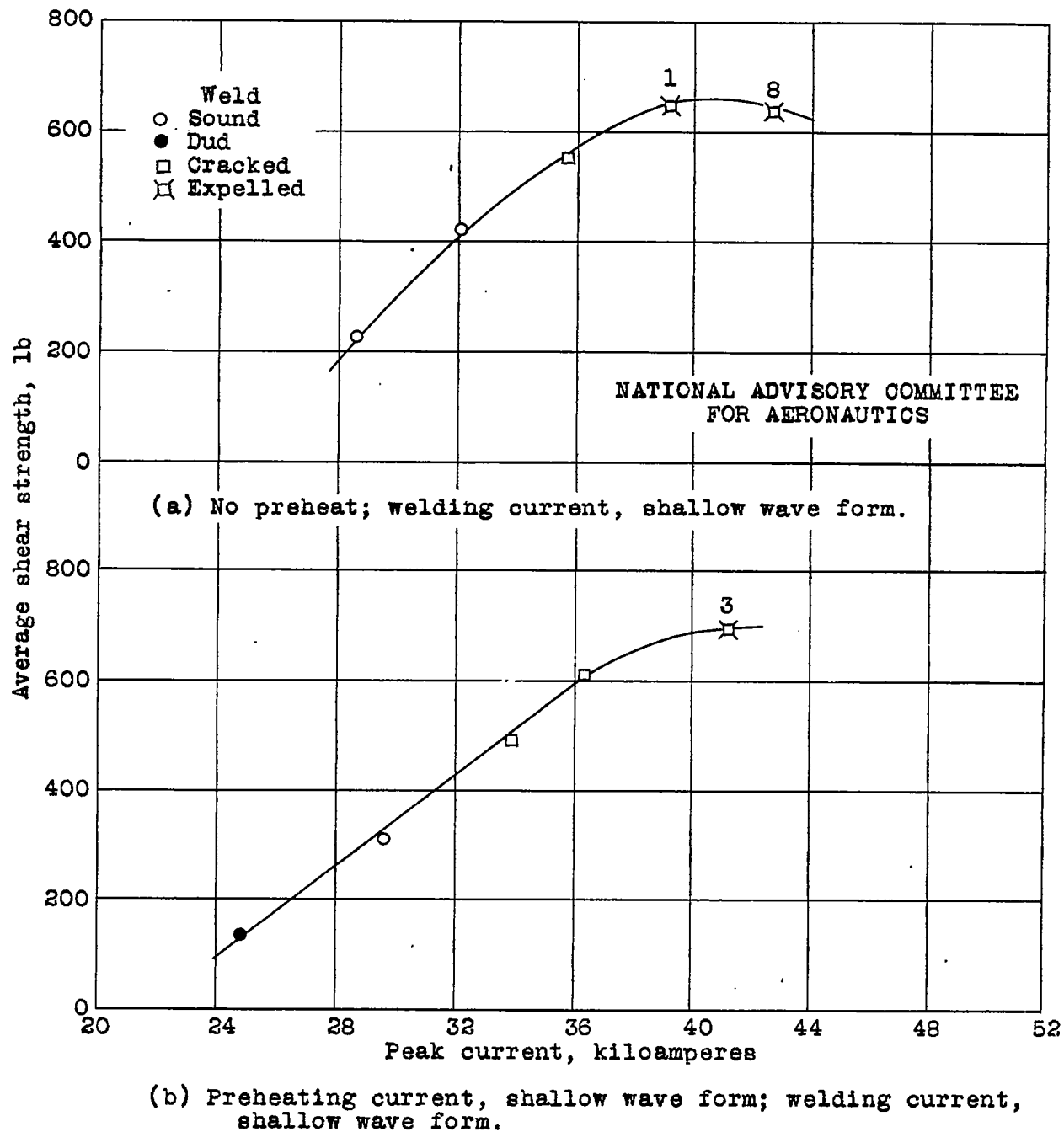
(a) No preheat; welding current, shallow wave form.

(b) Preheating current, shallow wave form; welding current, shallow wave form.

Figure 3.- Strength-current characteristic of bare 24S-T. Thickness, 0.040 inch; electrode dome-tip radius, 2-1/2 inches; electrode force, 1200 pounds; chemically treated.
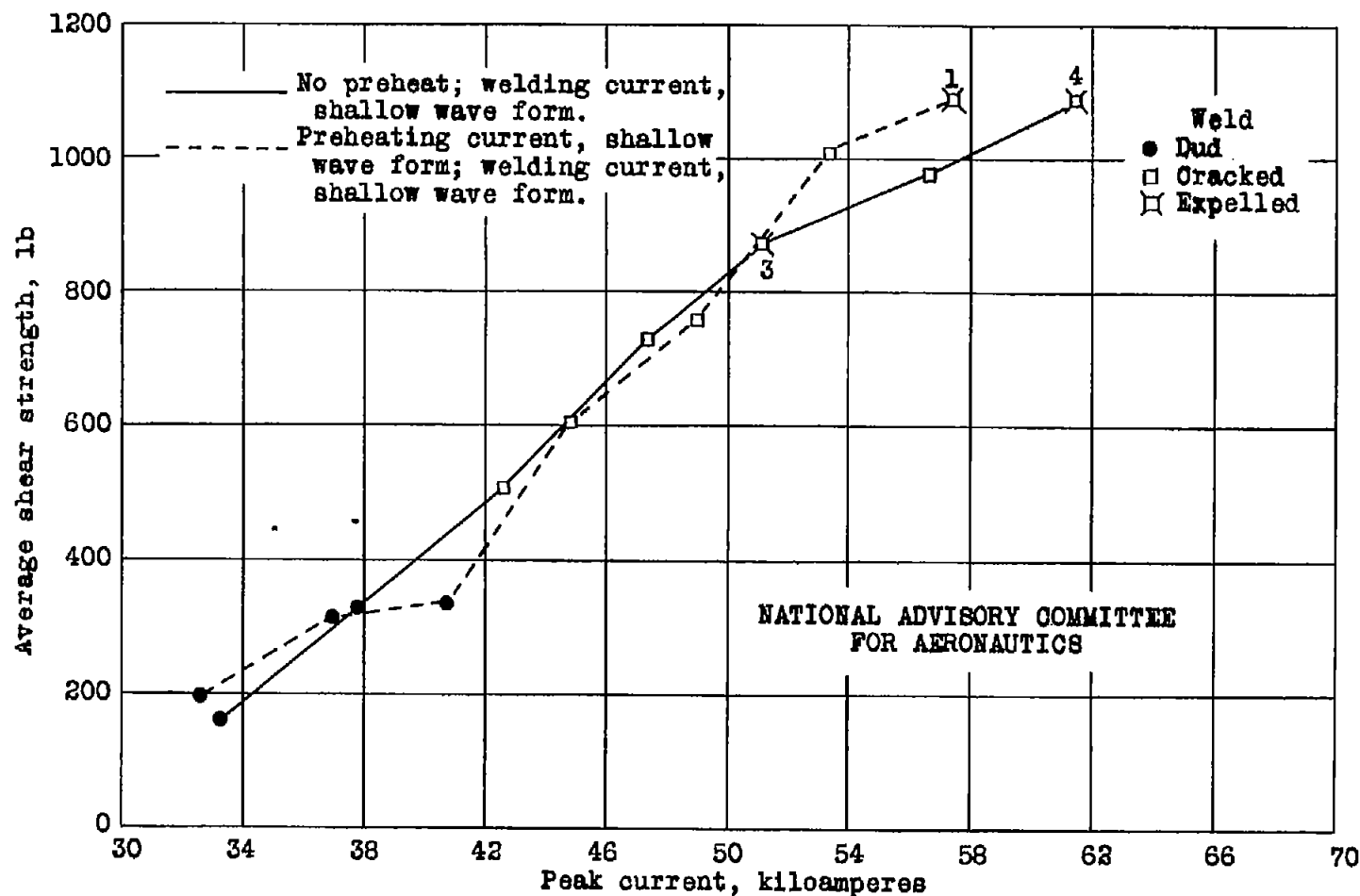
Figure 4.- Strength-current characteristic of bare 24S-T. Thickness, 0.064 inch; electrode dome-tip radius, 4 inches; electrode force, 3000 pounds; chemically treated.

(a) No preheat; welding current, shallow wave form.

(b) Preheating current, shallow wave form; welding current, steep wave form.

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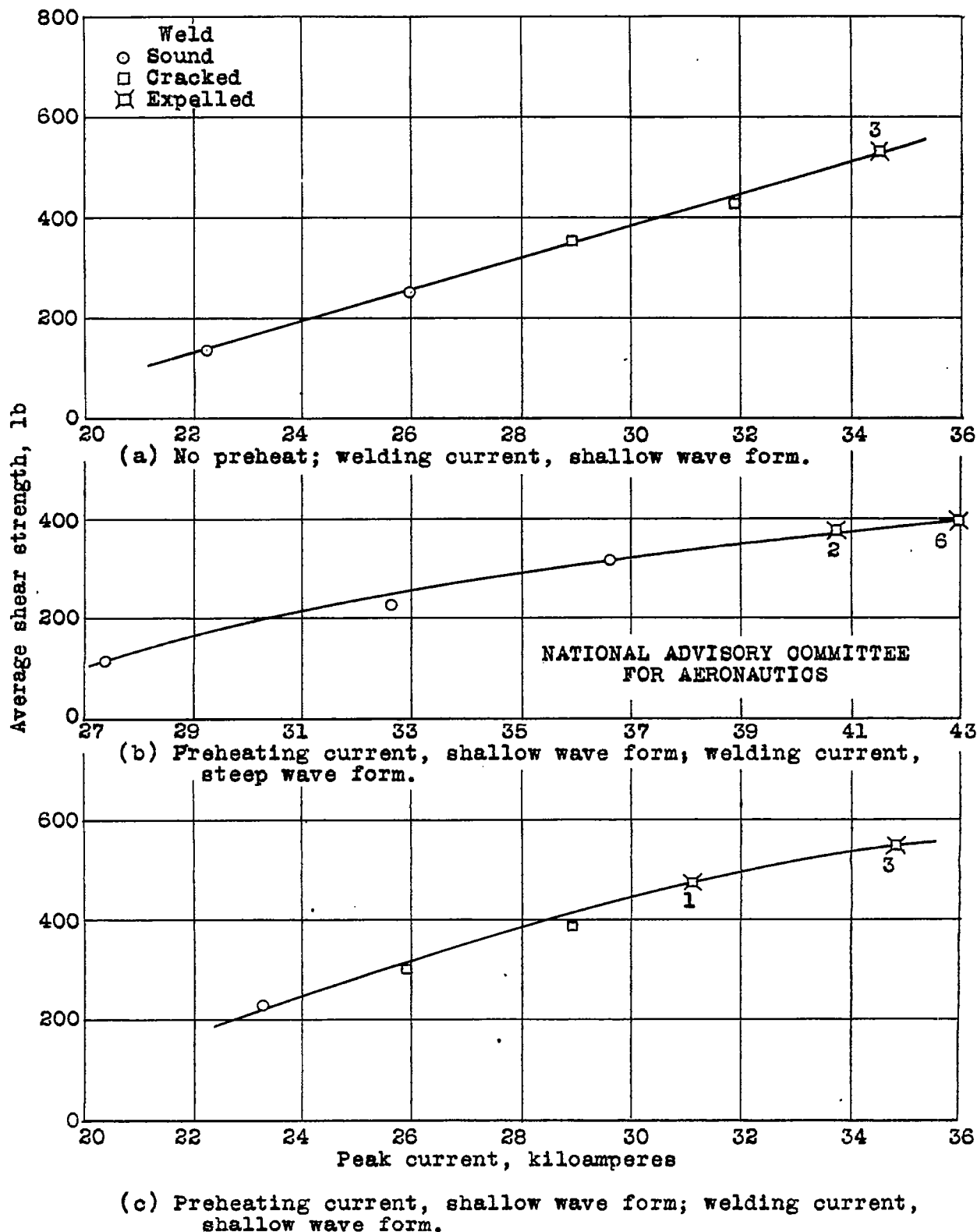(c) Preheating current, shallow wave form; welding current, shallow wave form.

Figure 5.- Strength-current characteristic of 61S-T. Thickness, 0.040 inch; electrode dome-tip radius, 2-1/2 inches; electrode force, 600 pounds; chemically treated.