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Evaluation of ANSI/AASHTO/AWS D1.5-88 Bridge Welding Code and AASHTO Guide Specifications for Fracture-Critical Non-Redundant Steel Bridge Members Pertaining to Submerged Arc Welding Procedures

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I. Introduction

The ANSI/AASHTO/AWS D1.5-88 Bridge Welding Code is a document that was developed to address the specific concern of ensuring that fabricators would be able to produce welds meeting certain minimum requirements while operating within a limited variable range. Any problems with the weld procedure as tested could then be addressed prior to actual fabrication to ensure the quality and safety of the welded joint. The document contains requirements for fabricating and testing weld qualification plates, and for control of variables once the procedure is approved for use. Additionally, D1.5 allows for the prequalification of shielded metal arc welding (SMAW) procedures, providing the electrode to be used is listed in Table 4.1 of the code. To control welding procedures on non-redundant bridge members, the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering Association (AREA) have both developed specifications for fracture critical members (FCM's). Both of these documents act as additions to D1.5, and differ primarily in the number of specimens which must be tested and in the size of the plates which are used for the test weld.

In the D1.5 qualification process, two plates of either 3/4 inch or 1-1/2 inch steel are welded together with a B-U2-S groove weld. Procedure qualification falls under section 5.6 or, optionally, section 5.7 if the metals and consumables are listed in Table 4.1 of the code and the joint detail is one of those listed in Chapter 2 of the code as prequalified. If the metals and consumables are found in Table 4.2 of the code or are not listed, or if the joint detail is not prequalified, qualification must follow the provisions of section 5.7. The basic difference between the two sets of specifications is that procedures tested under 5.7 are subject to more stringent controls during fabrication, as stated in section 5.10 of the code.

Figure 1 gives an overview of the D1.5 procedure qualification process and the limits on production welds.

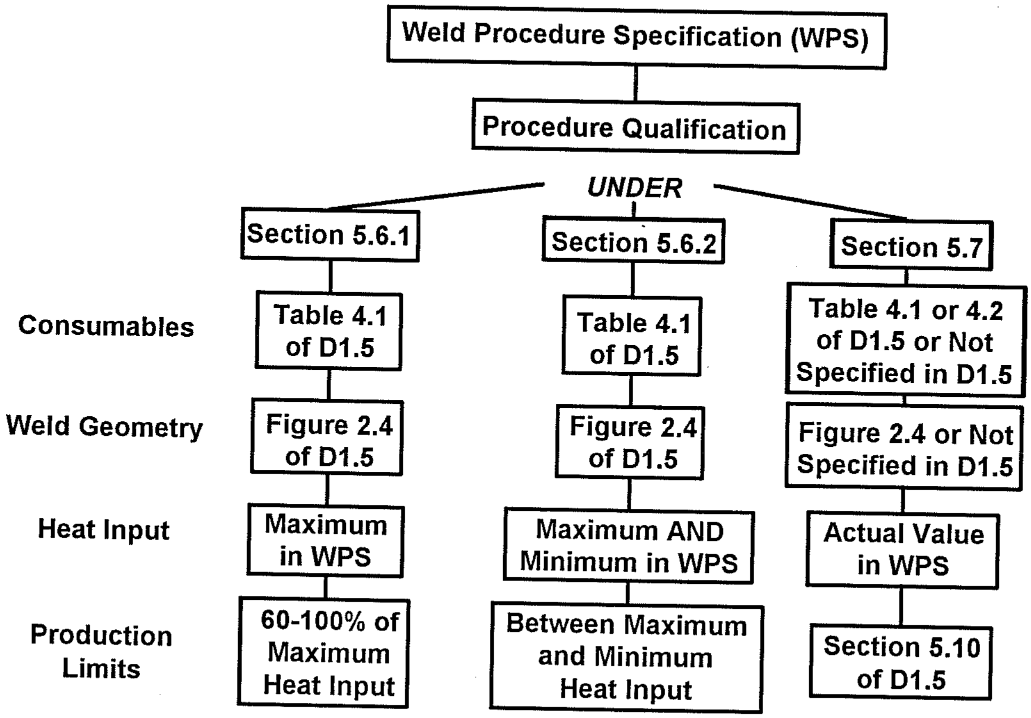


Figure 1 - Schematic of procedure qualification process under D1.5.

AASHTO FCM test plate fabrication requirements are similar to those of D1.5, except that one test weld must be made between plates 1 inch thick. In addition, if the production weld will be made between two members thicker than 1-1/2 inch, an additional weld must be made between plates of the same thickness as the production base metal. An exception to this rule is for welds which in production will join plates greater than 2 inches thick, in which case the additional test weld need only join plates 2 inches thick.

The tests required by D1.5 include a set of five Charpy V-notch toughness tests, an all-weld metal tensile test, two tensile tests with coupons milled transverse to the weld, four side bend tests, and a radiographic test. FCM requirements call for these same tests from the 1 inch thick plates, but require a set of ten Charpy tests and two all-weld metal tensile tests from the thicker plates. The Charpy and tensile tests require that specimens be machined from the welded test plates, introducing considerable cost into the testing procedure. The machine work required for the side bend tests is less expensive than for the Charpy and tensile tests, as specimens are simply sliced from a cross section of the test plates. The radiographic test requires no milling of the test plate, and is a less expensive method testing than those requiring machining. The qualification is considered valid only for the qualifying fabricator for a period of three years under D1.5 or one year under the FCM guidelines, after which the procedure must be requalified.

A few procedures, limited to shielded metal arc welding (SMAW) processes using electrodes enumerated in Table 4.1 of the code, are exempted from qualification testing. Although the AASHTO Commentary on the ANSI/AASHTO/AWS D1.5-88 Bridge Welding Code provides no explanation as to why these procedures were exempted, it does make a distinction between the consumable-base metal combinations in Table 4.1 and Table 4.2, stating that those processes in Table 4.2 are assumed to be more susceptible to changes in mechanical properties arising from variability in weld technique. It can be inferred that the exclusion of the SMAW processes from testing was made for a similar reason, namely that welds made with SMAW are not generally susceptible to variability in technique.

II. Purpose

Fabricators involved with bridge welding have expressed displeasure with the D1.5 code primarily because of the time and money investment required for testing, which is linked to the number of tests and the frequency of testing required, as well as to the lack of reciprocity in accepting test results. Prior to D1.5, bridge welds fell under the authority of ANSI/AWS D1.1 Structural Welding Code--Steel, and did not require the fabricator to perform tests of the welding procedure, allowing him instead to predict weld strength on the basis of the consumable manufacturer's tests. The responsibility for testing weld quality was switched from the consumable manufacturer to the fabricator because it was felt that production welding procedures had little in common with the methods used by manufacturers to produce test welds.

The fundamental motivation behind this study was to determine whether or not the provisions and limitations of the D1.5 code are in fact applicable to the real-world welds that fabricators make in the manufacture of bridge structural members. One of the primary questions was why SMAW is the only process to be prequalified, even though it is the only process which cannot be automated, and is therefore subject to greater variability in welder technique. Also questioned was the effect that the controlled welding variables have on weld quality, and whether the correct variables are being controlled in the qualification process.

Aside from weld joint geometry, the D1.5 code places most emphasis on controlling heat input, preheat temperature and interpass temperature of production welds to achieve weld strength and toughness comparable to the weld tested. Heat input is found by:

$$HeatInput = \frac{Current x Voltage x 60}{TravelSpeed(Inches/\mathrm{min}) x 1000} \tag{1}$$

For welds tested under the provisions of section 5.6, the code limits heat input in production to between 60 and 100 percent of tested heat input, unless both maximum and minimum heat input welds are tested, in which case any heat input may be used between the two values. For procedures tested under 5.7, heat input is limited by section 5.10 to between 70 and 110 percent of the tested value. In addition, 5.10 lists specific limits on the current, voltage, and travel speed, the three components of heat input. Section 5.10 also adds restrictions on other procedural variables, including consumables, preheat and interpass temperatures, and technique.

The code's overriding concern is to require that the test weld be formed by using the highest heat input and slowest cooling rate allowed in the procedure specification, providing conditions which generally result in low weld notch toughness. If the test weld can then pass all of the tests, the code takes the position that the fabricator will be able to make production welds with satisfactory properties for heat inputs as low as 70% or 60% of that qualified, or alternatively for the maximum-minimum test series, as low as the minimum heat input qualified.

III. Investigation

The data for this study consisted of Procedure Qualification Records (PQR's) from 22 fabricators involved in bridge welding. A total of 796 PQR's were entered into a database on Microsoft Excel 4.0. The quality of the information contained in the PQR's ranged from excellent, where the fabricator used a reporting format based on that suggested in D1.5 and filled in all necessary information, to poor, where fabricators used their own formats and even then left data blanks incomplete.

The breakdown of this data with respect to process, given in Table 1, shows the overwhelmingly high proportion of those procedures qualified using the submerged arc welding (SAW) process. Because of the comparatively large number of submerged arc welding reports, it was decided to begin the study by concentrating on the SAW procedures. The SAW investigation also benefited from including records from all fabricators but one, allowing a cross-sectional view of procedures used by fabricators to investigate whether procedures varied between fabricators or were essentially the same for all those using submerged arc welding. It was initially hypothesized that if many fabricators were using similar or identical procedures and achieving comparable results from those processes, that particular method might be suggested for prequalification.

Process	**# of PQR's**	**# of Fabricators Using Process**
SAW	489	21
SMAW	145	12
SAW-Twin Arc	95	7
FCAW	65	13
Other	2	2
All Processes	796	22 Fabricators Total

Table 1 - Weld Procedures Documented in Study.

A final factor influencing the decision to begin with SAW welds is the fact that most SAW welds are performed automatically or semi-automatically, which translates into good potential for repeatability of technique between fabricators. If SAW welds performed by one or more fabricator were consistently passing PQR requirements, then the repeatable quality of SAW welding would give reinforcement to the possibility of prequalifying a technique or group of techniques for producing SAW welds. Presently, D1.5 makes no provision for allowing one fabricator to use a process which has been qualified by another without repeating the qualification.

IV. Observations

Given the strong emphasis which D1.5 puts on controlling heat input, it was surprising to find that heat input has no observable effect on the Charpy notch toughness of the tested welds. In all comparisons of Charpy notch toughness to heat input, no correlation was found which would suggest that toughness was significantly affected by weld heat input. In the final stages of the study, the heat input versus notch toughness comparison was made within groups of the same base metal, welding consumable type, fabricator, electrode diameter, and base plate thickness, such that essentially the only variable left to influence notch toughness was heat input. Even at that level, a correlation was not evident. Figures 2 through 13 consist of plots of Charpy notch toughness as a function of heat input, with data divided by base metal type, base metal thickness, electrode diameter, and fabricator. The distribution of data shows the lack of a relationship between heat input and notch toughness, even when these possible influences are factored out.

Other input variables likewise had little effect on notch toughness. Figures 14 through 34 are plots of Charpy notch toughness within different flux-electrode combination types versus current density, preheat temperature, interpass maximum and minimum temperatures, current, electrode travel speed, and voltage. Although the data points are not broken down by groups as are those in Figures 2 through 13 in the interest of limiting repetition, these plots show the same insensitivity to electrode diameter, base metal thickness, base metal type, and fabrication shop.

The only variable which seemed to influence notch toughness was the flux-electrode combination. Figure 35 shows the relationship between the notch toughnesses of the different combinations, as well as the distribution of values within the combination sets. As noted in Table 2, the largest body of consumables used were manufactured by the Lincoln Electric Company, and in most cases consisted of a Lincoln L66 or L61 (AWS classification EM12K) electrode with a flux. According to a Lincoln representative, both of these electrodes can be considered identical as far as achievable weld quality. A detailed study of welds produced with consumables from Lincoln showed that the only observable predictor of notch toughness was the particular combination used. Among those welds made with L61 and L66 electrodes, which comprised the majority of the data, flux type arose as the sole influence on weld quality, since the two electrodes are nearly identical. Lincoln's results in testing the mechanical qualities of welds made with their fluxes support this observation by showing a strong difference between the notch toughness values of welds made using different fluxes.

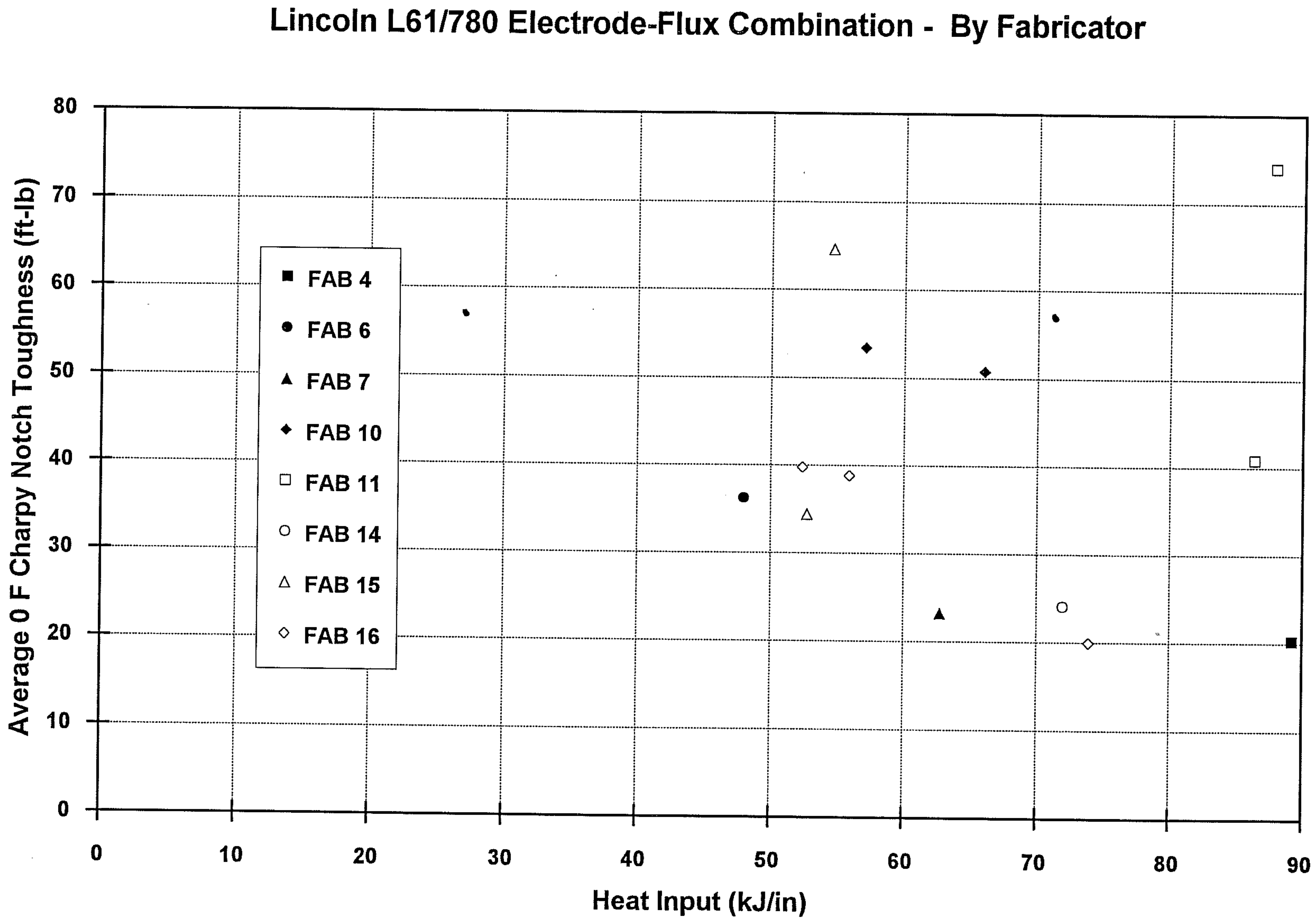


Figure 2 - 0 F Charpy notch toughness vs. heat input arranged by fabricator for Lincoln 780 flux and L61 electrode.

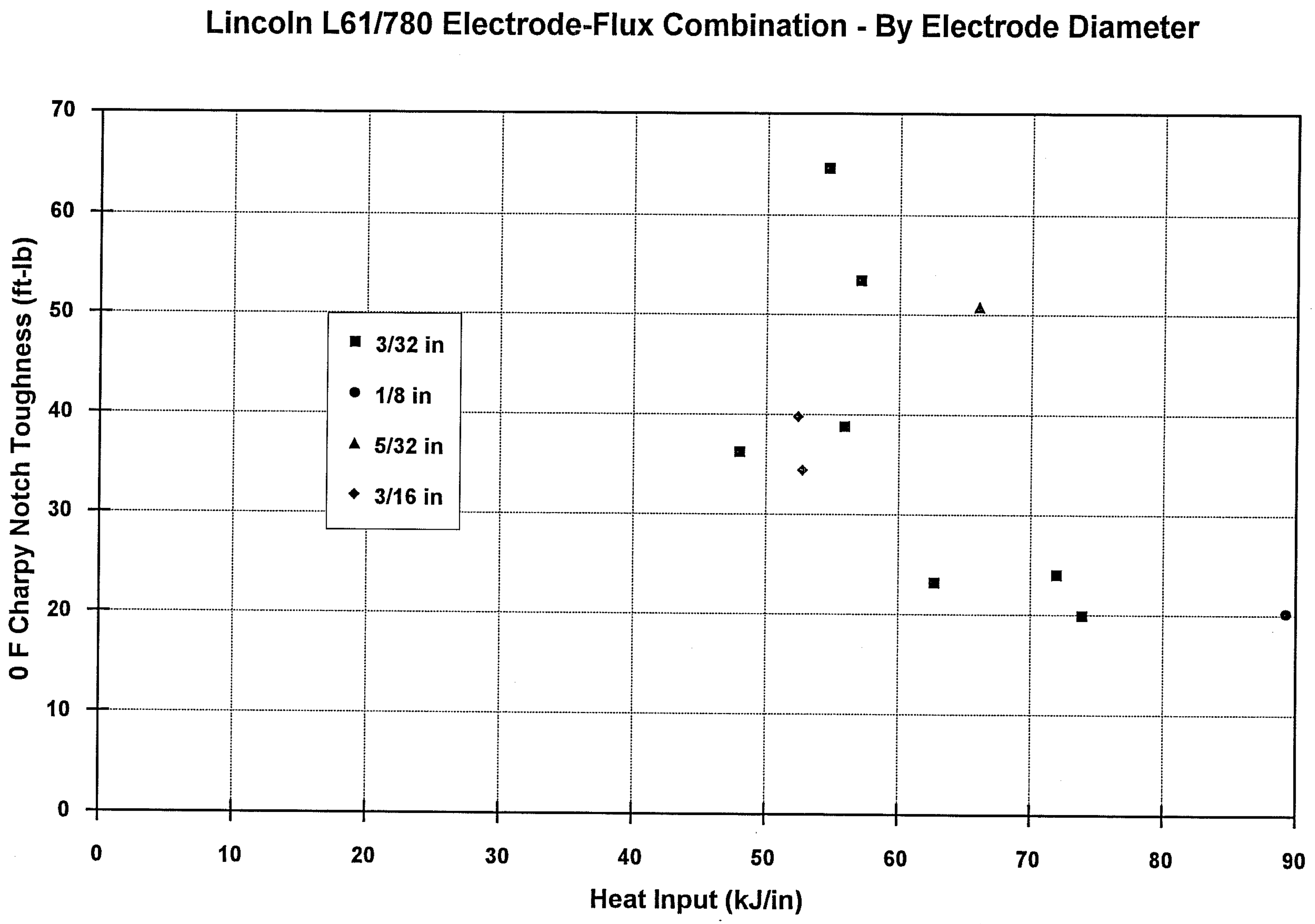
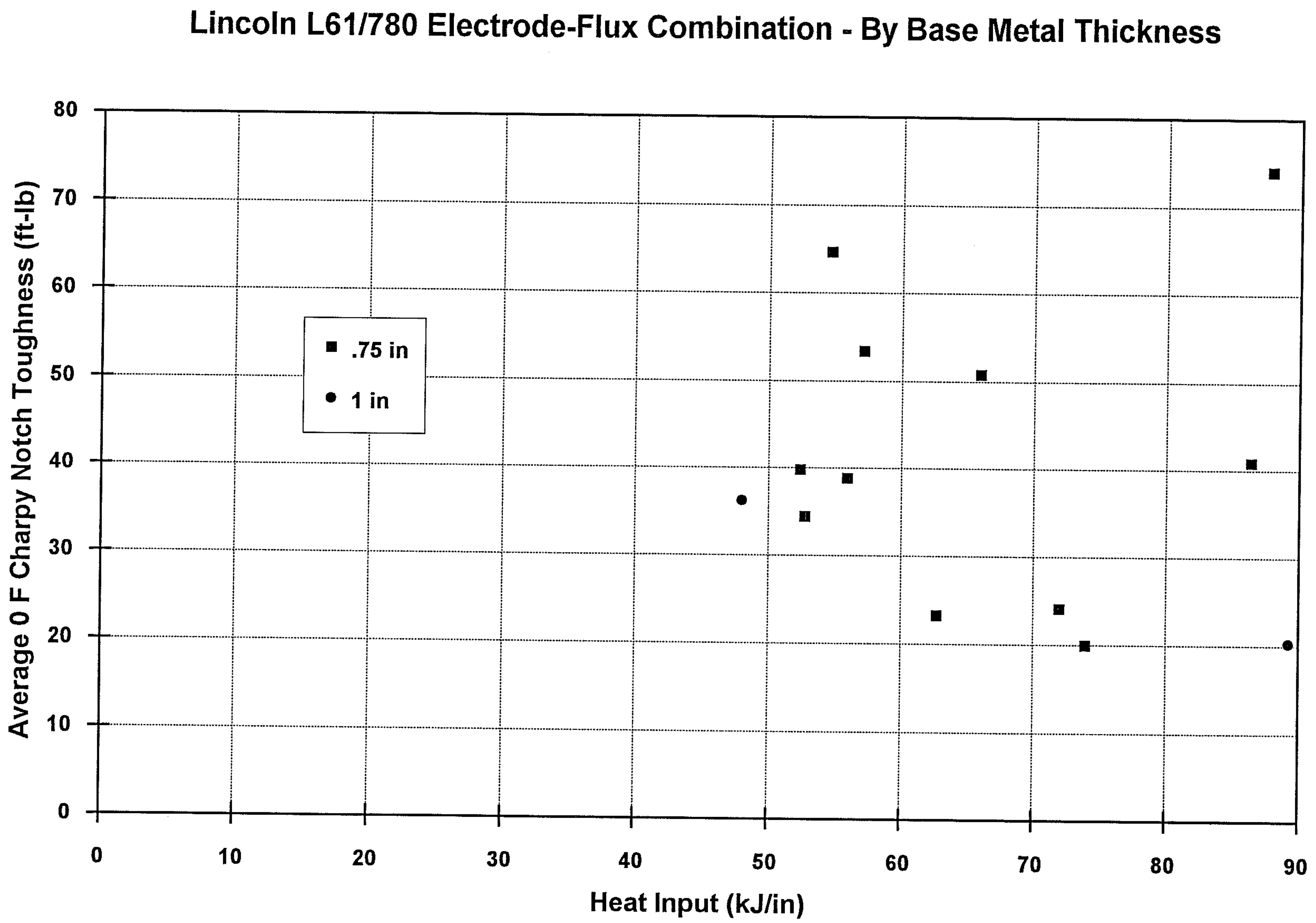


Figure 3 - 0 F Charpy notch toughness vs heat input arranged by electrode diameter for Lincoln 780 flux and L61 electrode.



Lincoln L61/780 Electrode-Flux Combination - By Base Metal Thickness

Figure 4 - 0 F Charpy notch toughness vs. heat input arranged by base metal thickness for Lincoln 780 Flux and L61 electrode.

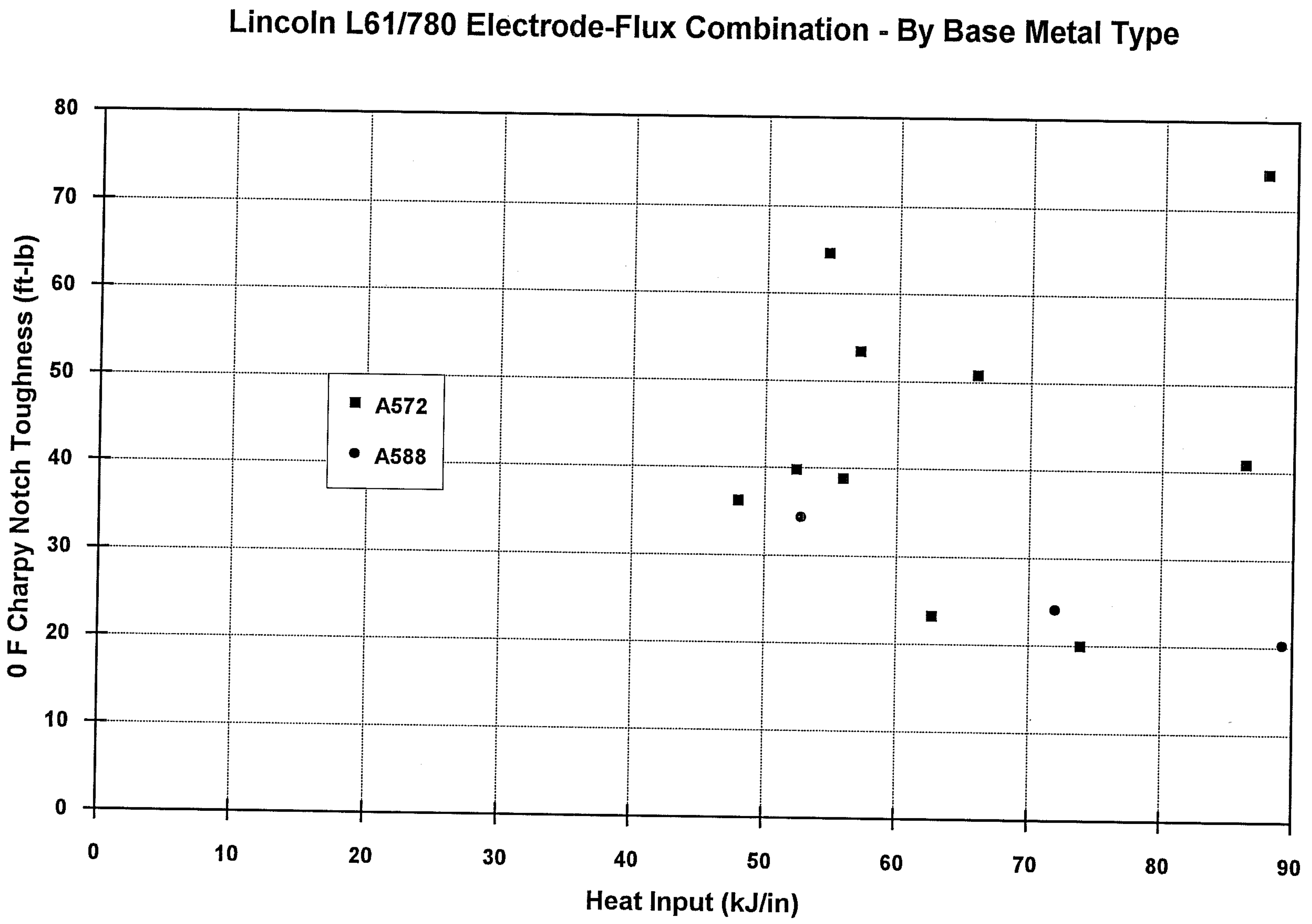


Figure 5 - 0 F Charpy notch toughness vs. heat input arranged by base metal type for Lincoln 780 flux and L61 electrode.

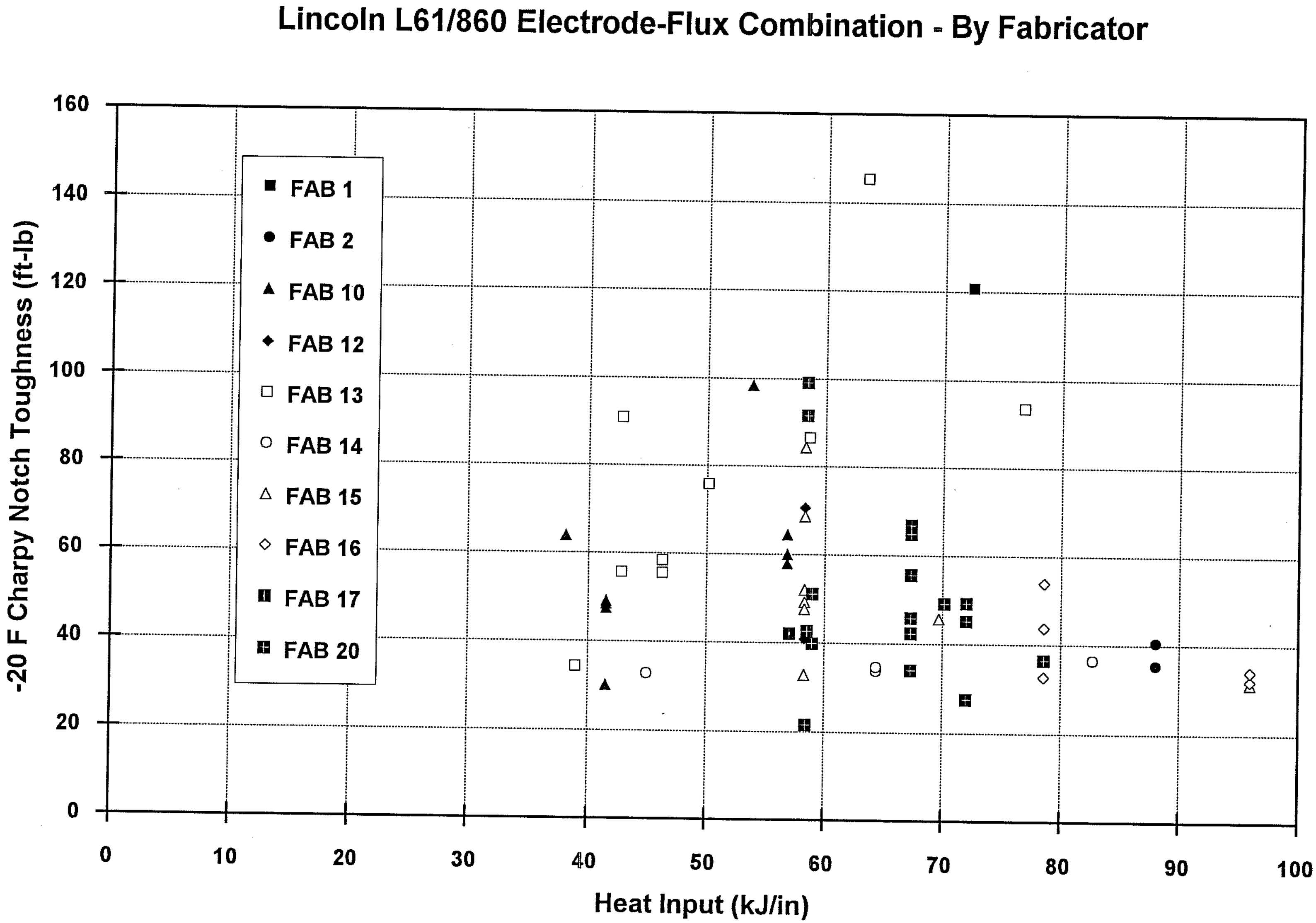


Figure 6 - -20 F Charpy notch toughness vs. heat input arranged by fabricator for Lincoln 860 flux and L61 electrode.

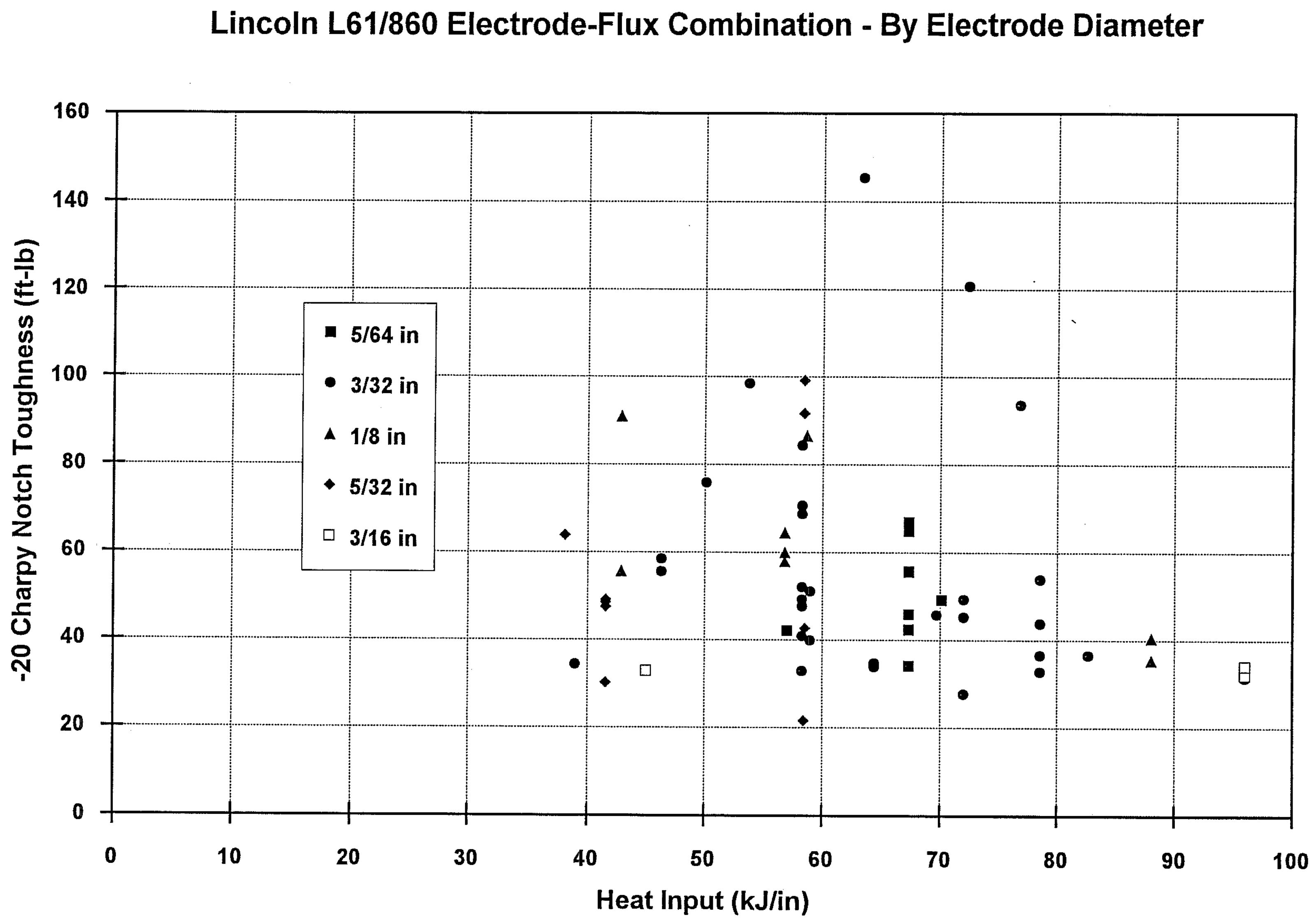


Figure 7 - -20 F Charpy notch toughness vs. heat input arranged by electrode diameter for Lincoln 860 flux and L61 electrode.

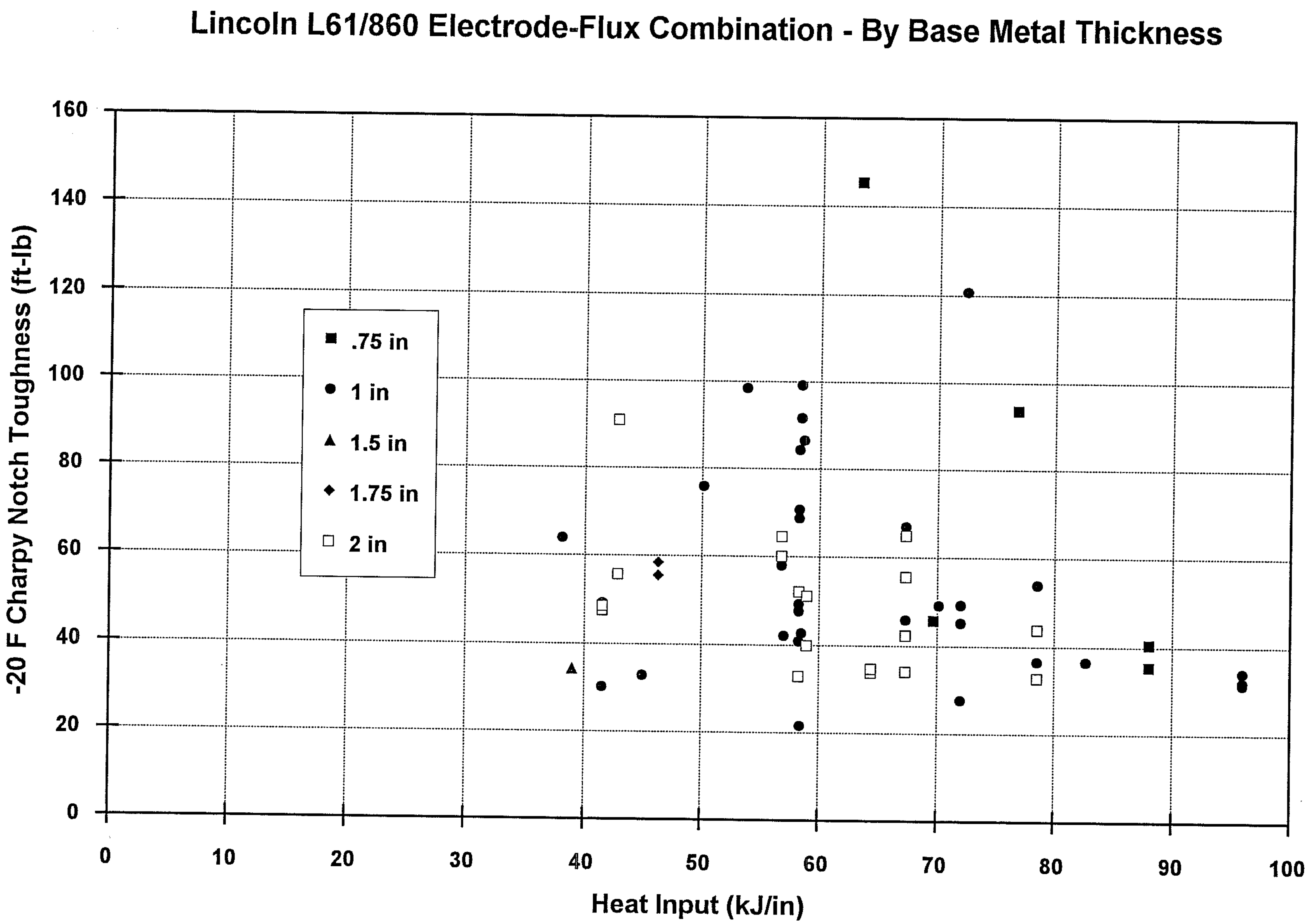


Figure 8 - -20 F Charpy notch toughness vs. heat input arranged by base metal thickness for Lincoln 860 flux and L61 electrode.

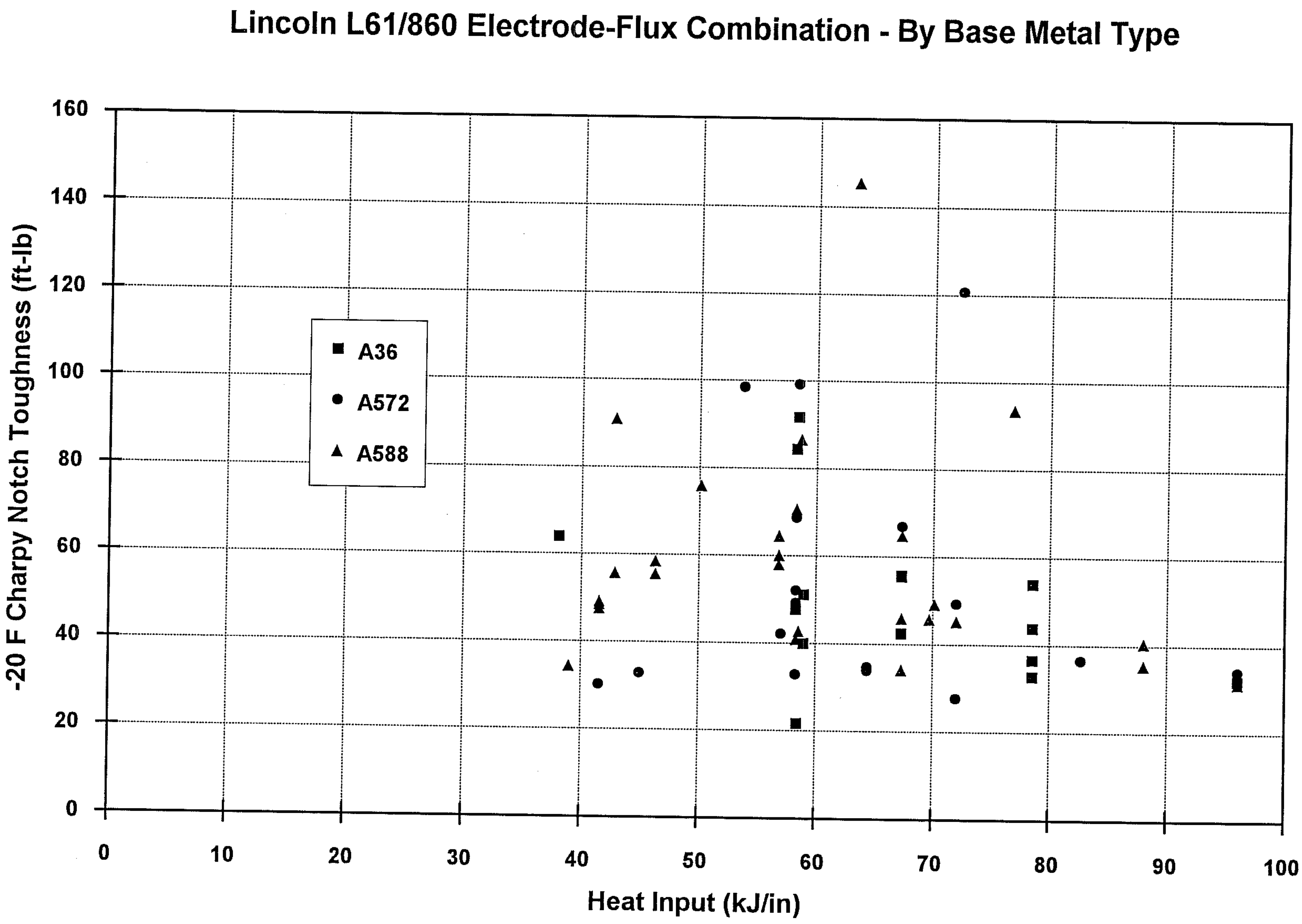


Figure 9 - -20 F Charpy notch toughness vs. heat input arranged by base metal type for Lincoln 860 flux and L61 electrode.

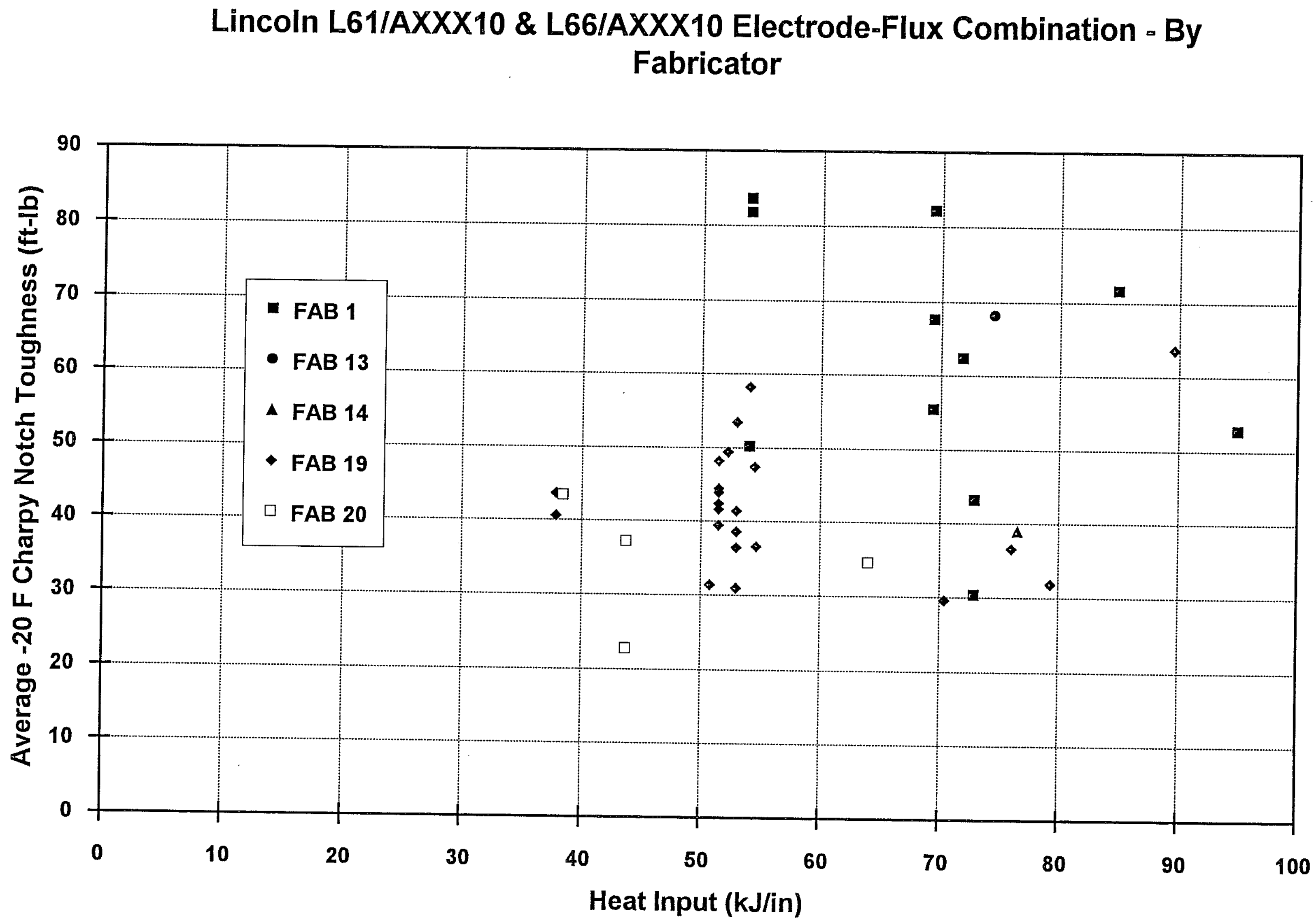


Figure 10 - -20 F Charpy notch toughness vs. heat input arranged by fabricator for Lincoln AXXX10 flux and L61 and L66 electrodes.

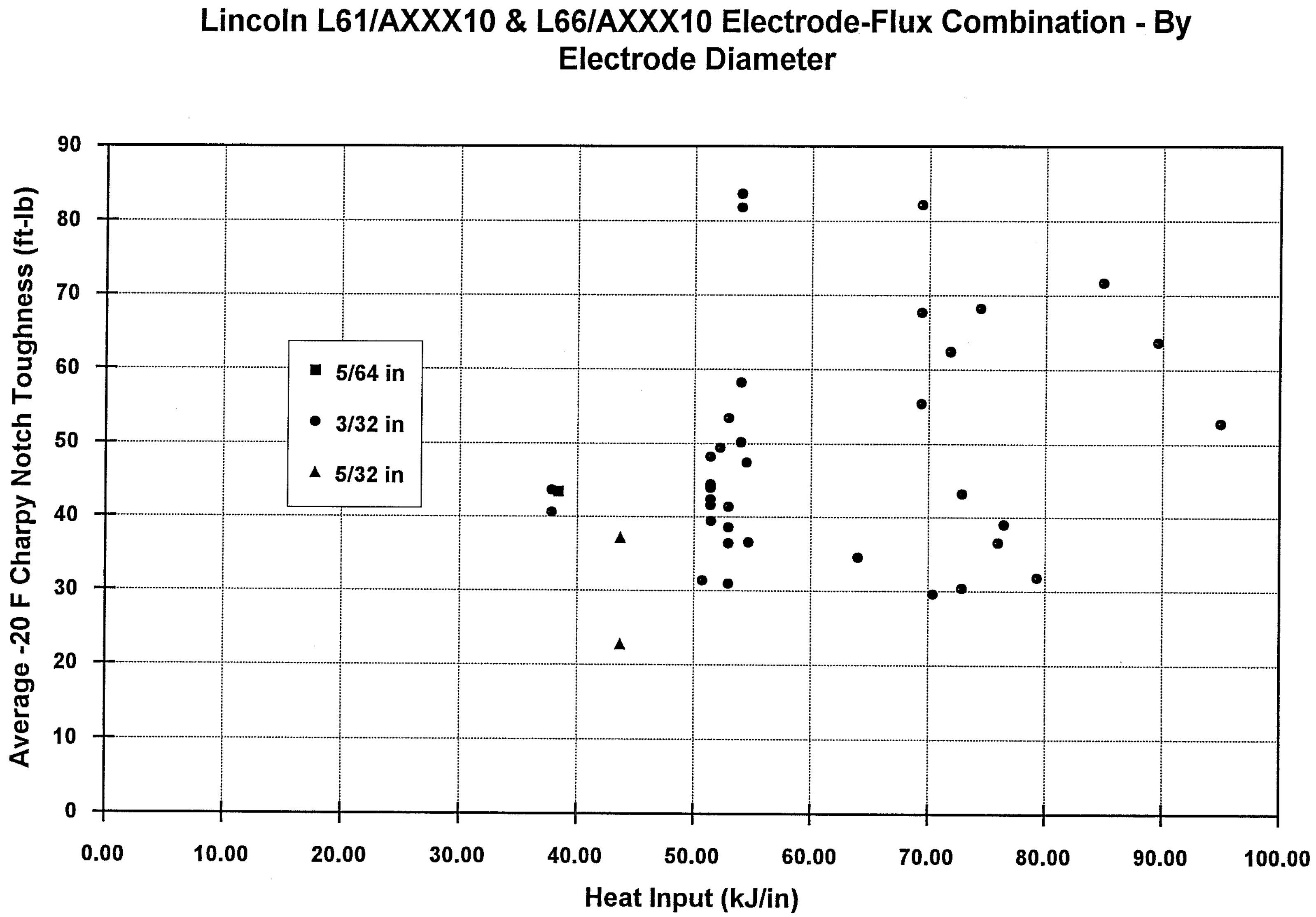


Figure 11 - -20 F Charpy notch toughness vs. heat input arranged by electrode diameter for Lincoln AXXX10 flux and L61 and L66 electrodes.

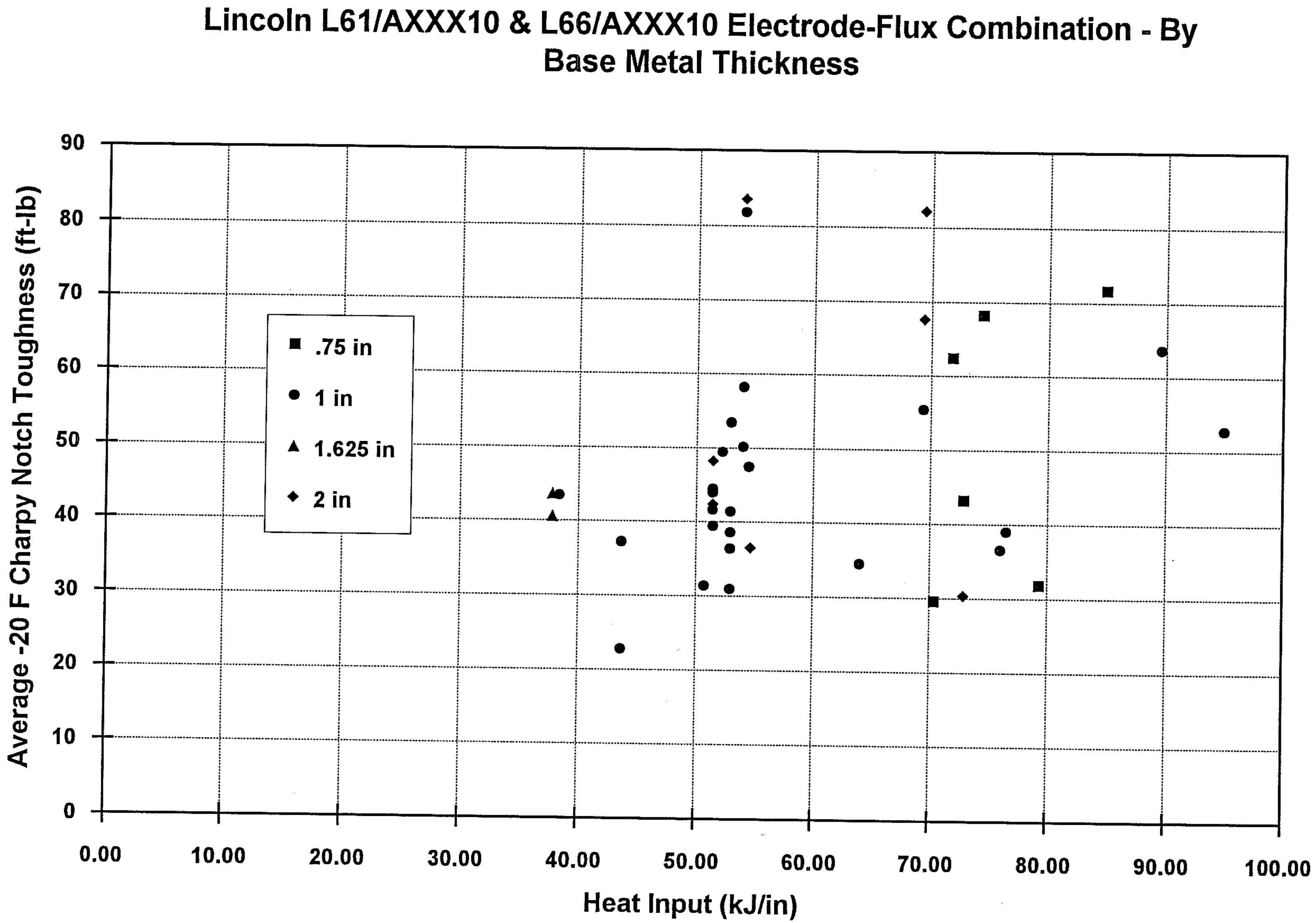


Figure 12 - -20 F Charpy notch toughness vs. heat input arranged by base metal thickness for Lincoln AXXX10 flux and L61 and L66 electrodes.

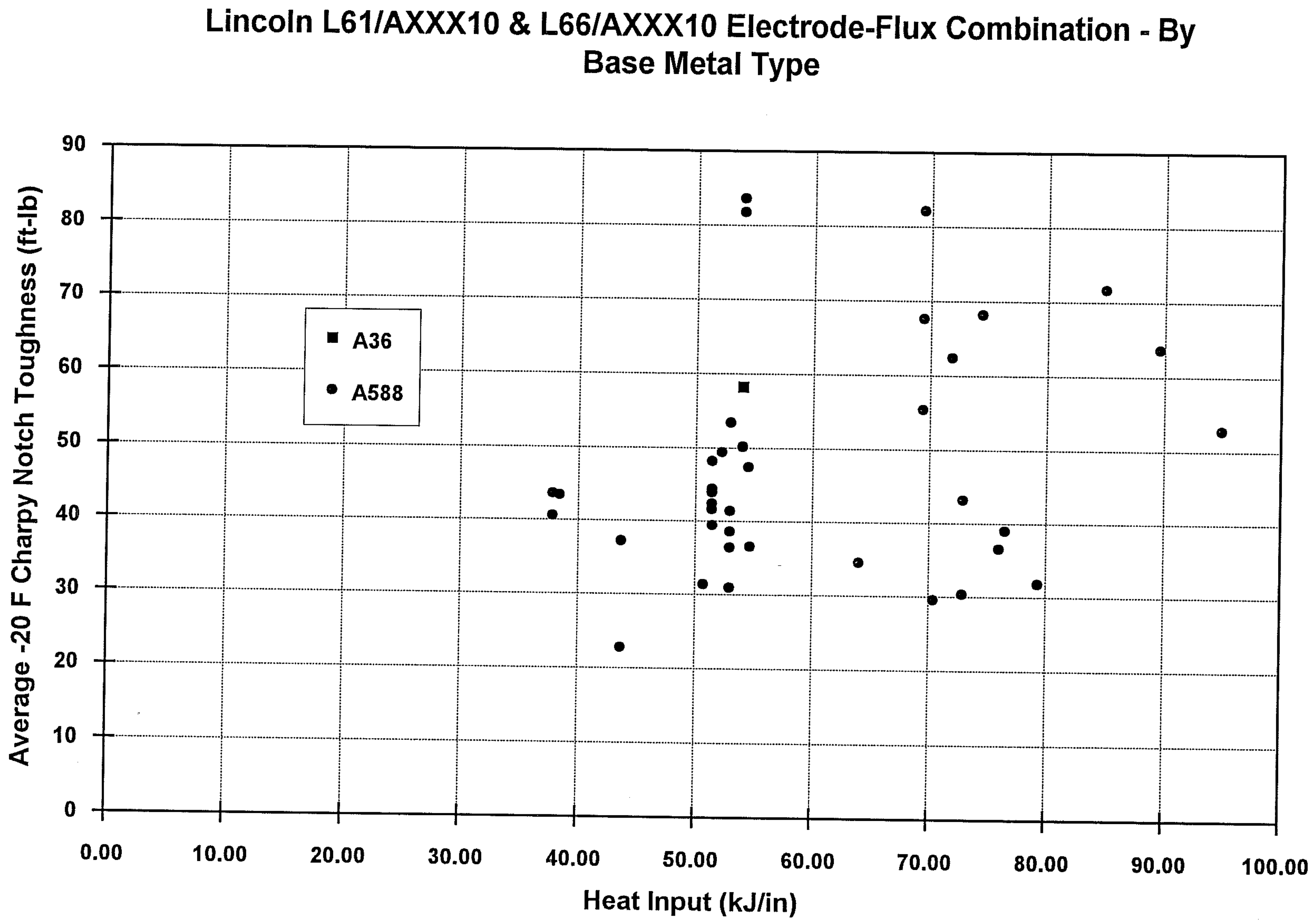


Figure 13 - -20 F Charpy notch toughness vs. heat input arranged by base metal type for Lincoln AXXX10 and L61 and L66 electrodes.

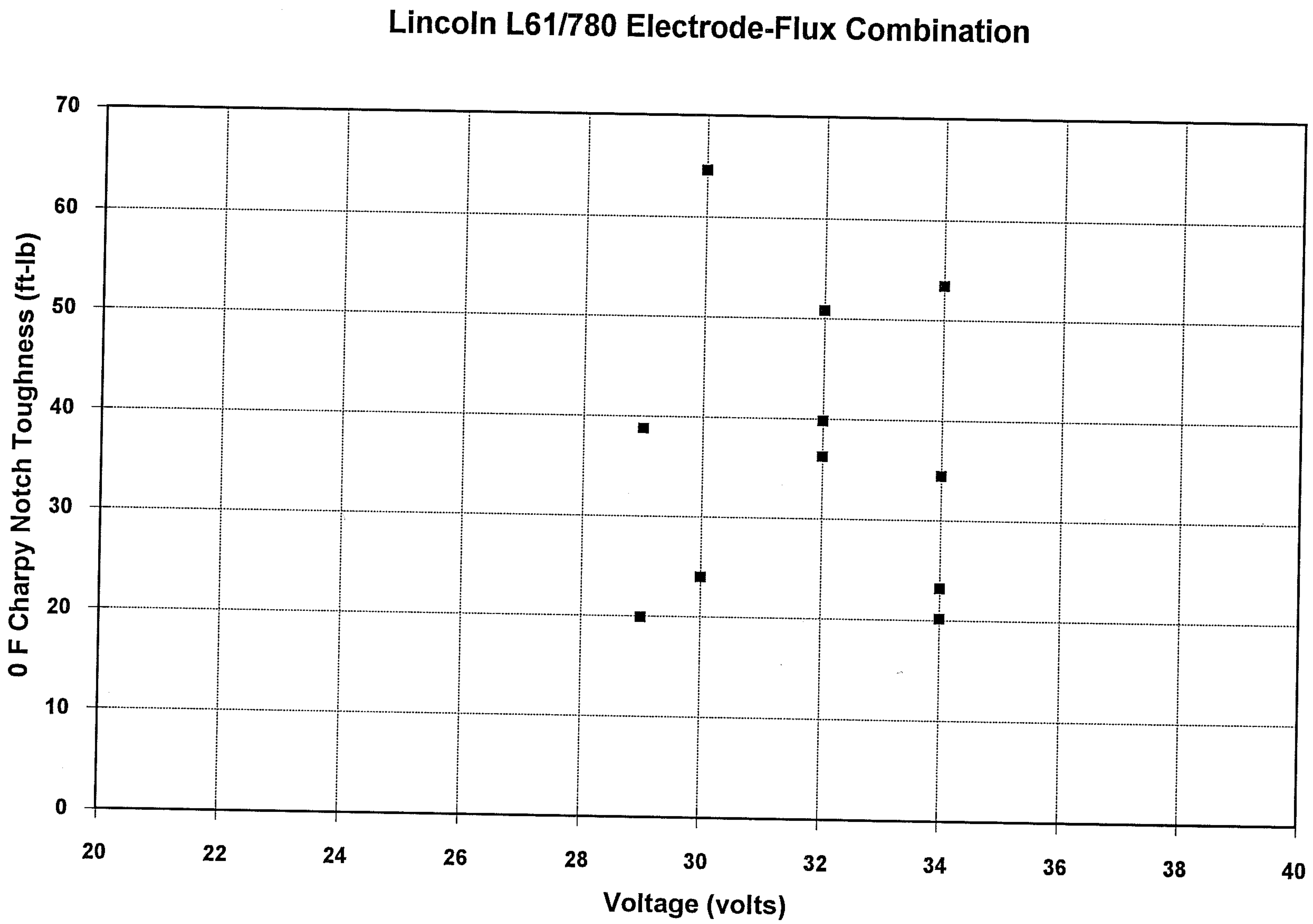


Figure 14 - 0F Charpy notch toughness vs. voltage for Lincoln 780 flux and L61 electrode.

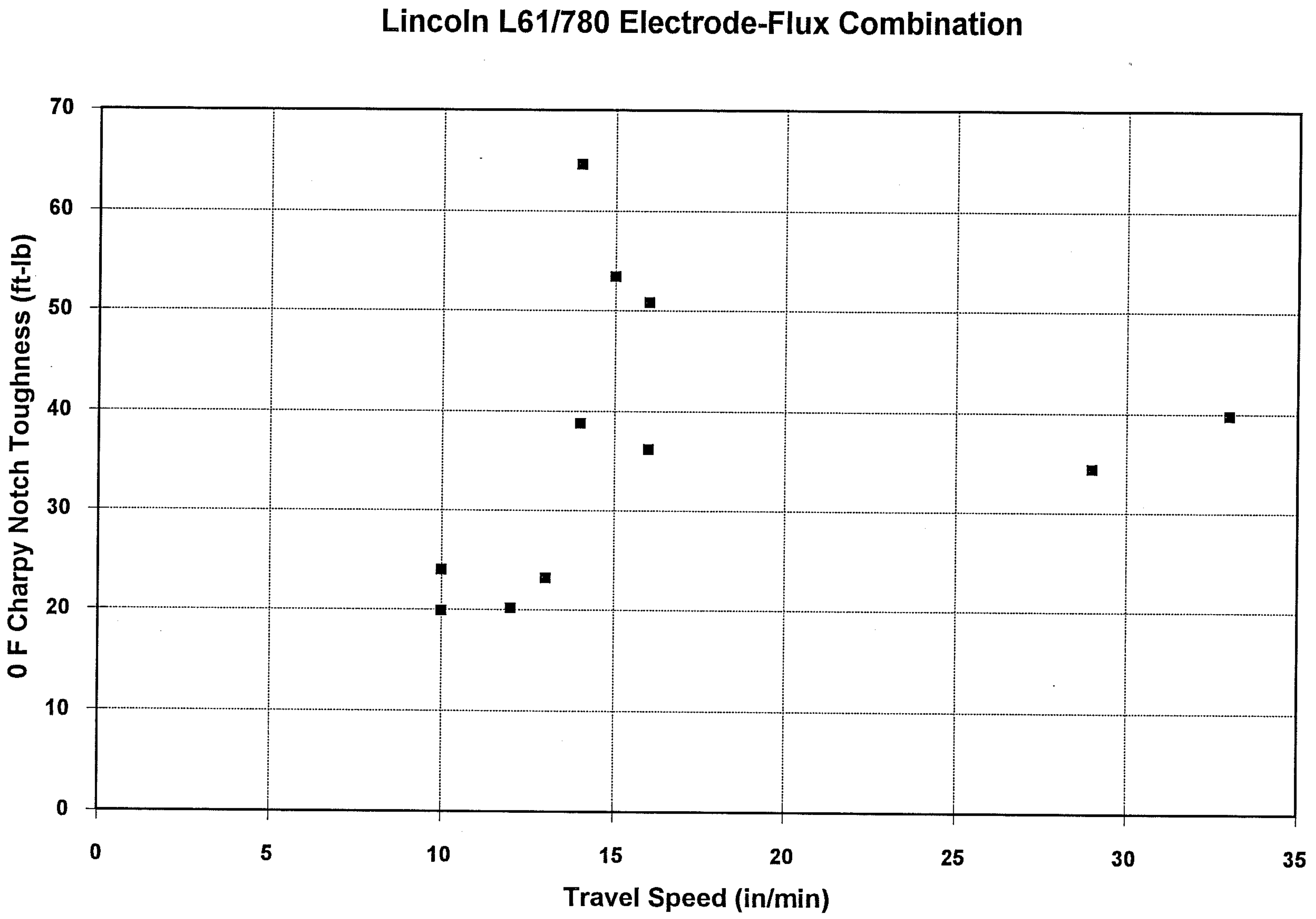


Figure 15 - 0 F Charpy notch toughness vs. travel speed for Lincoln 780 flux and L61 electrode.

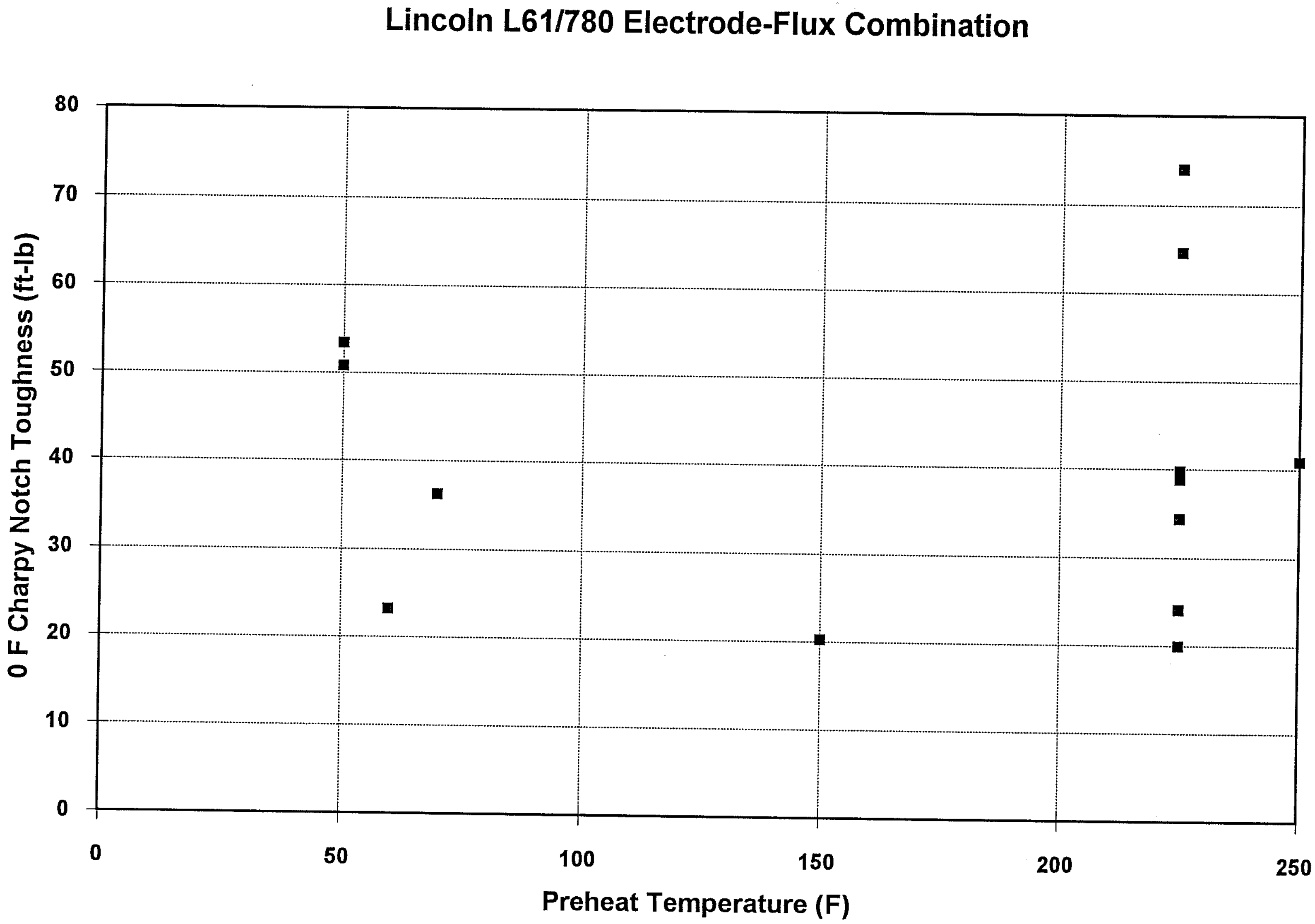


Figure 16 - 0 F Charpy notch toughness vs. preheat temperature for Lincoln 780 flux and L61 electrode.

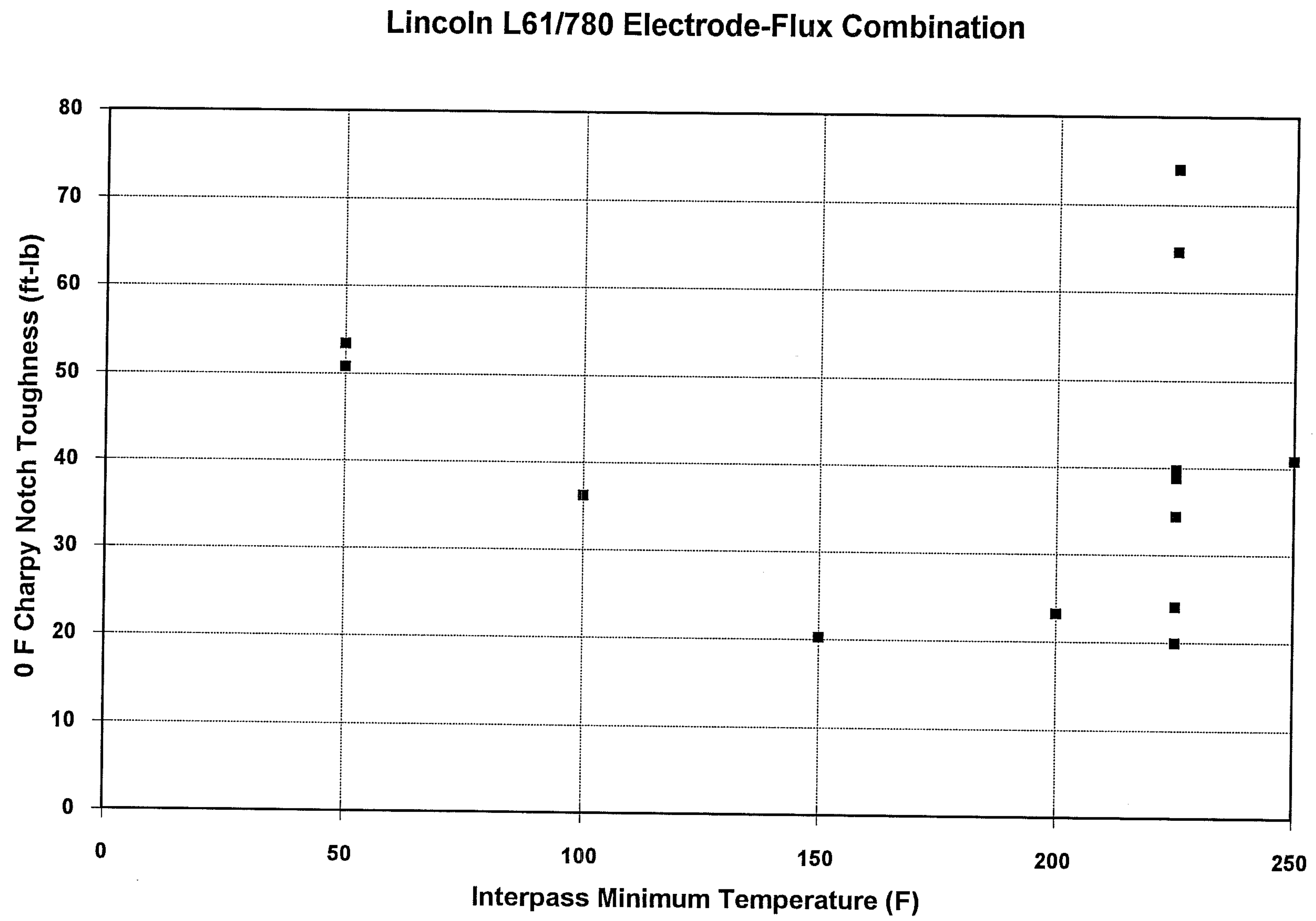


Figure 17 - 0 F Charpy notch toughness vs. minimum interpass temperature for Lincoln 780 flux and L61 electrode.

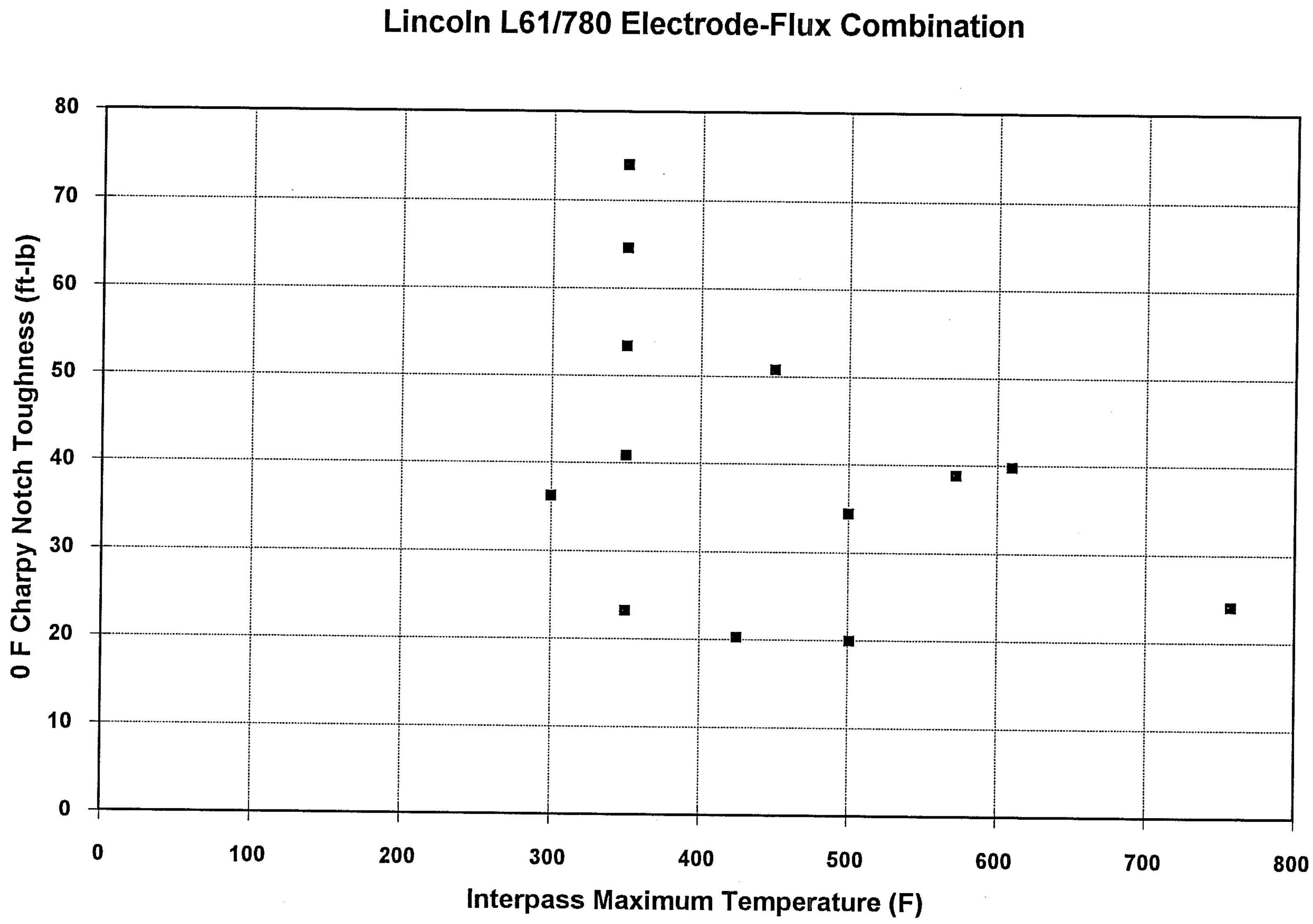


Figure 18 - 0 F Charpy notch toughness vs. maximum preheat temperature for Lincoln 780 flux and L61 electrode.

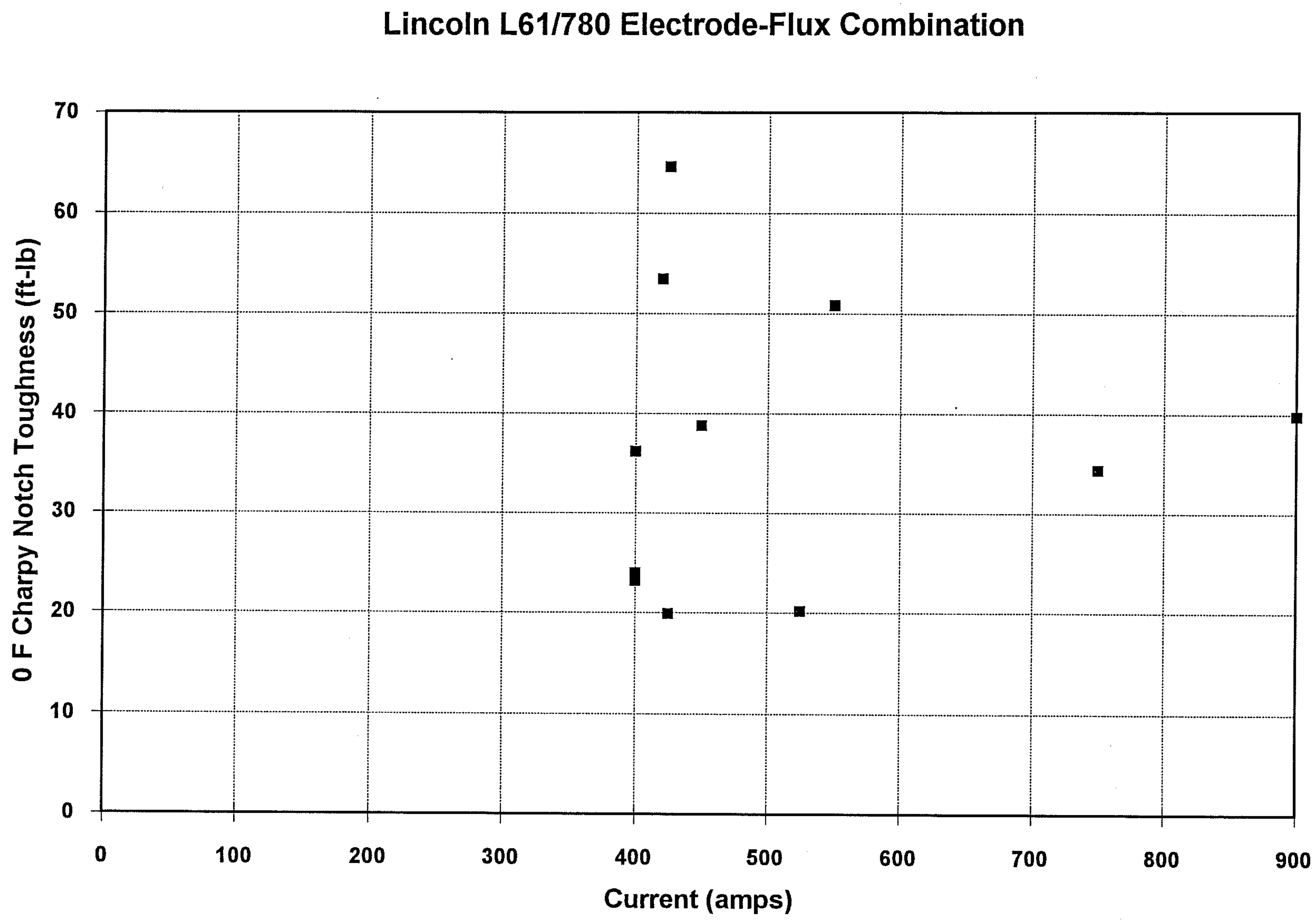


Figure **19 -** 0 F Charpy notch toughness vs. current for Lincoln 780 flux and L61 electrode.

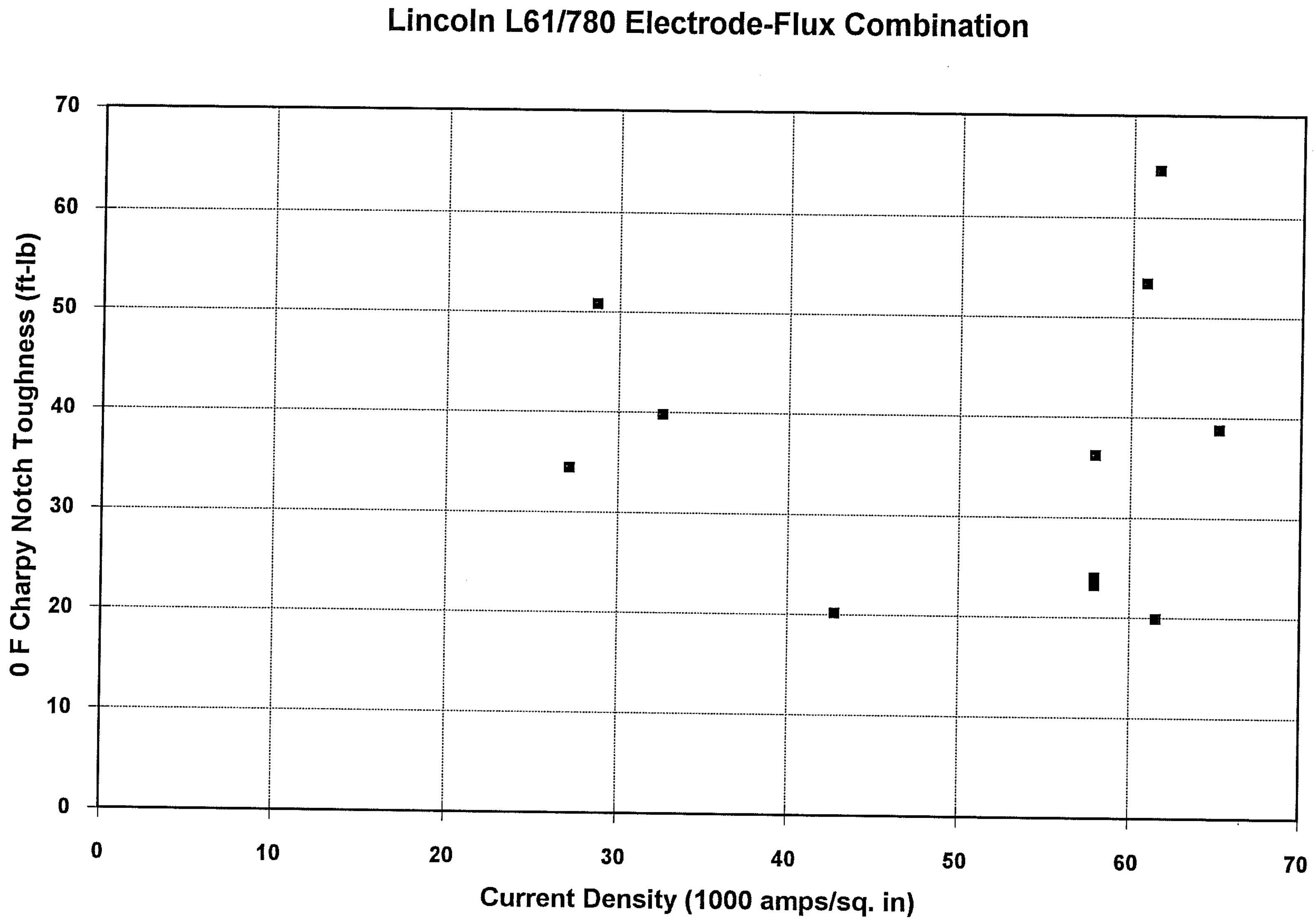


Figure 20 - 0 F Charpy notch toughness vs. current density for Lincoln 780 flux and L61 electrode.

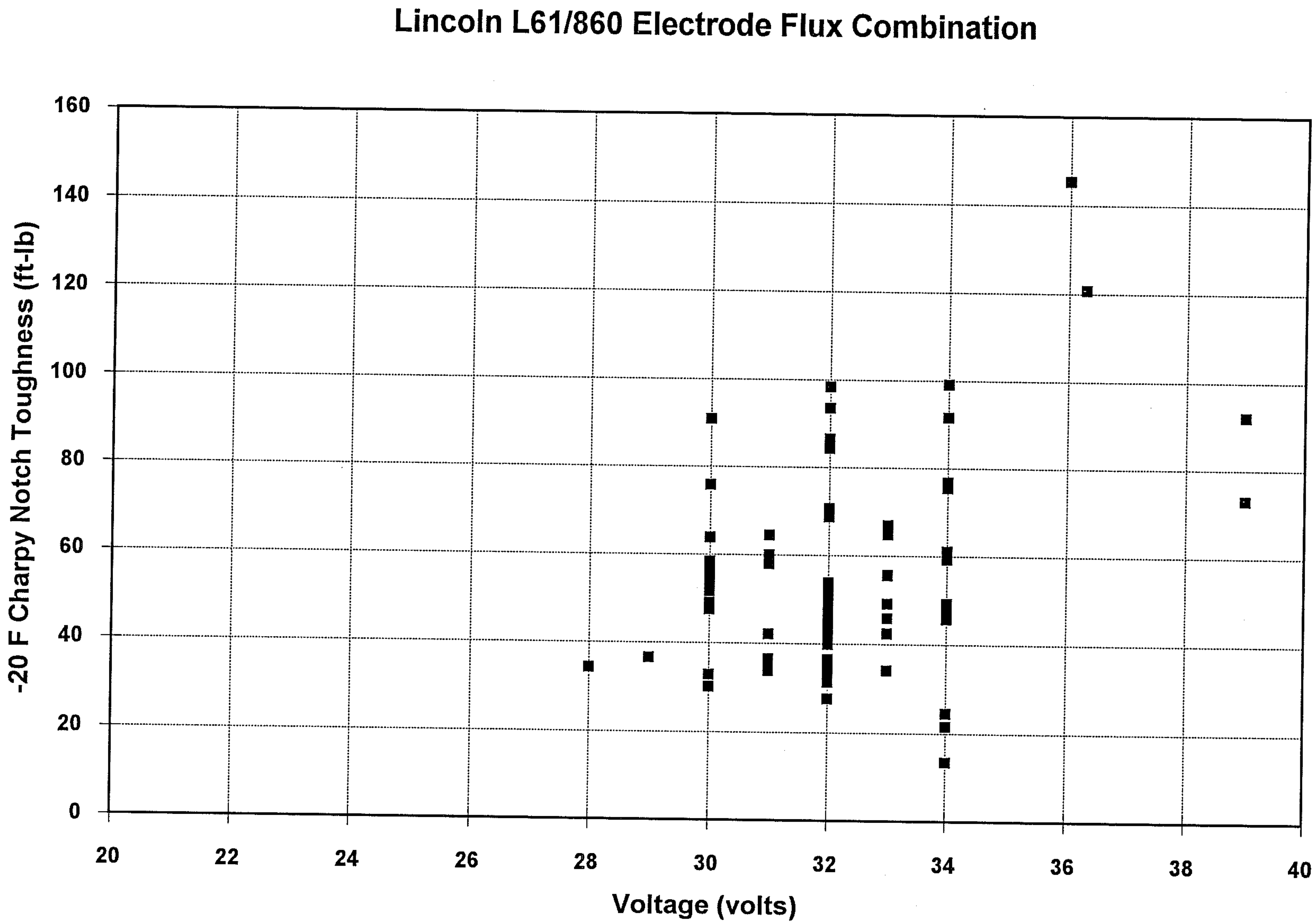


Figure 21 - -20 F Charpy notch toughness vs. voltage for Lincoln 860 flux and L61 electrode.

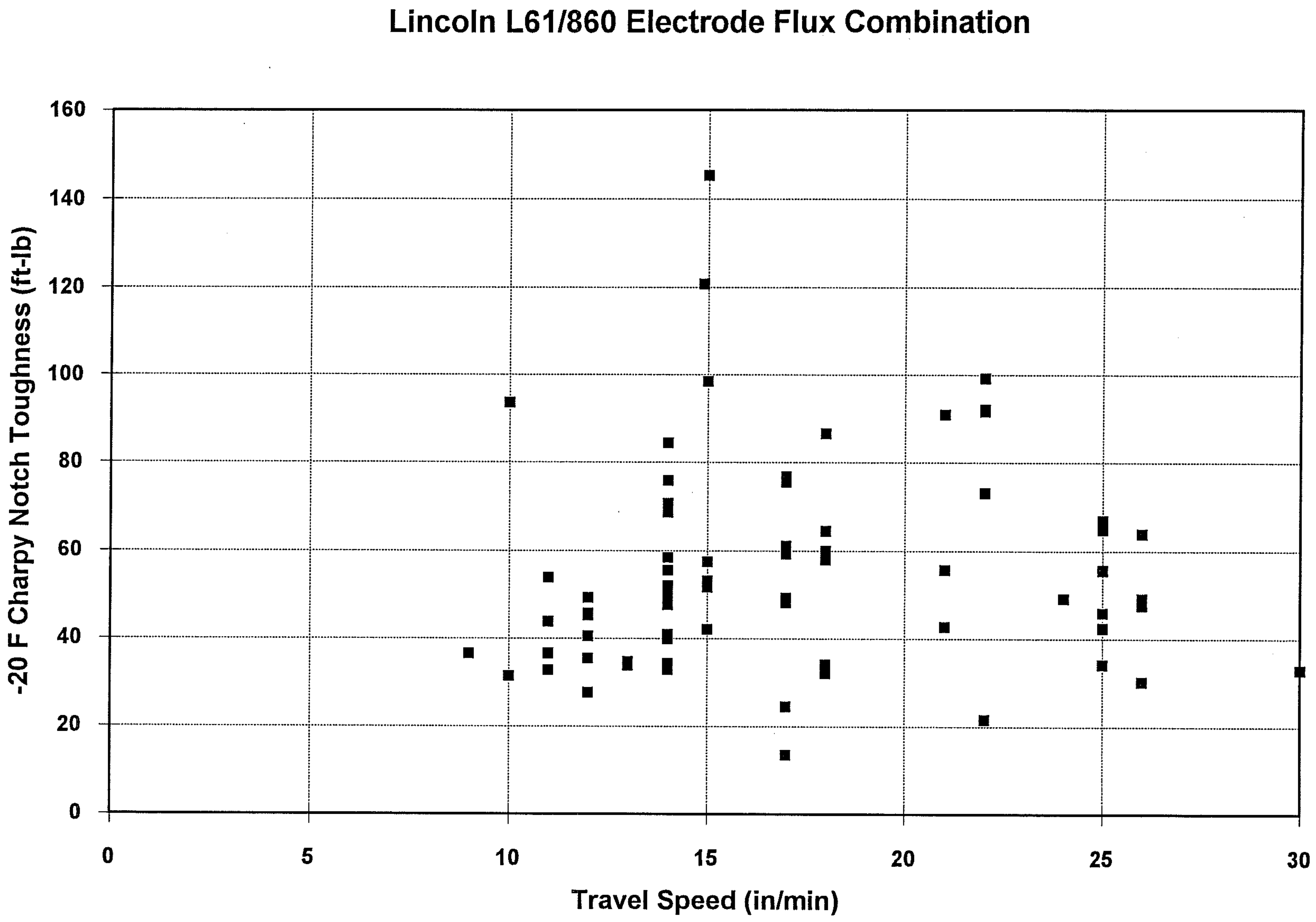


Figure 22 - -20 F Charpy notch toughness vs. travel speed for Lincoln 860 flux and L61 electrode.

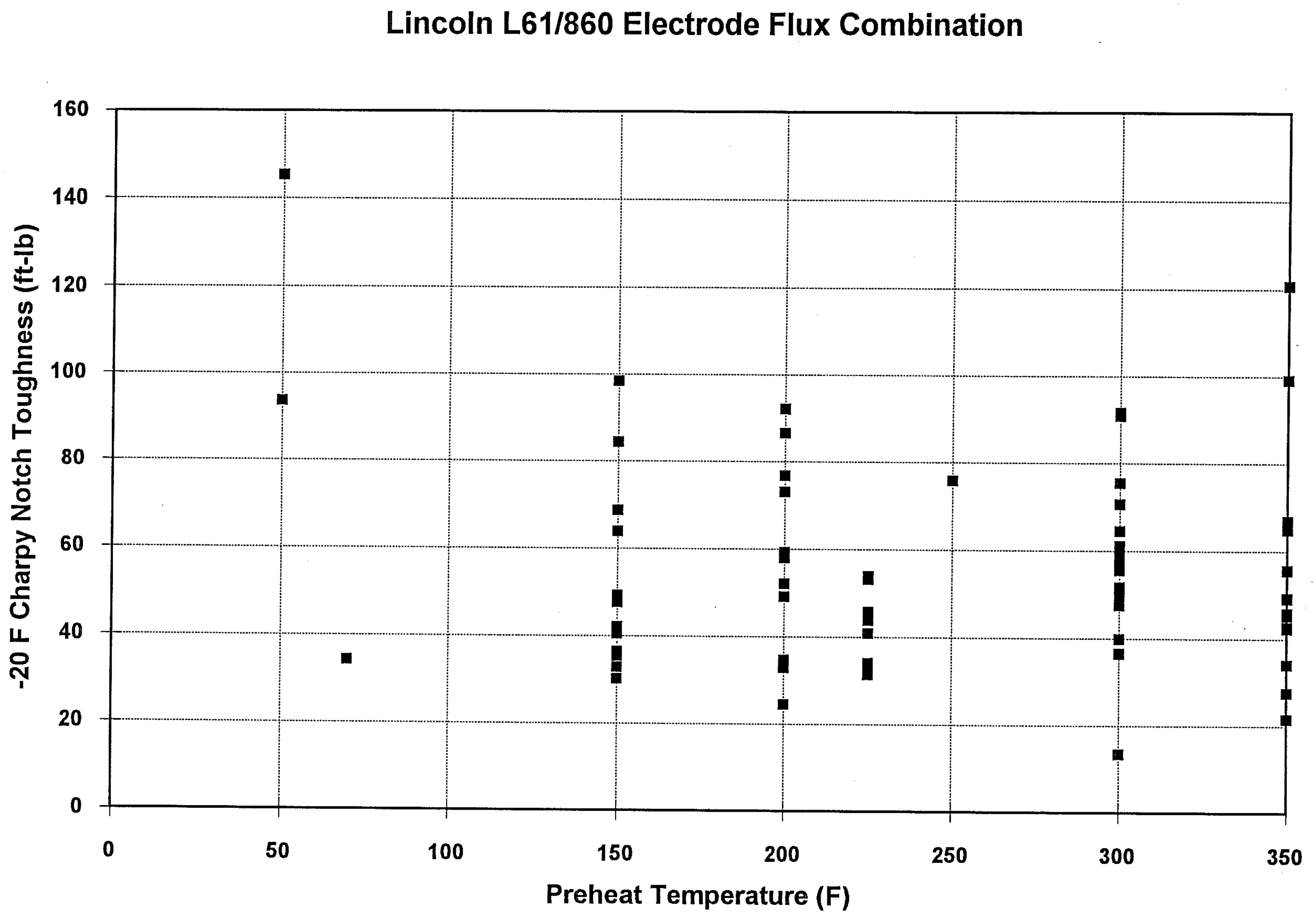


Figure 23 - -20 F Charpy notch toughness vs. preheat temperature for Lincoln 860 flux and L61 electrode.

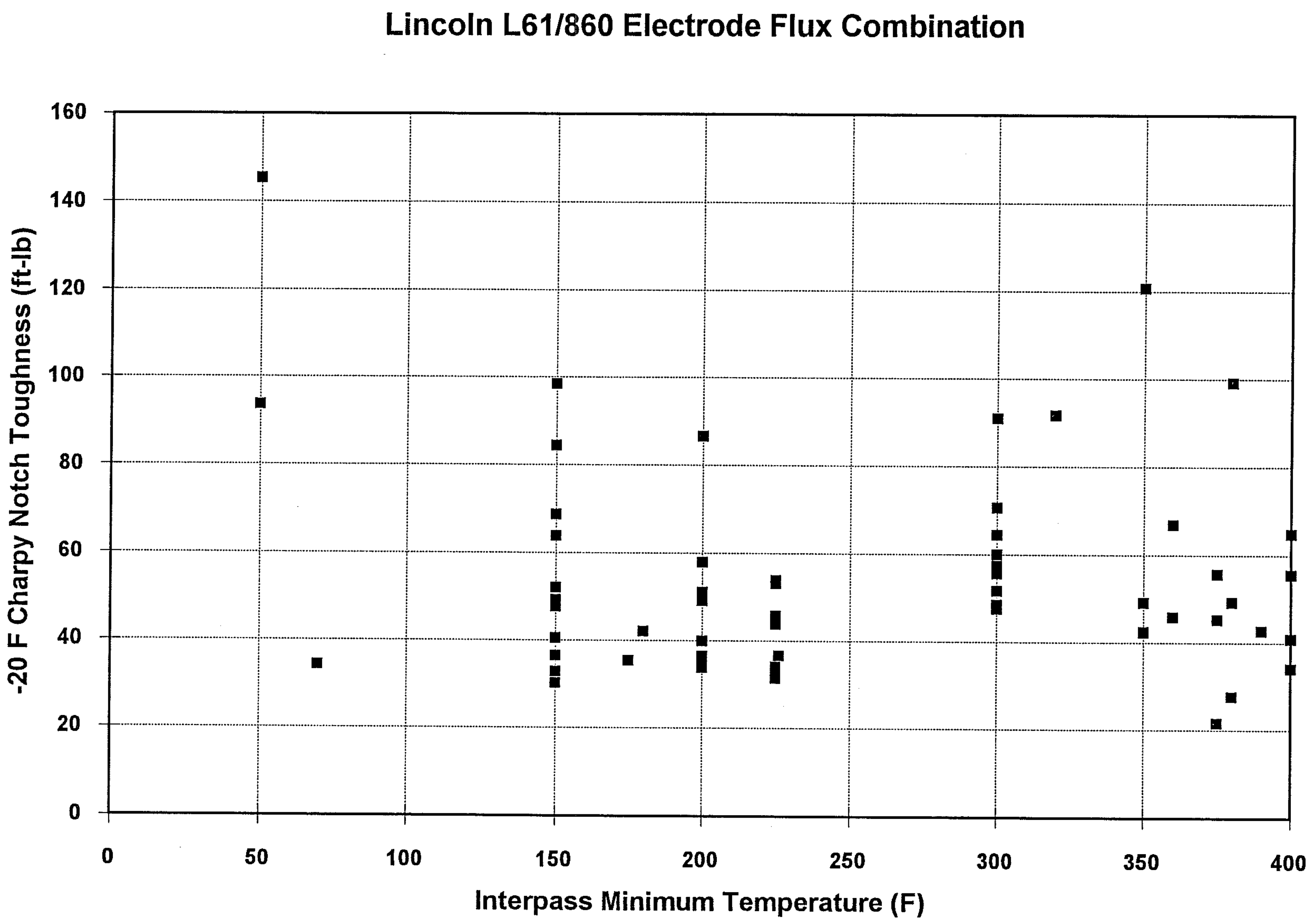


Figure 24 - -20 F Charpy notch toughness vs. minimum interpass temperature for Lincoln 860 flux and L61 electrode.

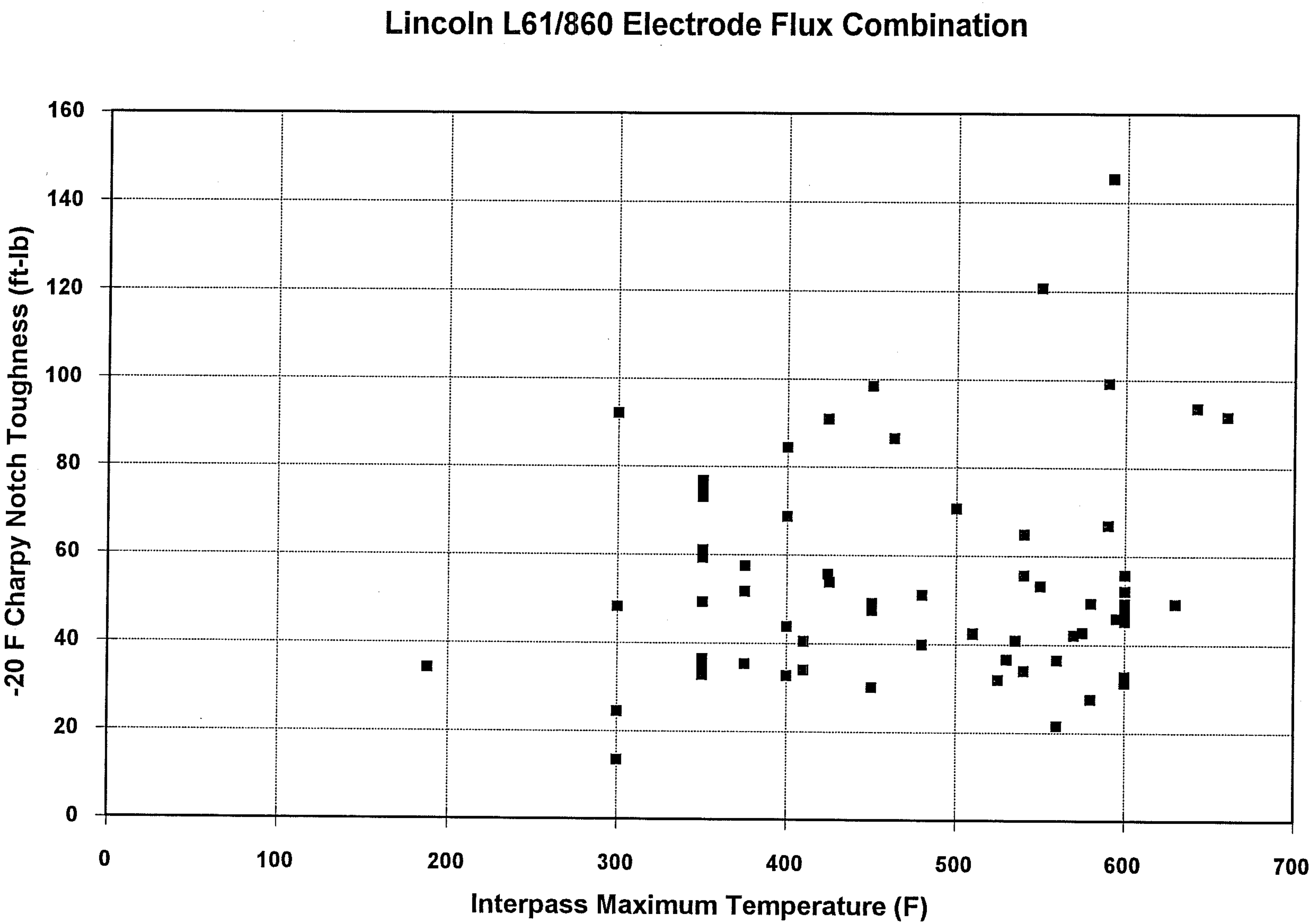


Figure 25 - -20 F Charpy notch toughness vs. minimum interpass temperature for Lincoln 860 flux and L61 electrode.

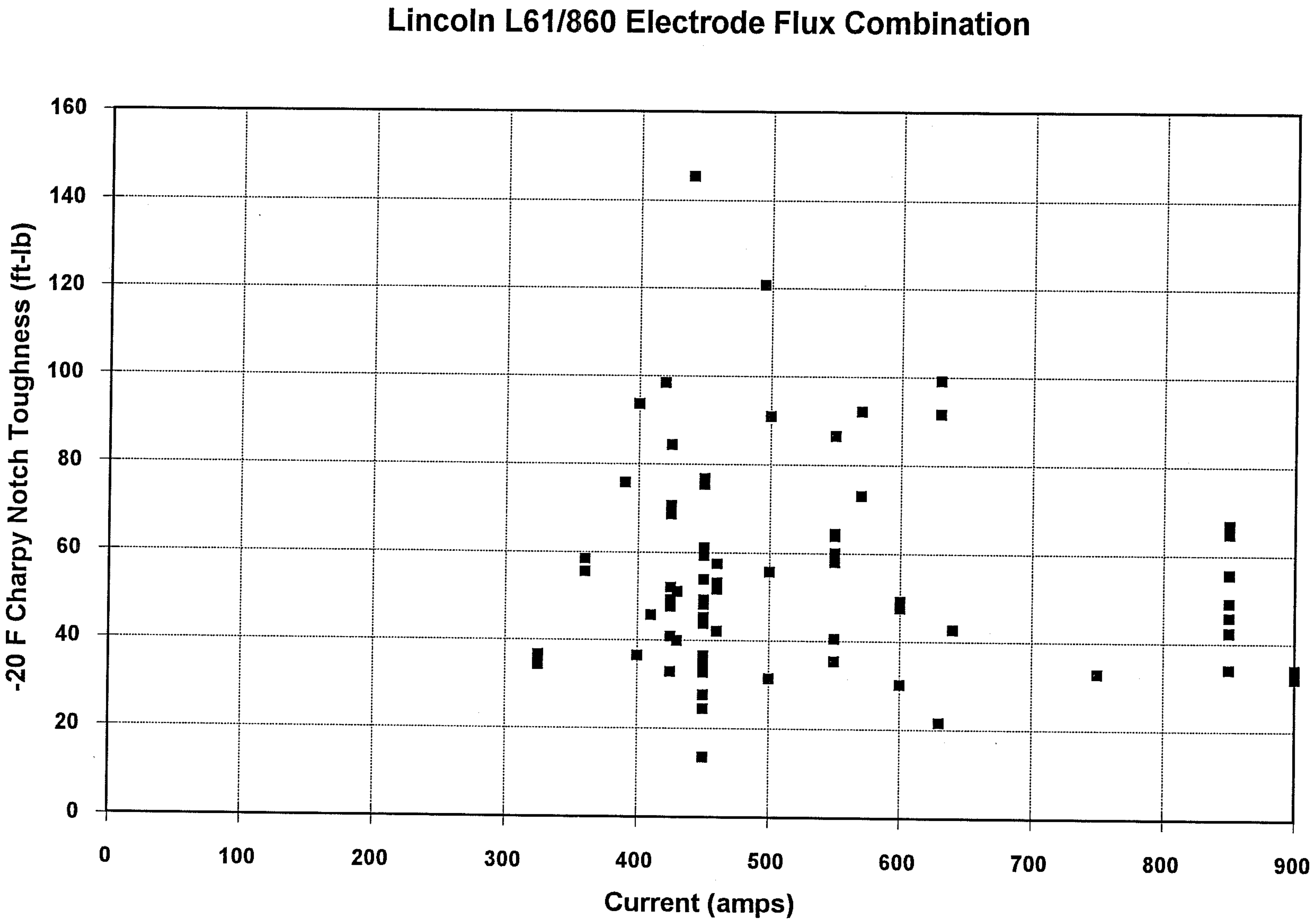


Figure 26 - -20 F Charpy notch toughness vs. current for Lincoln 860 flux and L61 electrode.

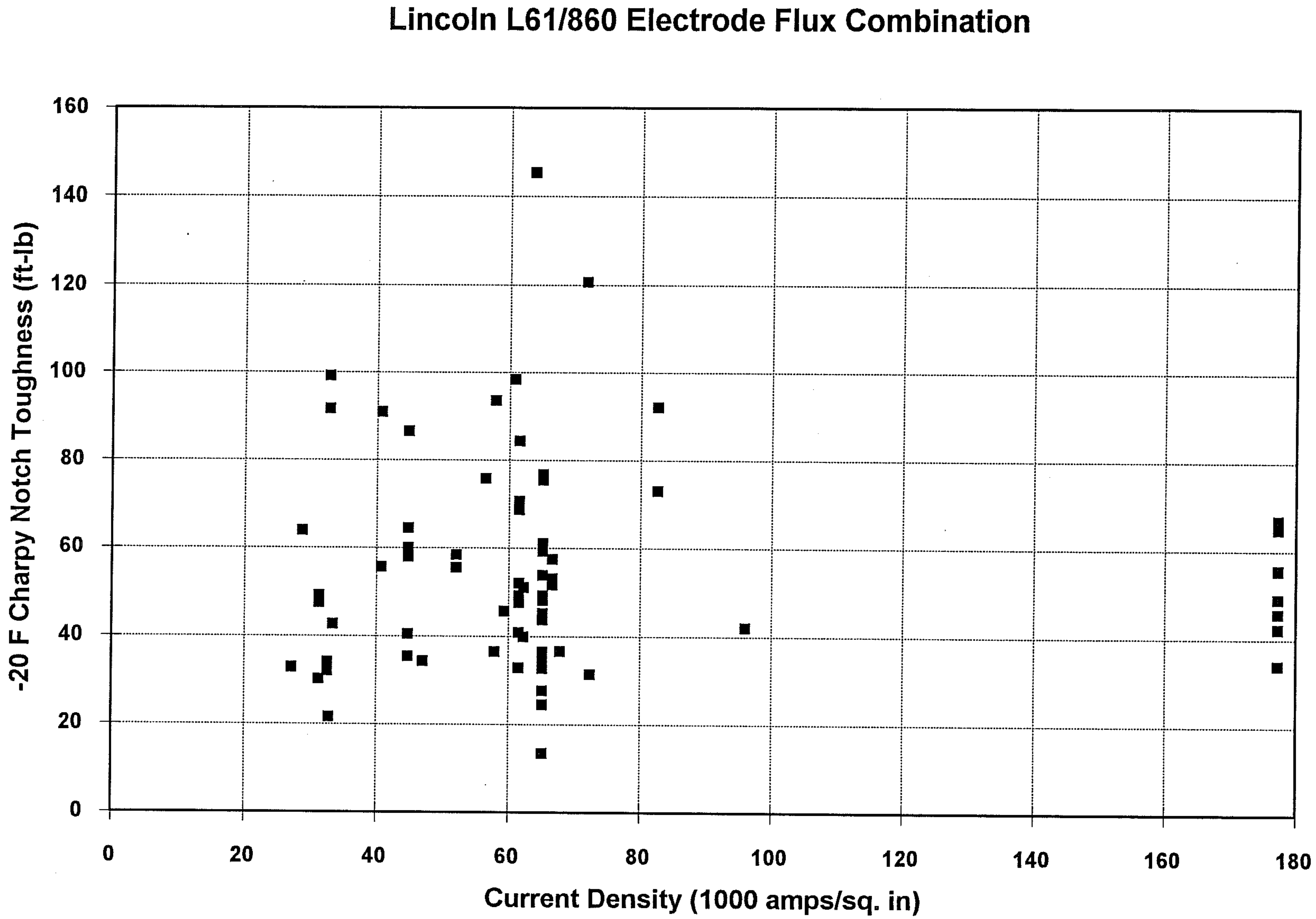


Figure 27 - -20 F Charpy notch toughness vs. current density for Lincoln 860 flux and L61 electrode.

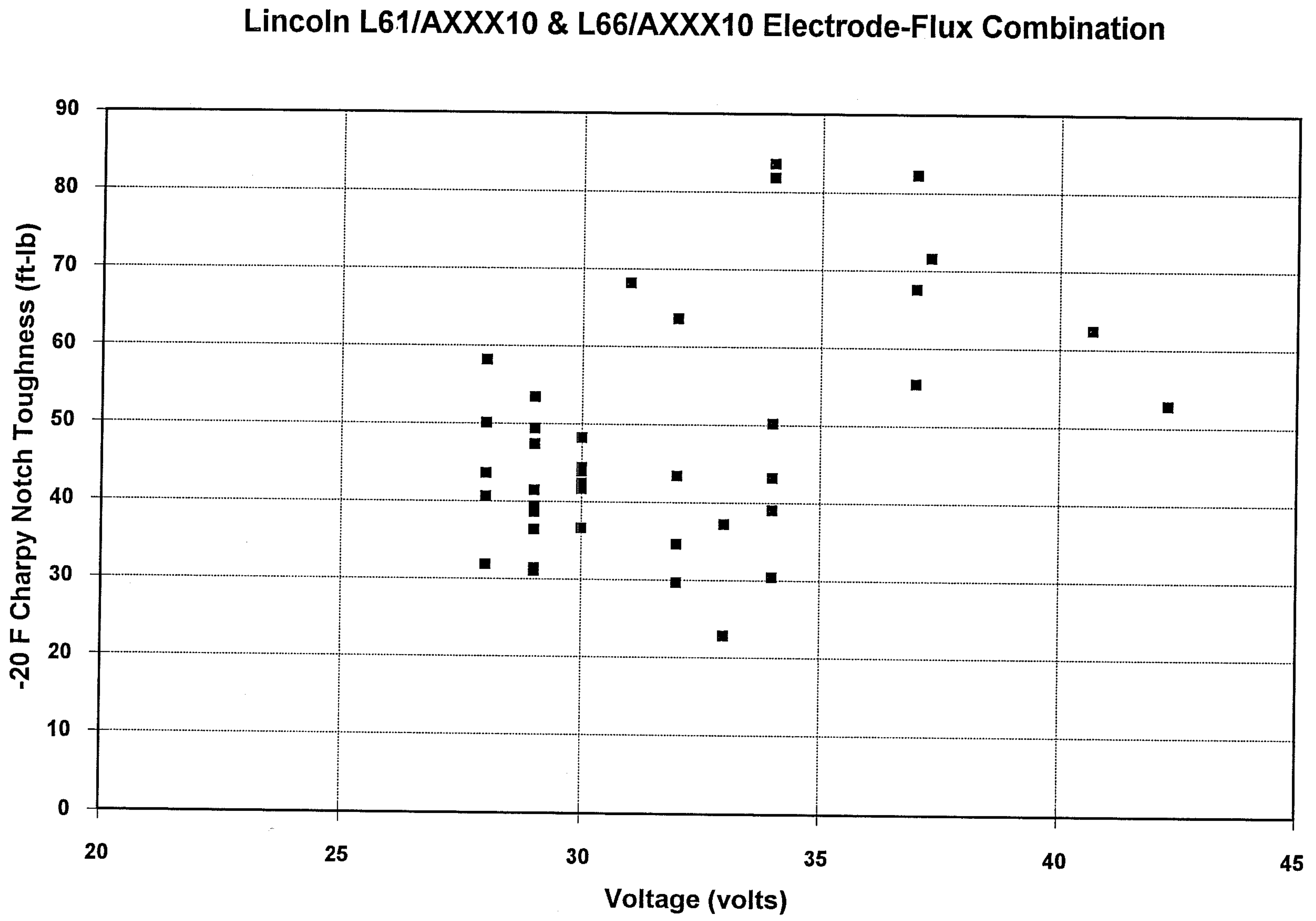

Lincoln L61/AXXX10 & L66/AXXX10 Electrode-Flux Combination

Figure 28 - -20 F Charpy notch toughness vs. voltage for Lincoln AXXX10 flux and L61 and L66 electrodes.

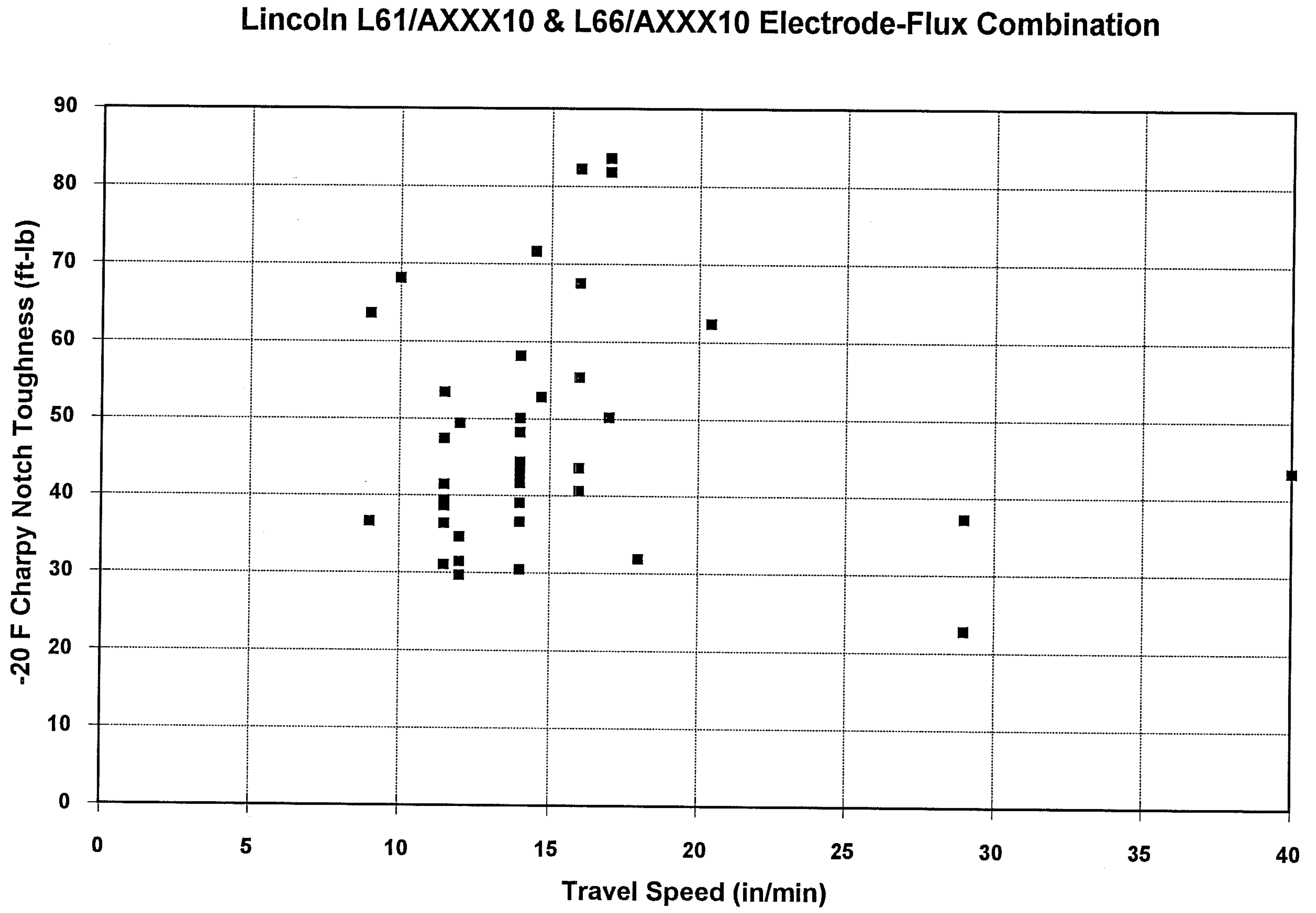


Figure 29 - -20 F Charpy notch toughness vs. travel speed for Lincoln AXXX10 flux and L61 and L66 electrodes.

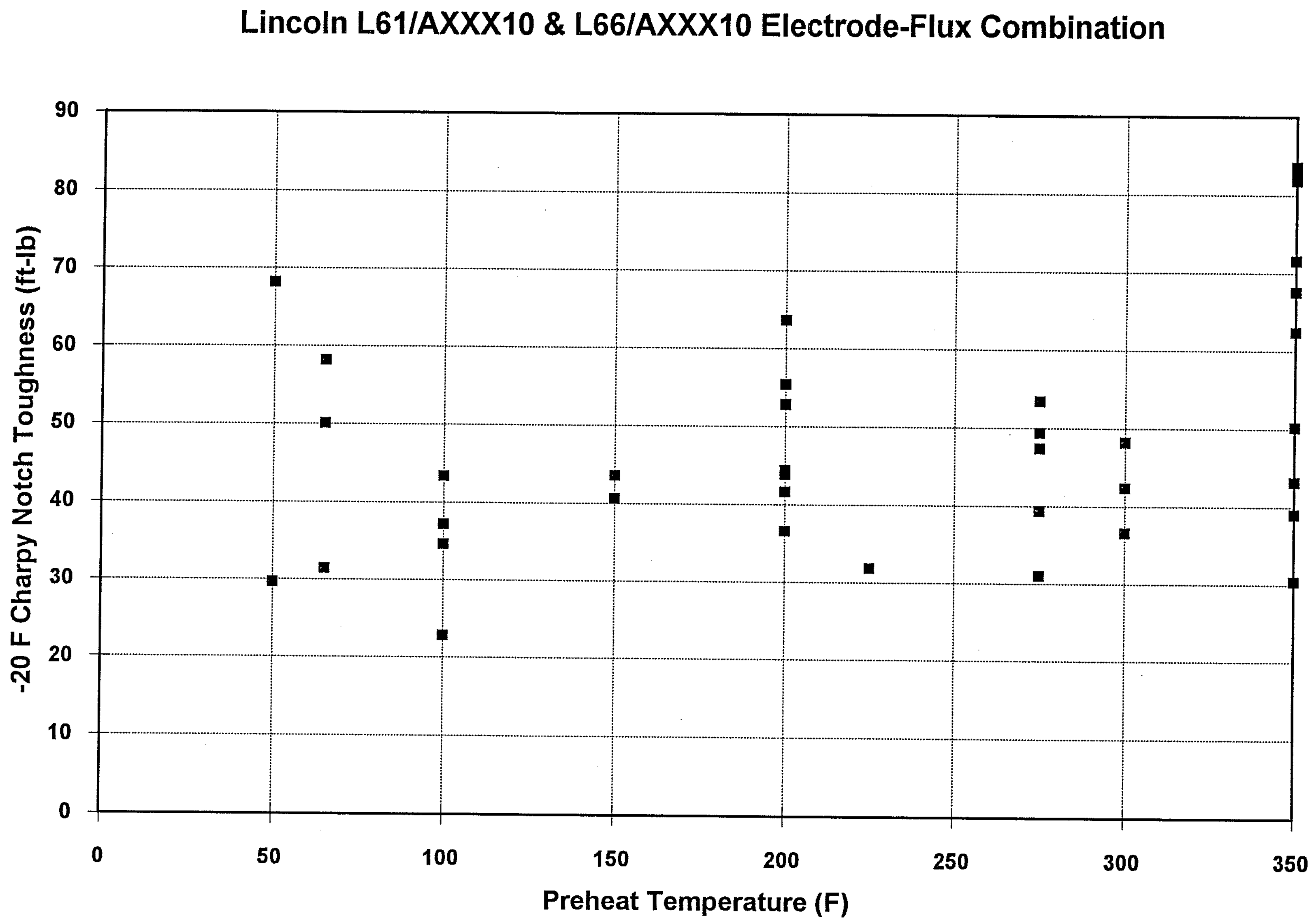


Figure 30 - -20 F Charpy notch toughness vs. preheat temperature for Lincoln AXXX10 flux and L61 and L66 electrodes.

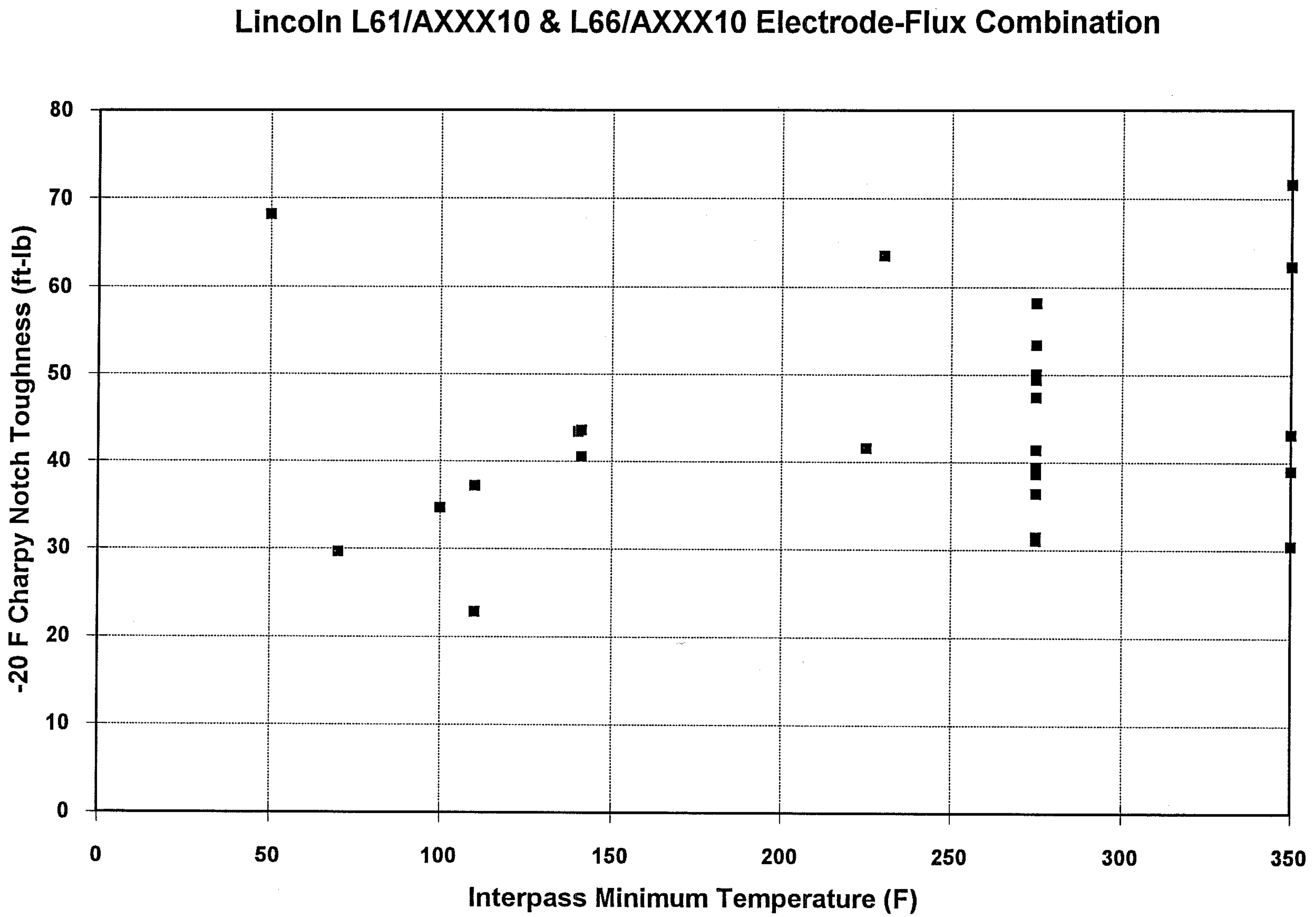


Figure 31 - -20 F Charpy notch toughness vs. minimum interpass temperature for Lincoln AXXX10 flux and L61 and L66 electrodes.

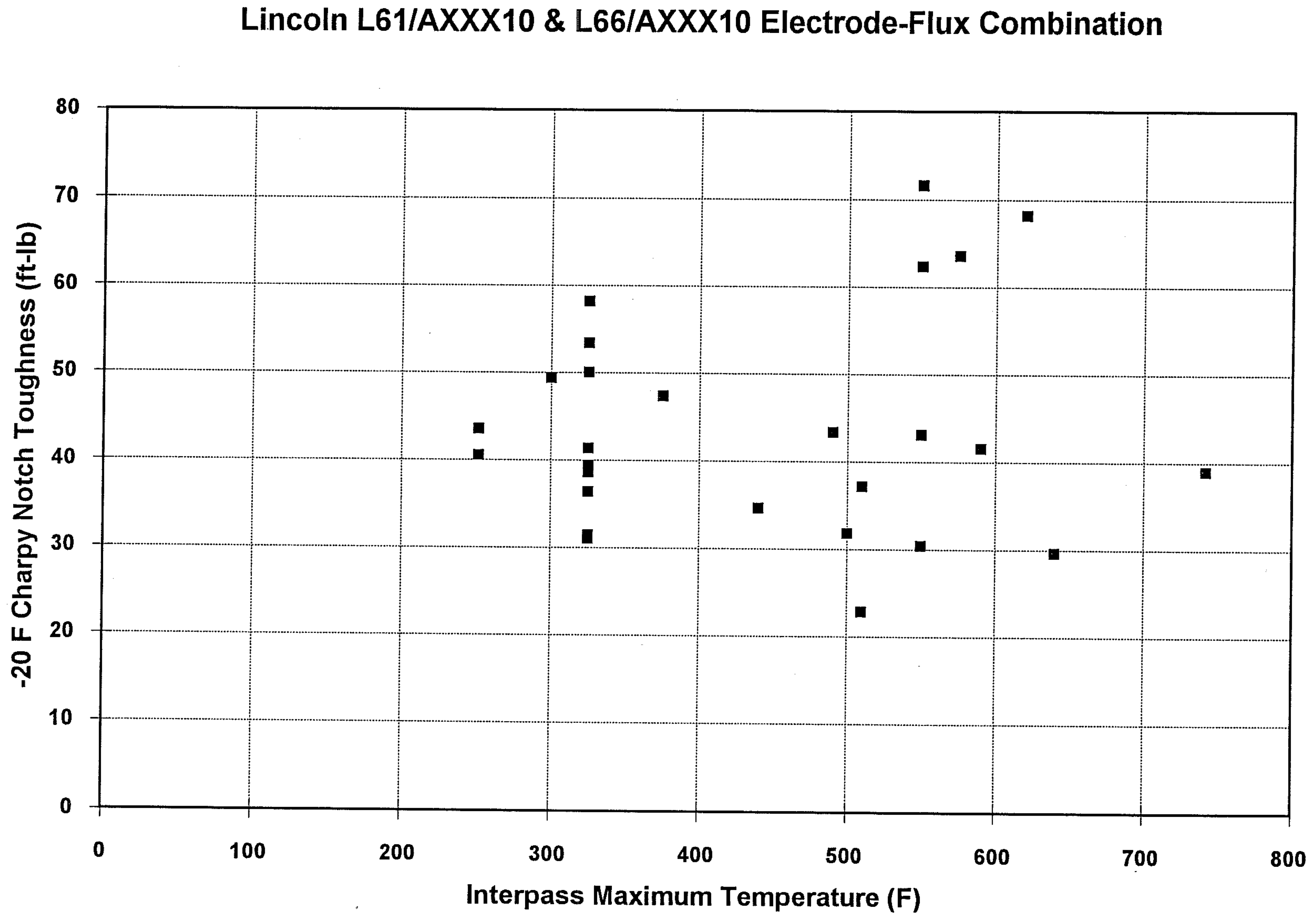


Figure 32 - -20 F Charpy notch toughness vs. minimum interpass temperature for Lincoln AXXX10 flux and L61 and L66 electrodes.

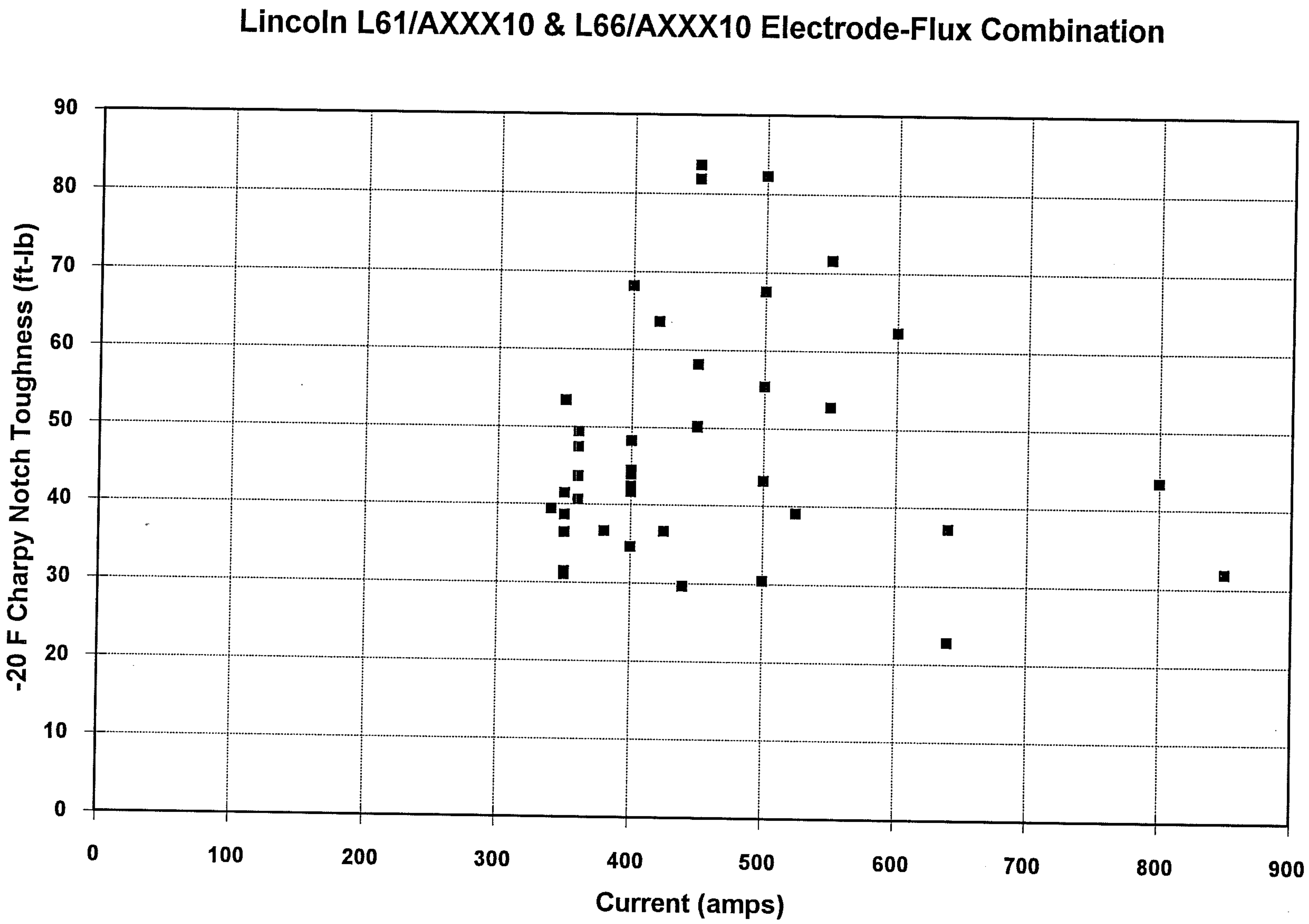


Figure 33 - -20 F Charpy notch toughness vs. current for Lincoln AXXX10 flux and L61 and L66 electrodes.

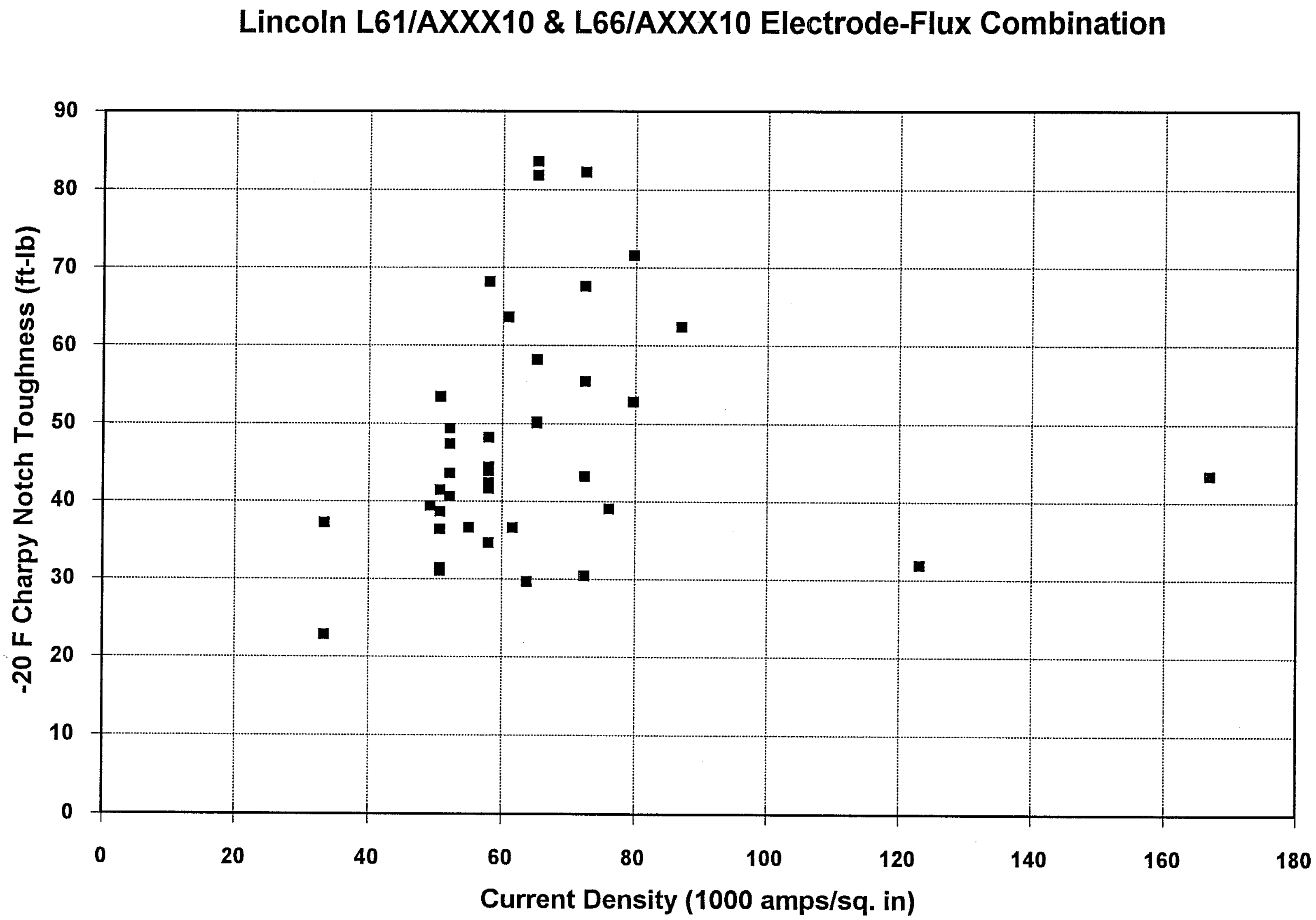


Figure 34 - -20 F Charpy notch toughness vs. current density for Lincoln AXXX10 flux and L61 and L66 electrodes.

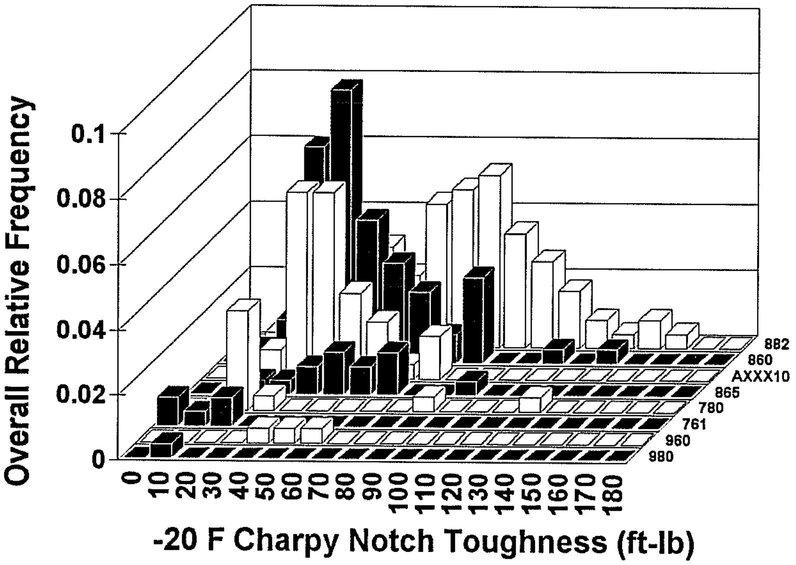


Figure 35 - -20 ° F Charpy Notch Toughness for various Lincoln fluxes used with L61 and L66 electrodes, arranged in order of increasing number of reports.

Lincoln Electric	Electrode				
Flux	**L61**	**L66**	**LA-75**	**LA-100**	**Ni 2**
AXXX10	54	4	0	0	0
761	11	0	0	0	0
780	28	0	0	0	0
860	106	22	4	0	0
865	21	0	4	0	0
880M	0	0	6	2	0
882	132	0	0	0	4
960	3	0	0	0	0
980	5	0	6	0	0

Table 2 - Numbers of Lincoln consumable combinations reported.

The Lincoln fluxes used are divided into four series: 700, 800, 900, and AXXX10. The 700 series notation is used for active fluxes, which contain some alloying ingredients and which may form altered weld metal chemistries with variations in voltage. Fluxes from the

800 and 900 series are neutral fluxes, in which the flux is not intended to change the weld metal chemistry, regardless of voltage. The difference between the two series is that the 900 fluxes are designed for more specialized applications than the fluxes of the 800 series. The AXXX10 flux is a special-use alloying flux used to conform to F7A4-EM12K-Ni 1 for welding A588 weathering steel.

Like the Charpy values, weld tensile strength appears to be disconnected from heat input while showing a strong correspondence between strength and flux. In general, weld tensile strength exhibits a negative correlation to notch toughness, as shown in Figure 36. In those cases where welds would have failed qualification because of a low Charpy notch toughness, the same weld would have failed in many cases due to an excessive ultimate tensile strength. Figures 37 through 48 are plots of tensile strength as a function of heat input, showing the lack of a correlation between the two variables.

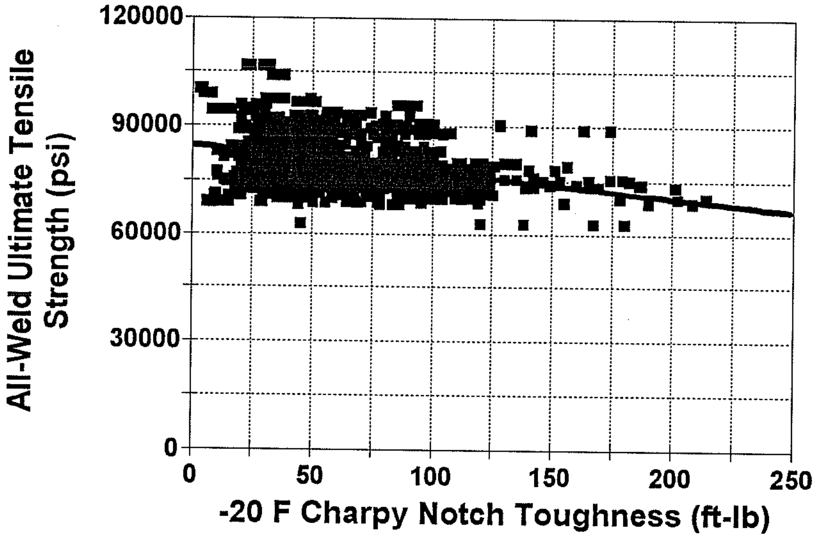


Figure 36 - All-weld metal ultimate tensile strength vs. Charpy notch toughness at -20 ° F for all SAW procedure reports.

The plots of Figures 49 through 69 show values of all-weld metal tensile strength as it varies with the value of current density, current, voltage, preheat temperature, interpass minimum and maximum temperature, and electrode travel speed. Like the corresponding Charpy plots, they do not group the data points as do Figures 37 through 48. Nonetheless, they serve to demonstrate the lack of a correlation between input variables and weld tensile strength.

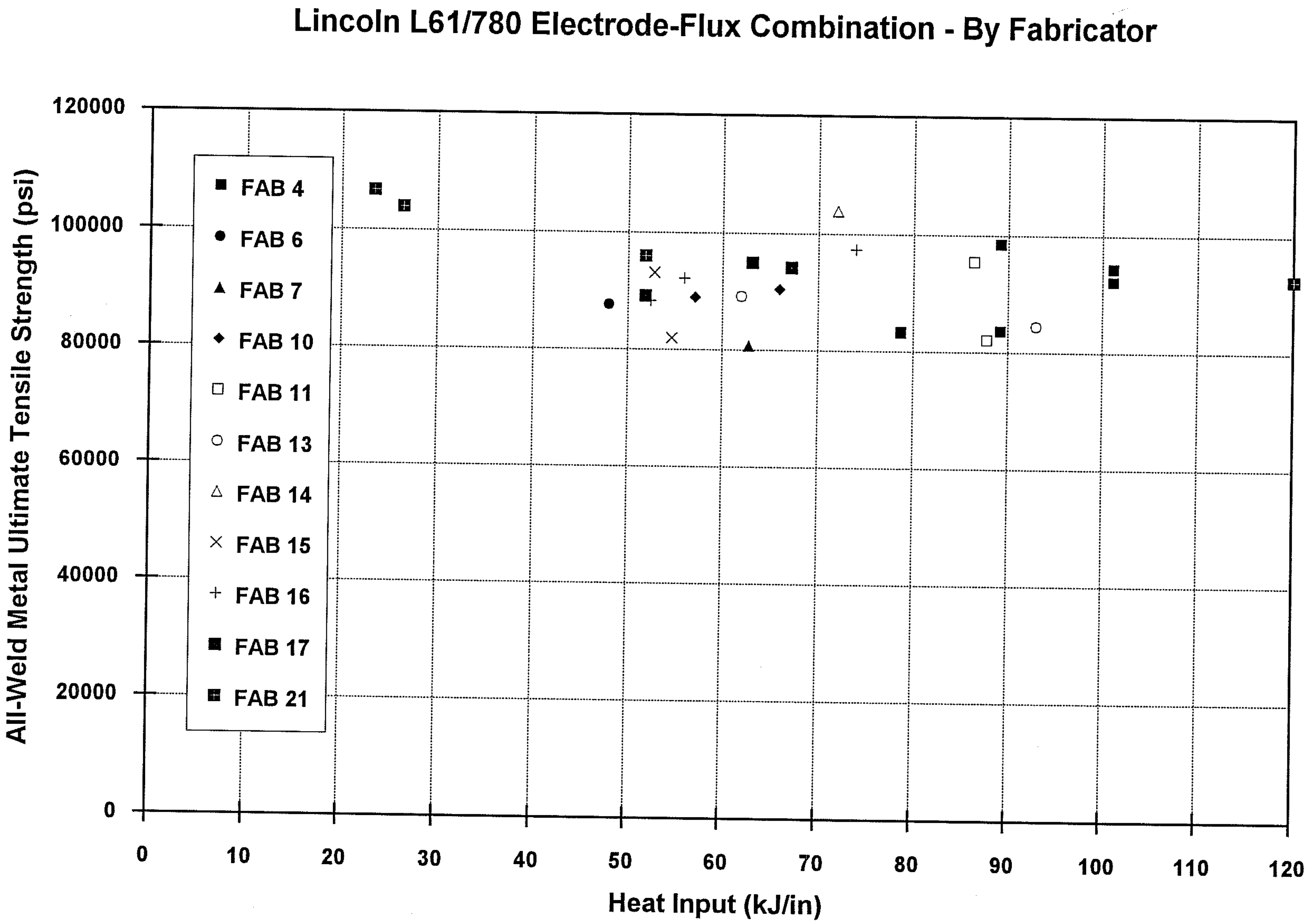


Figure 37 - Weld tensile strength vs. heat input arranged by fabricator for Lincoln 780 flux and L61 electrode.

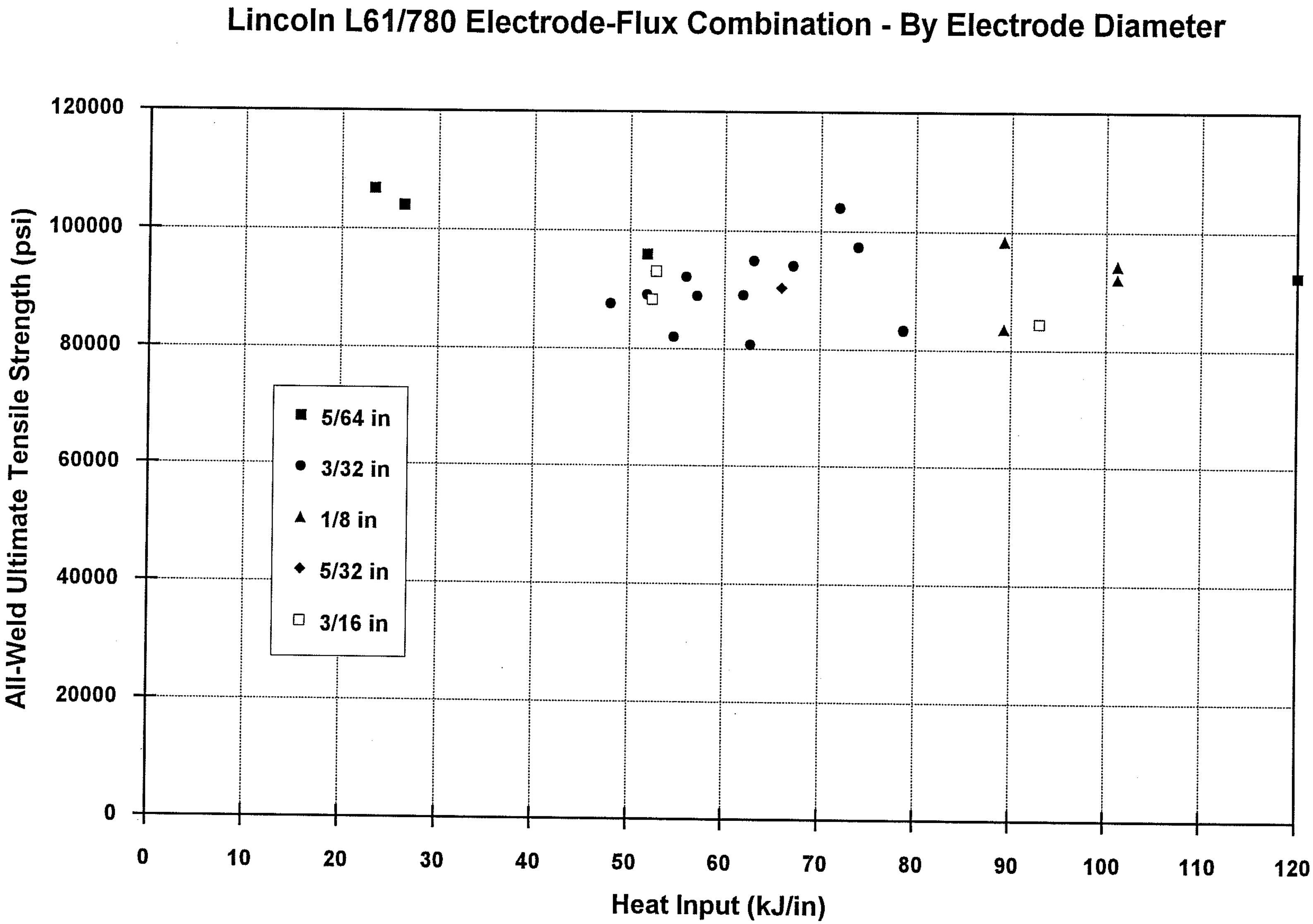


Figure 38 - Weld tensile strength vs. heat input arranged by electrode diameter for Lincoln 780 flux and L61 electrode.

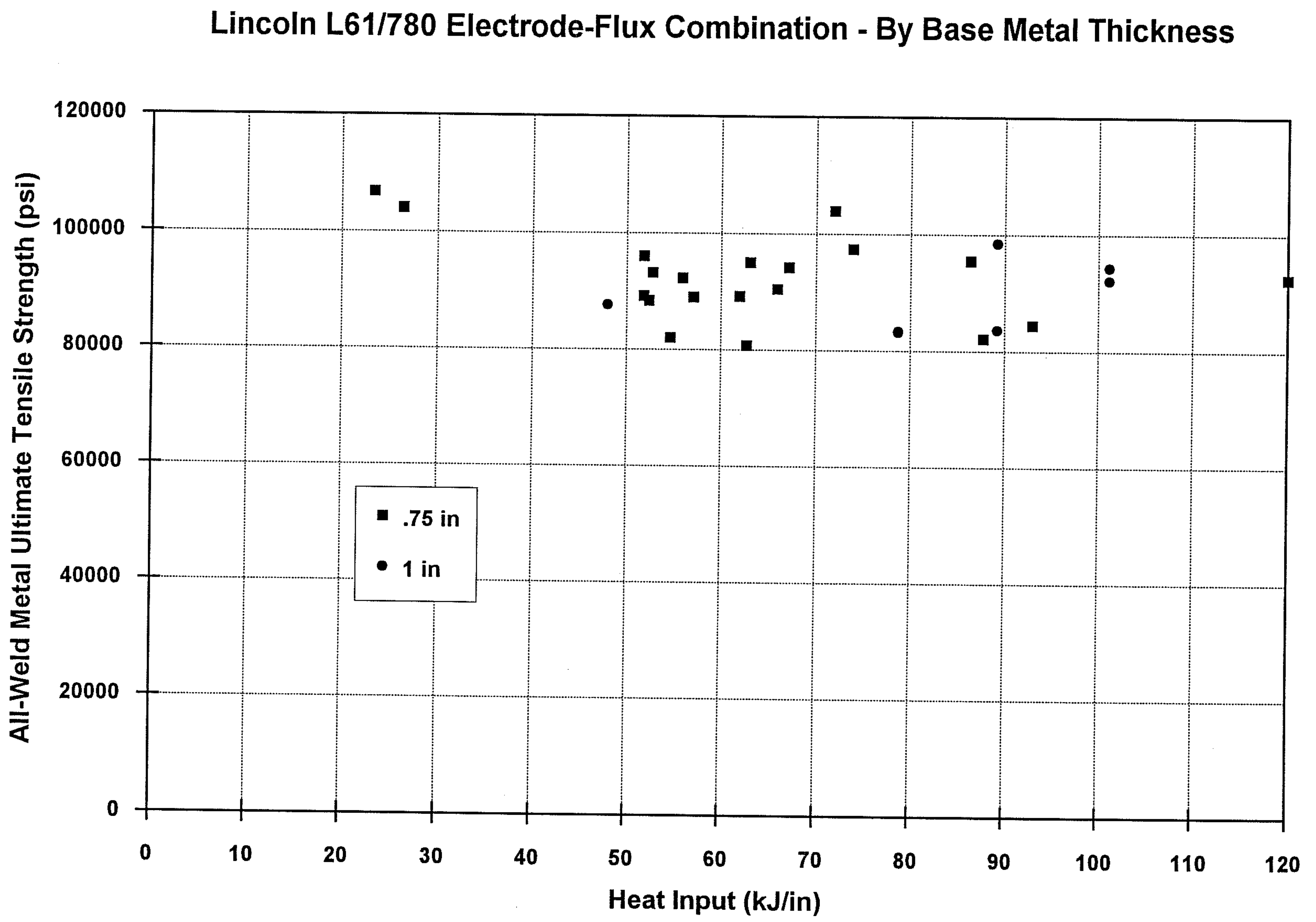


Figure 39 - Weld tensile strength vs. heat input arranged by base metal thickness for Lincoln 780 flux and L61 electrode.

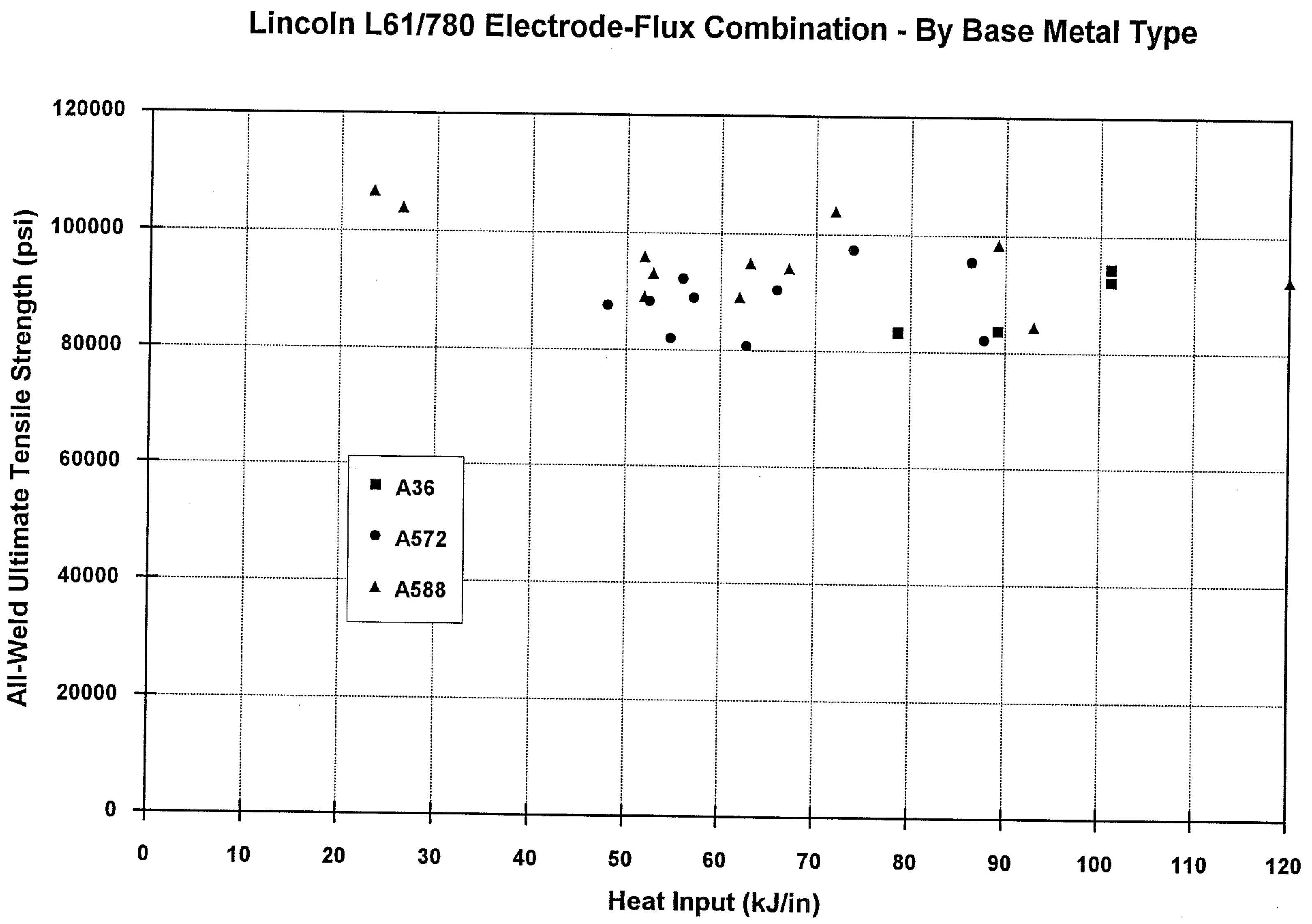


Figure 40 - Weld tensile strength vs. heat input arranged by base metal type for Lincoln 780 flux and L61 electrode.

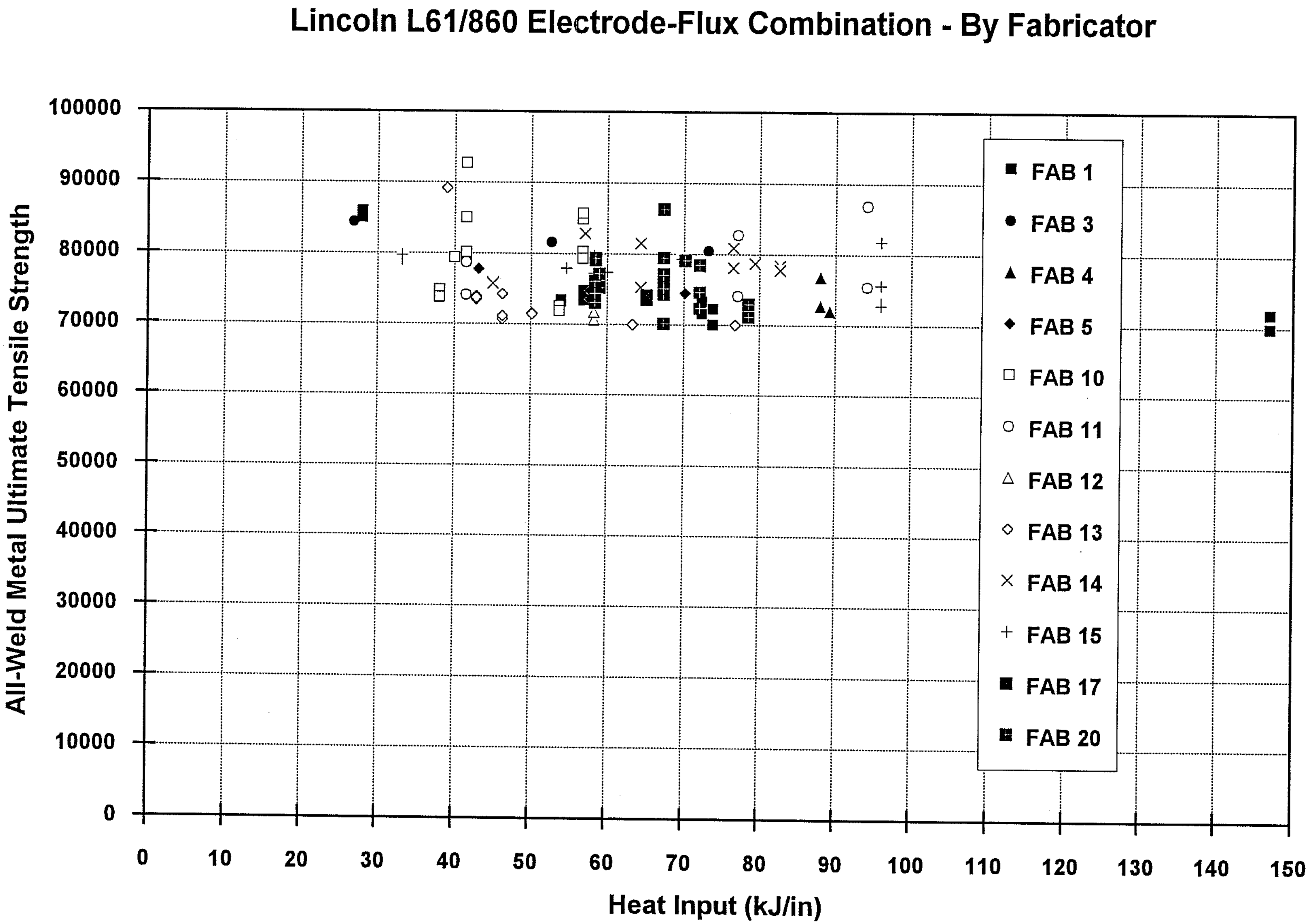


Figure 41 - Weld tensile strength vs. heat input arranged by fabricator for Lincoln 860 flux and L61 electrode.

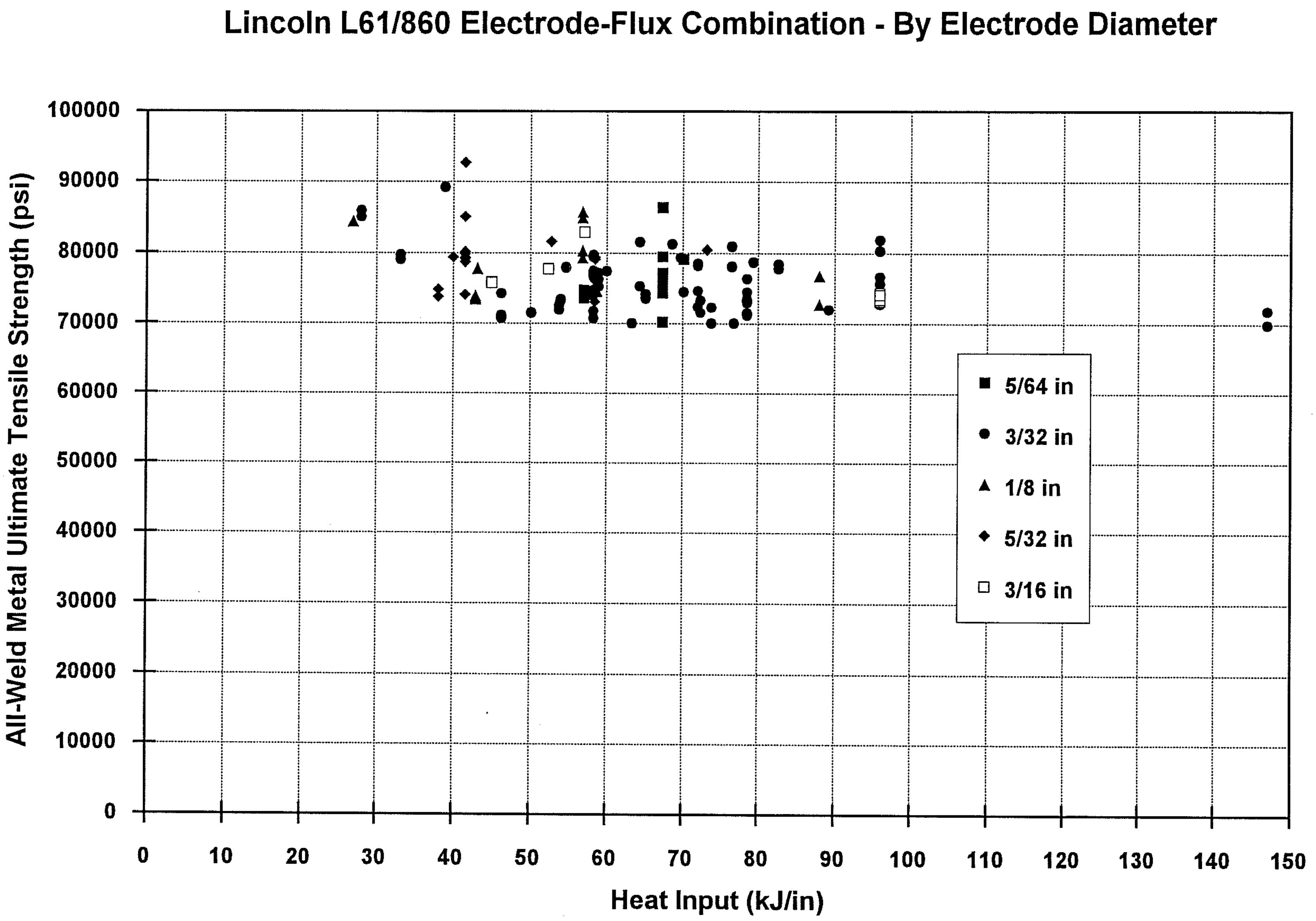


Figure 42 - Weld tensile strength vs. heat input arranged by electrode diameter for Lincoln 860 flux and L61 electrode.

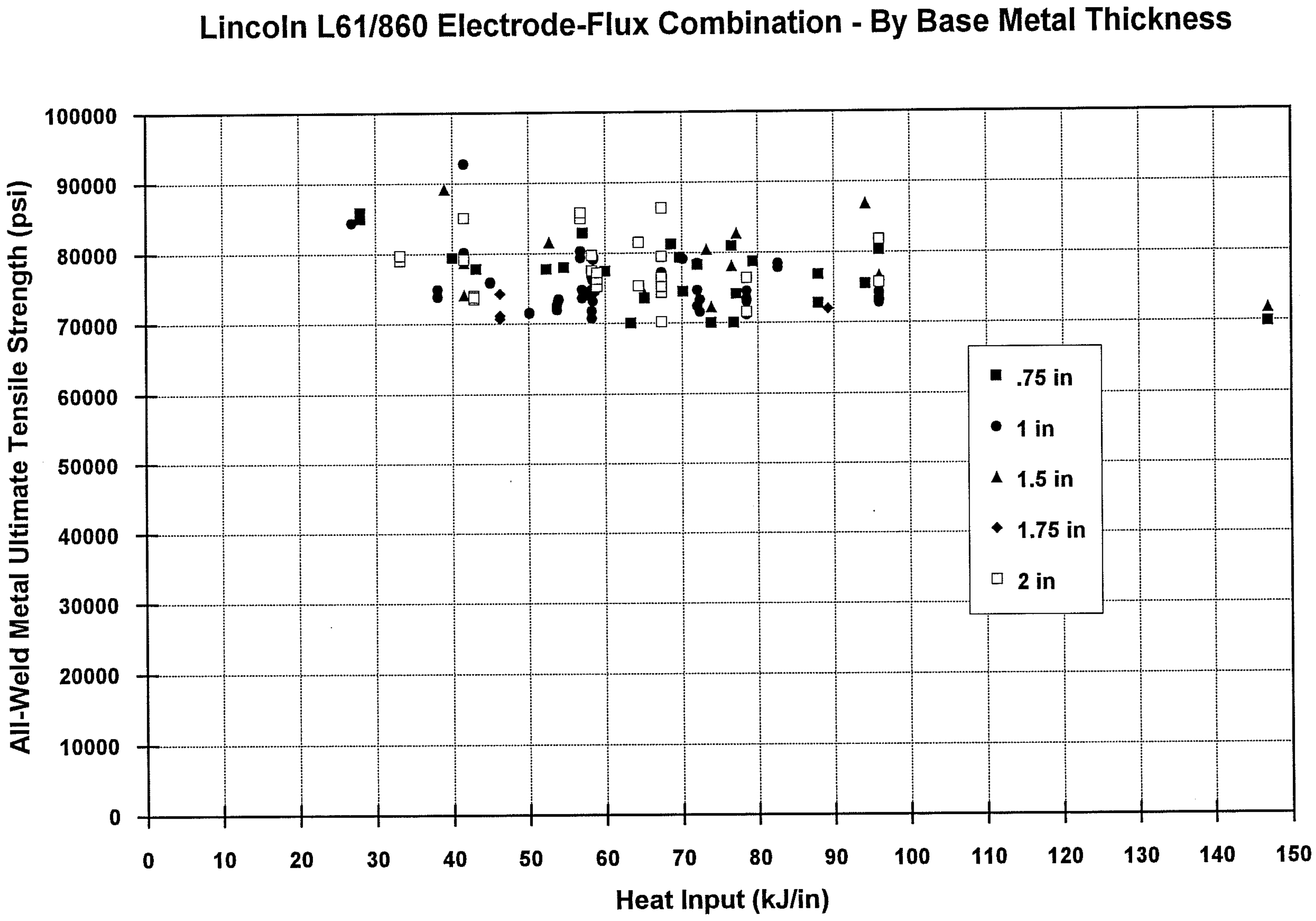


Figure 43 - Weld tensile strength vs. heat input arranged by base metal thickness for Lincoln 860 flux and L61 electrode.

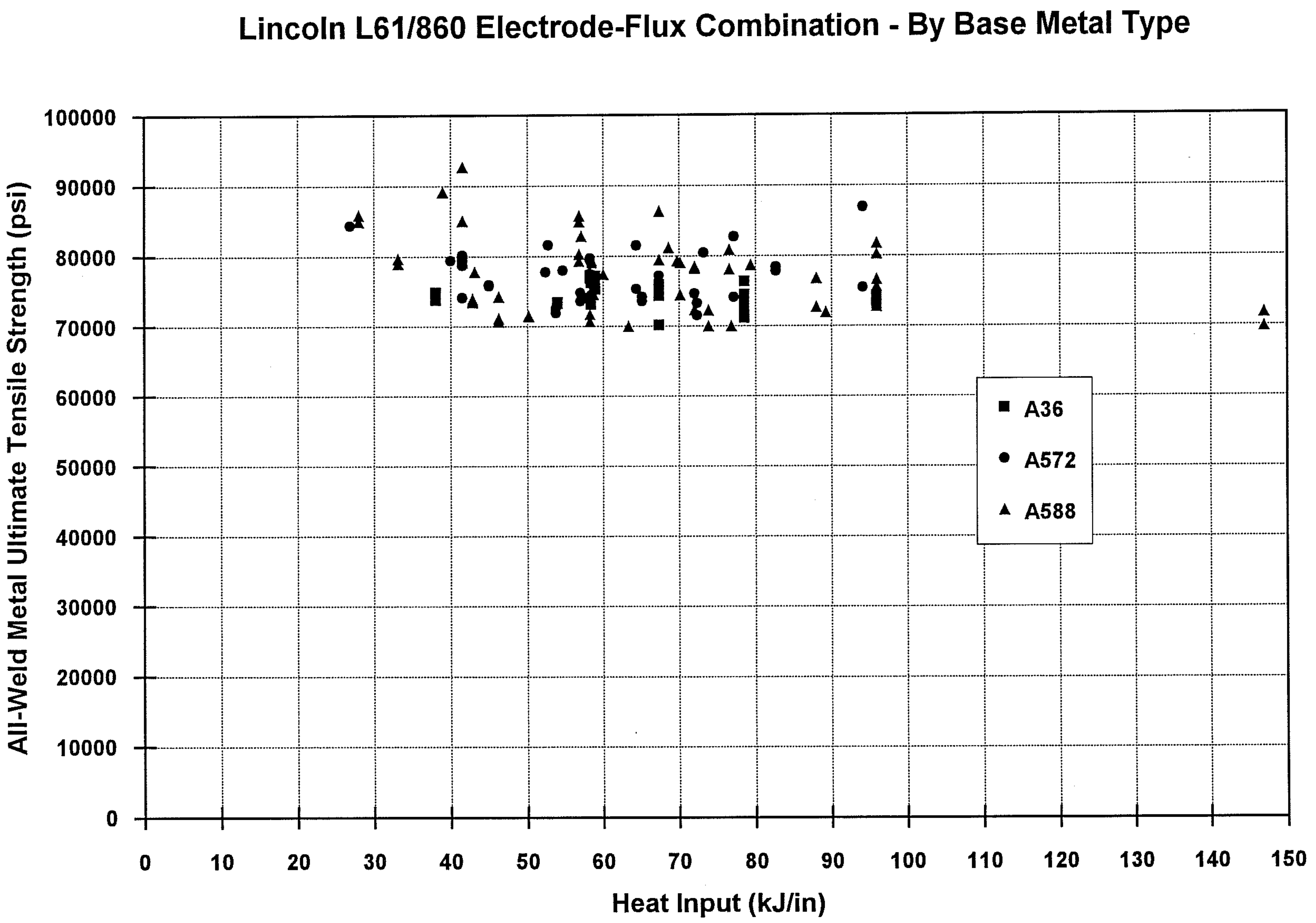


Figure 44 - Weld tensile strength vs. heat input arranged by base metal type for Lincoln 860 flux and L61 electrode.

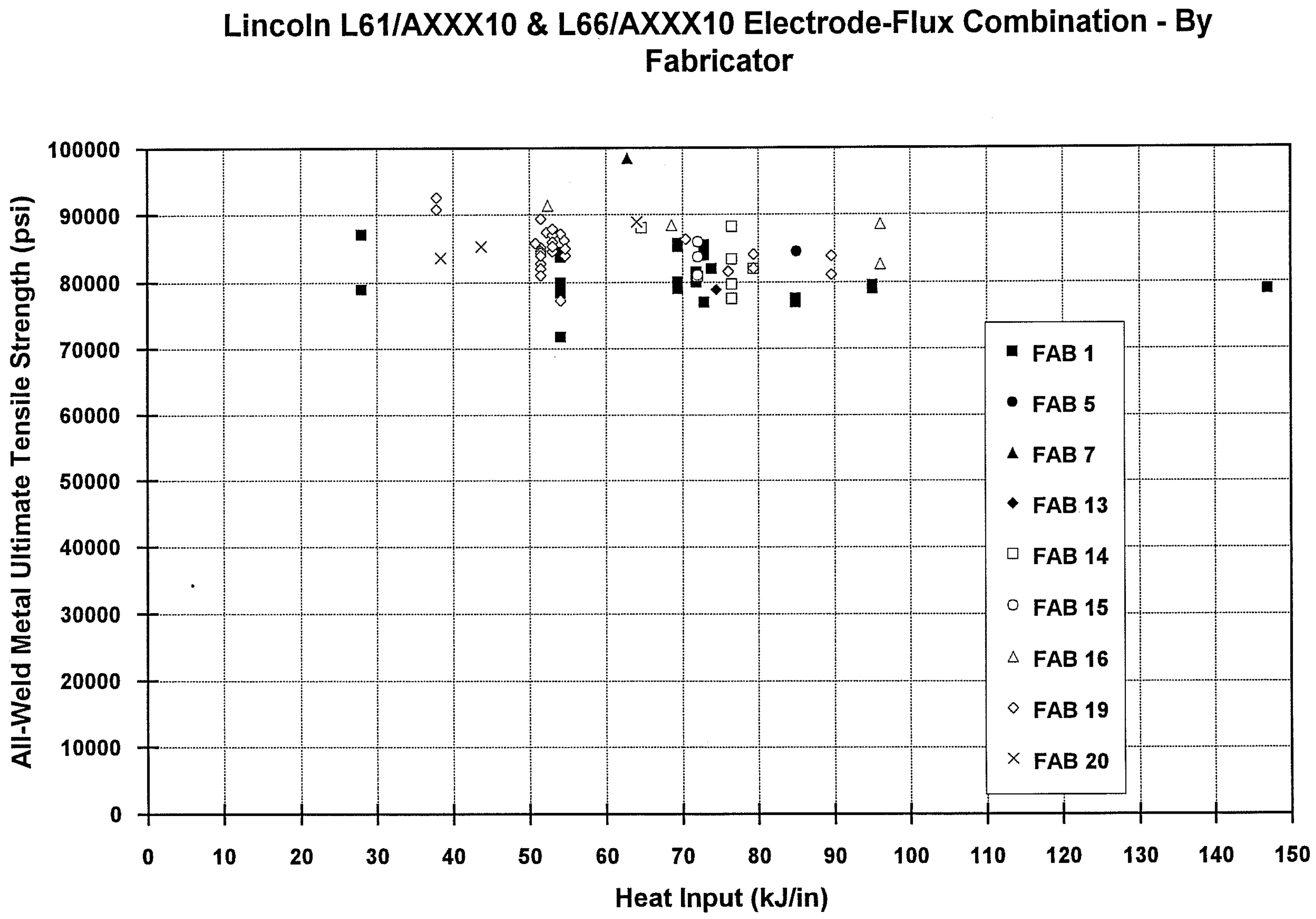


Figure 45 - Weld tensile strength vs. heat input arranged by fabricator for Lincoln AXXX10 flux and L61 and L66 electrodes.

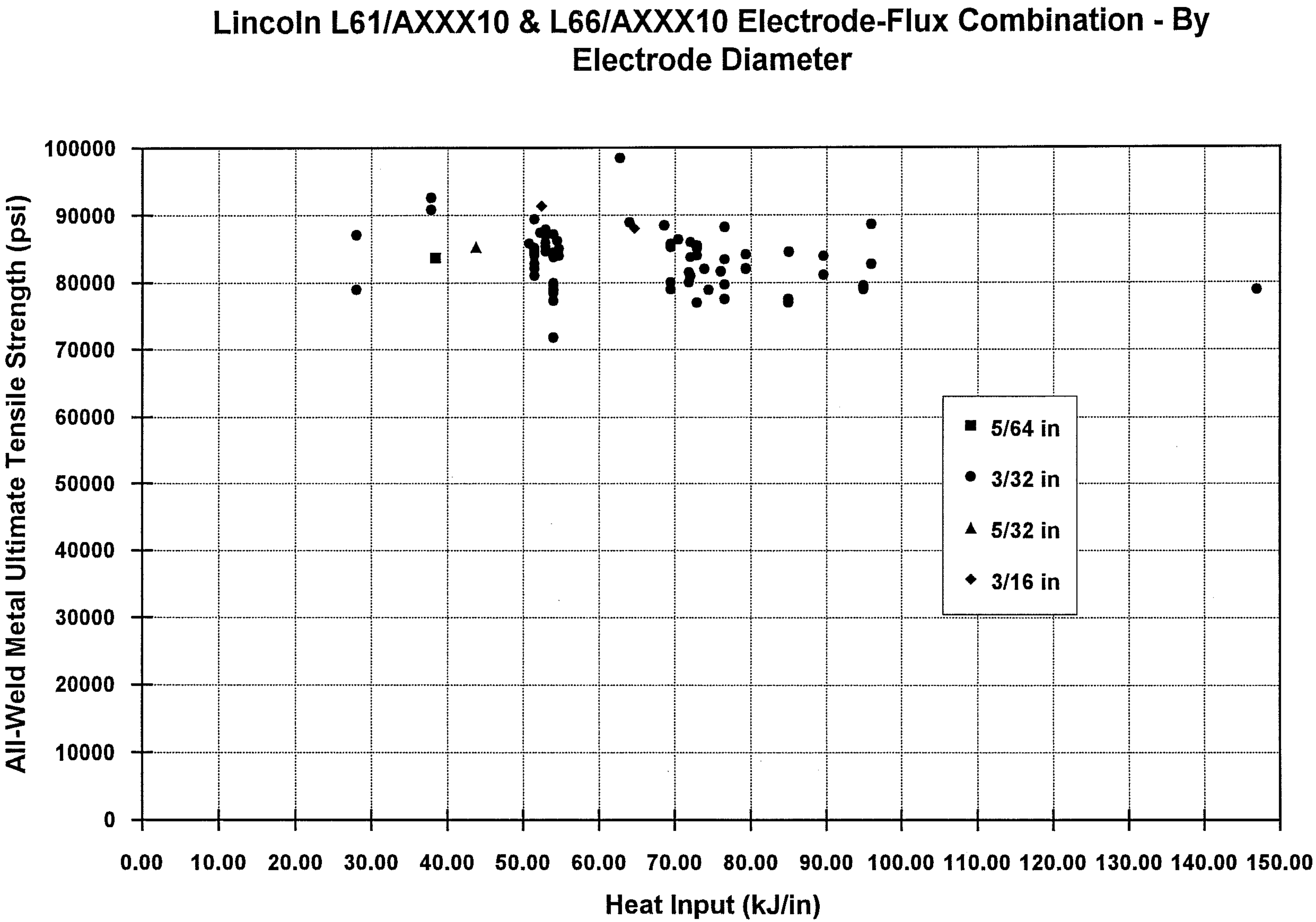


Figure 46 - Weld tensile strength vs. heat input arranged by electrode diameter for Lincoln AXXX10 flux and L61 and L66 electrodes.

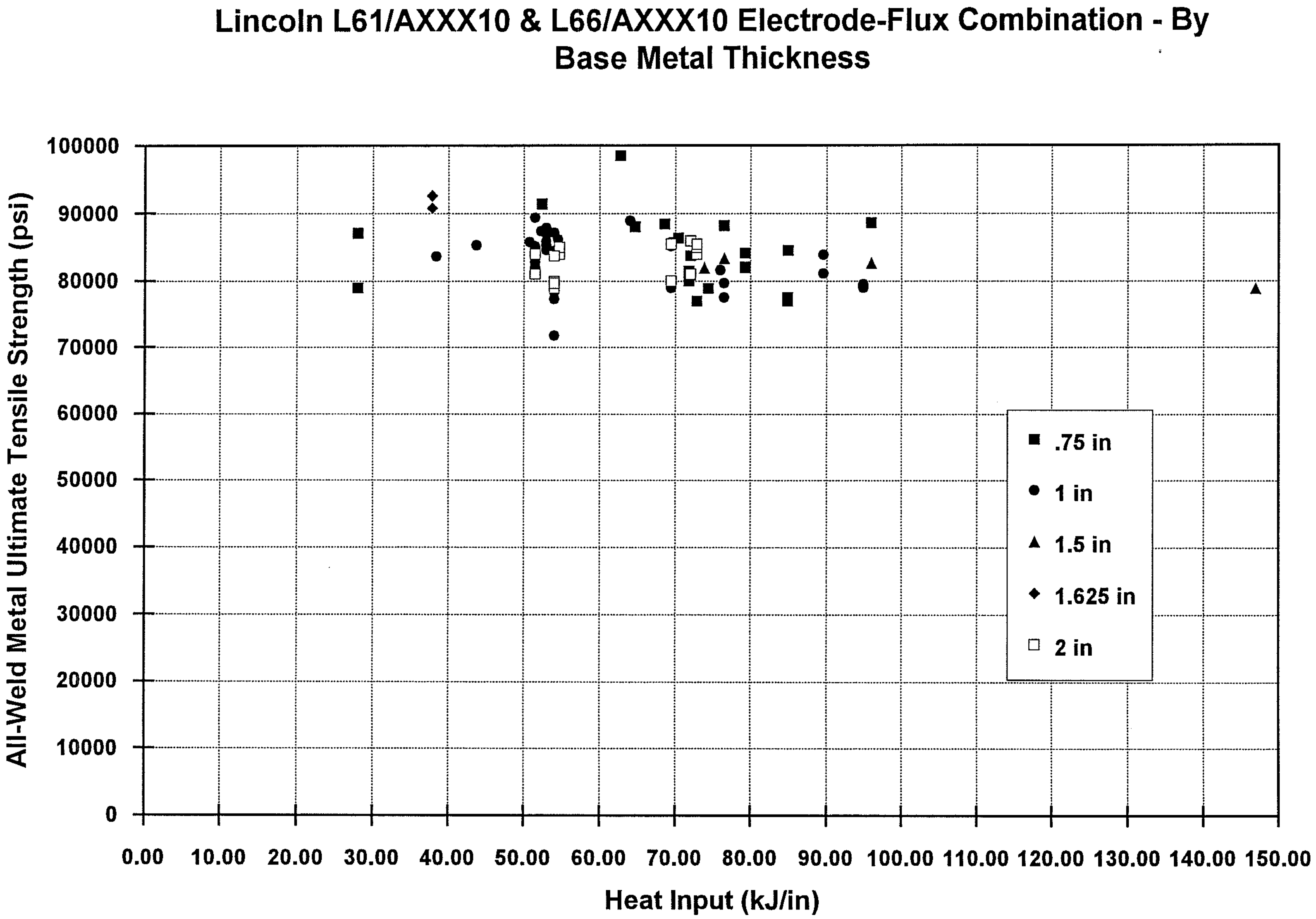


Figure 47 - Weld tensile strength vs. heat input arranged by base metal thickness for Lincoln AXXX10 flux and L61 and L66 electrodes.

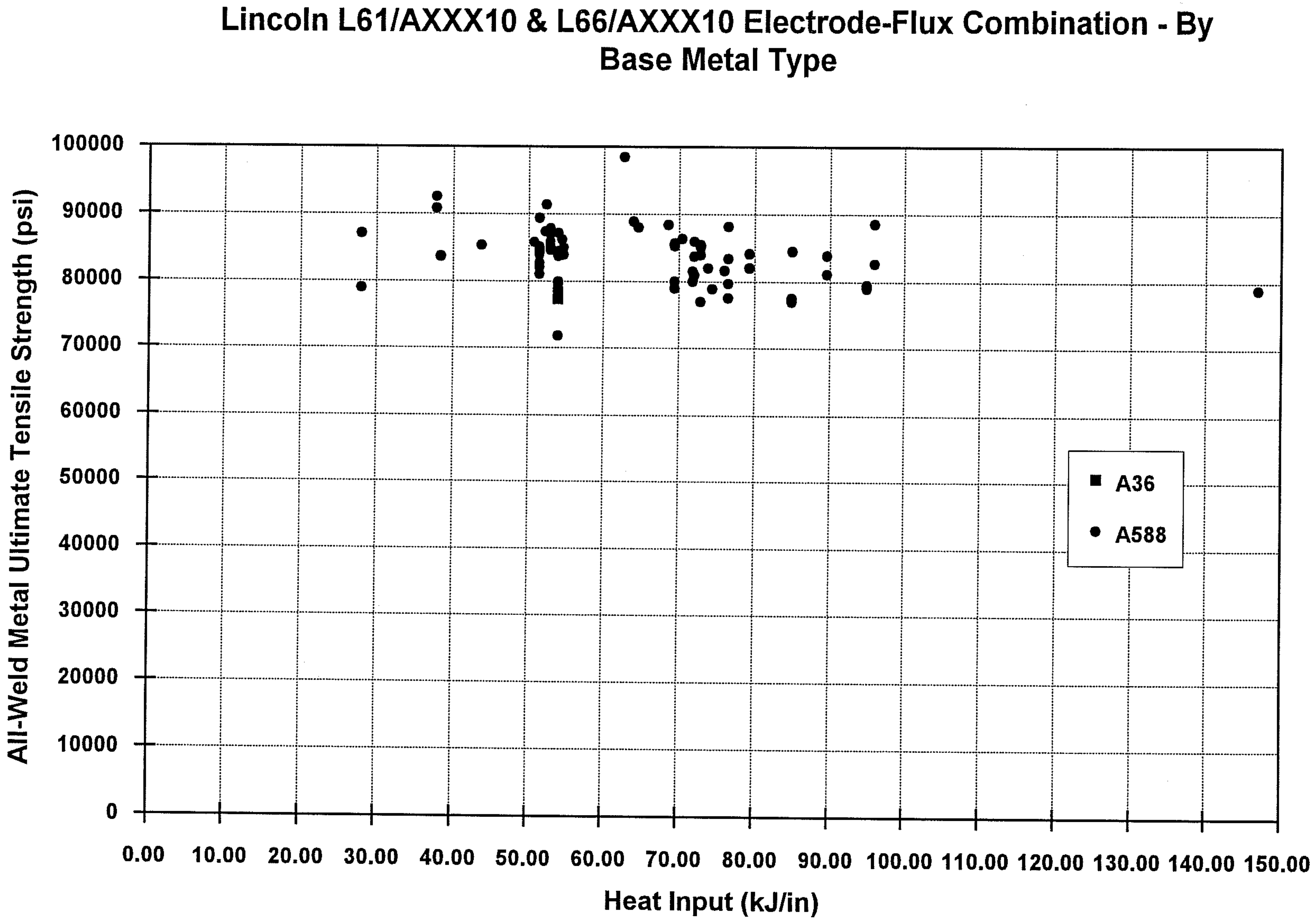


Figure 48 - Weld tensile strength vs. heat input arranged by base metal type for Lincoln AXXX10 flux and L61 and L66 electrodes.

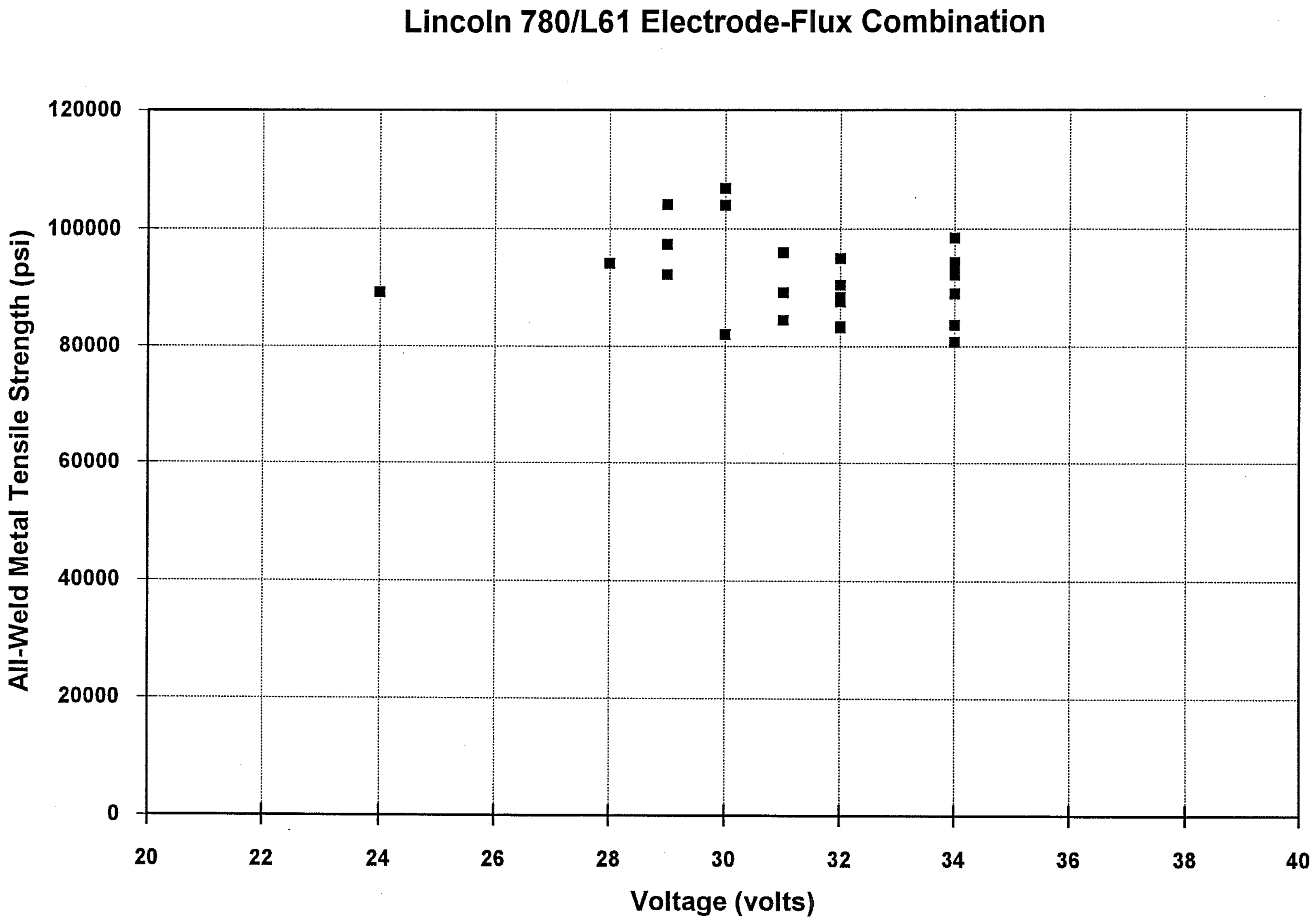


Figure 49 - All-weld tensile strength vs. voltage for Lincoln 780 flux and L61 electrode.

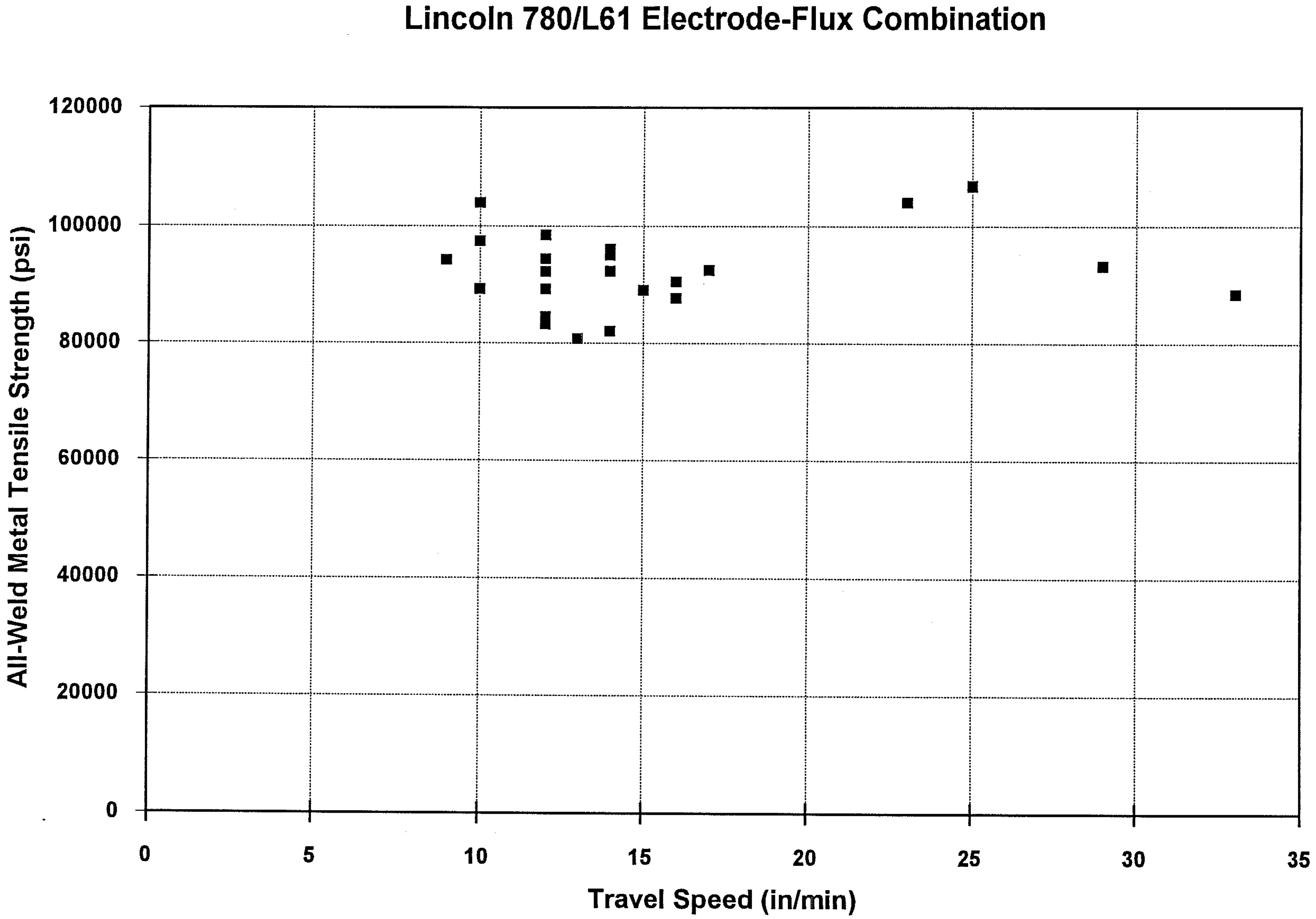


Figure 50 - All-weld tensile strength vs. travel speed for Lincoln 780 flux and L61 electrode.

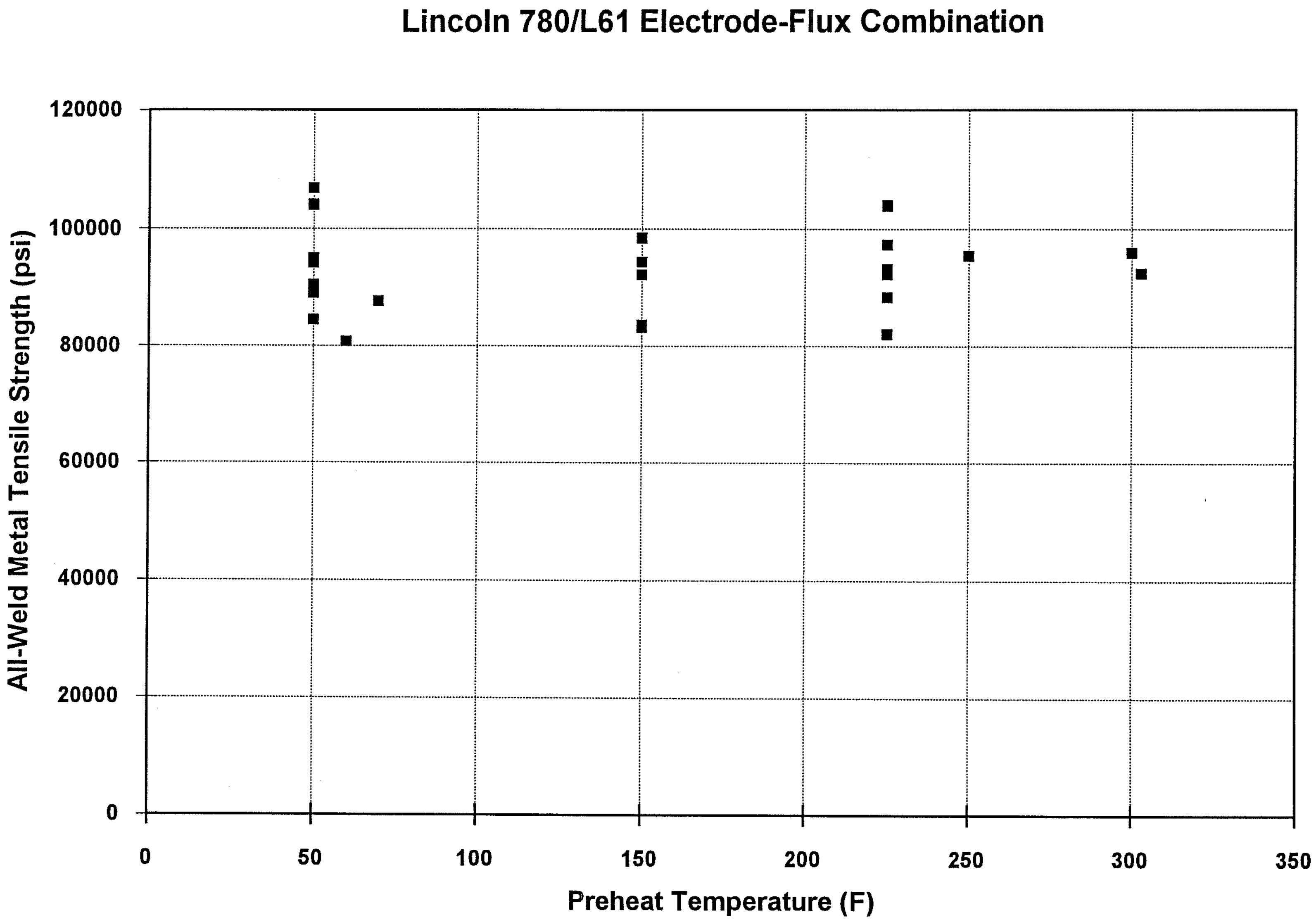


Figure 51 - All-weld tensile strength vs. preheat temperature for Lincoln 780 flux and L61 electrode.

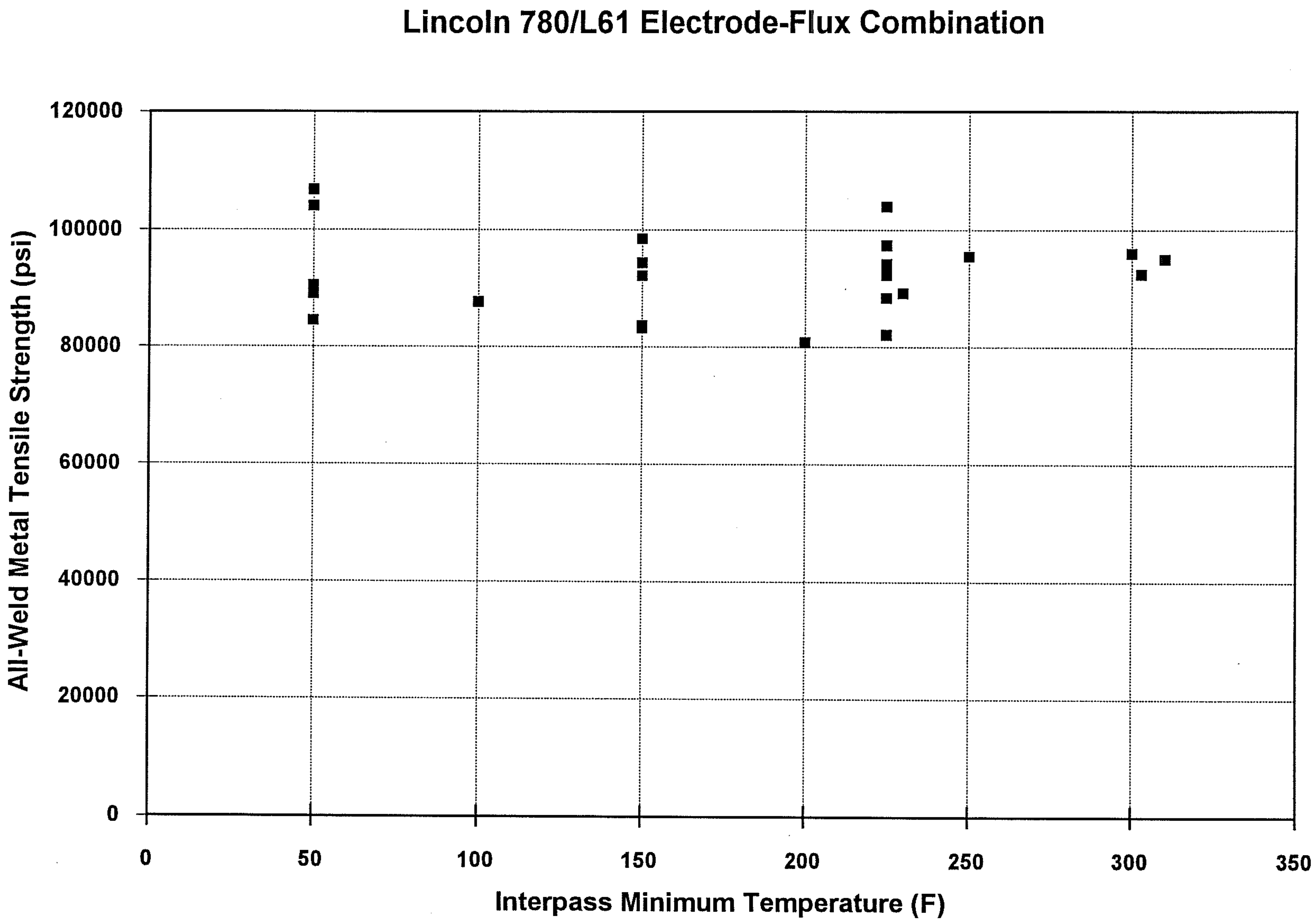


Figure 52 - All-weld tensile strength vs. minimum interpass temperature for Lincoln 780 flux and L61 electrode.

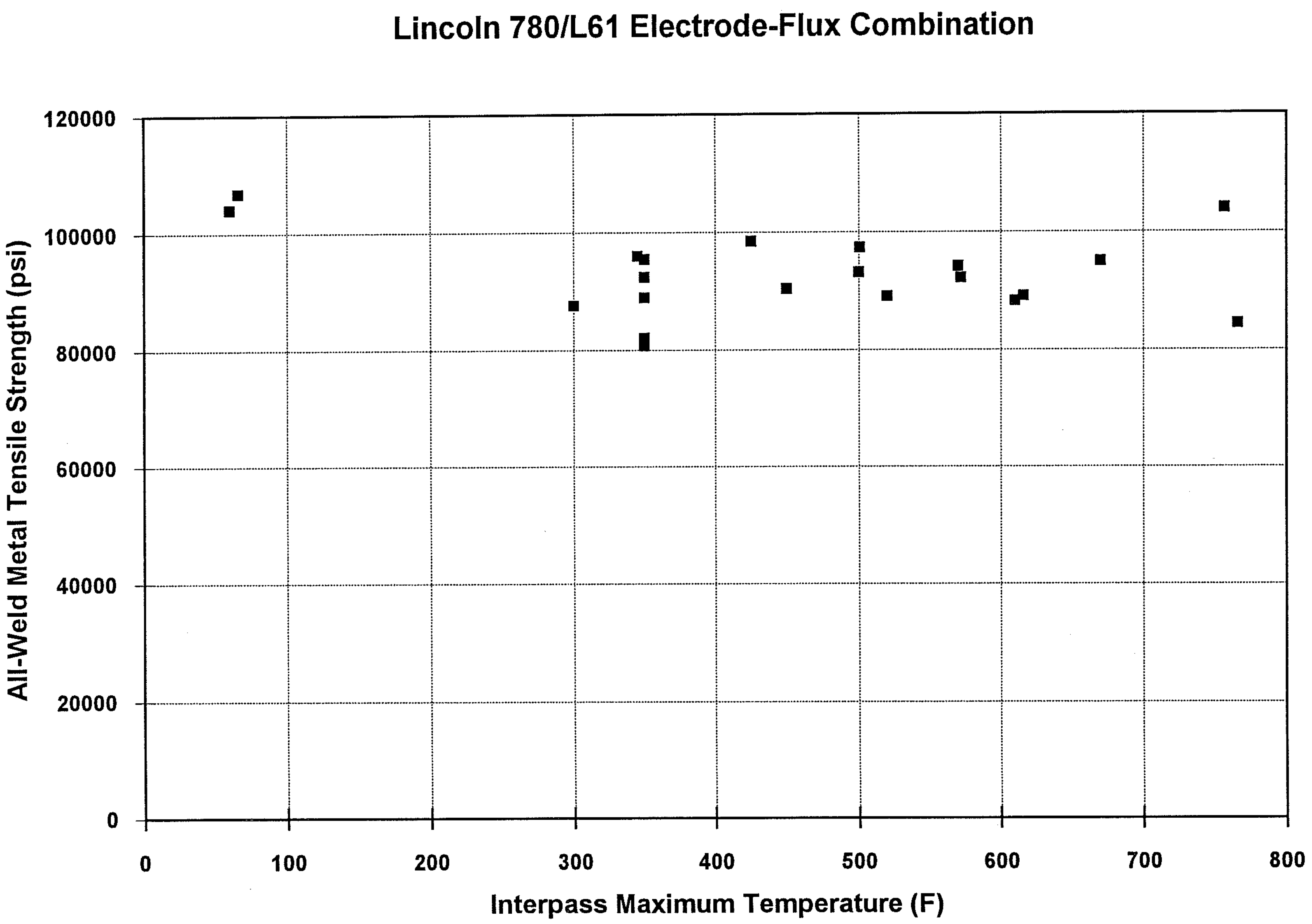


Figure 53 - All-weld tensile strength vs. maximum interpass temperature for Lincoln 780 flux and L61 electrode.

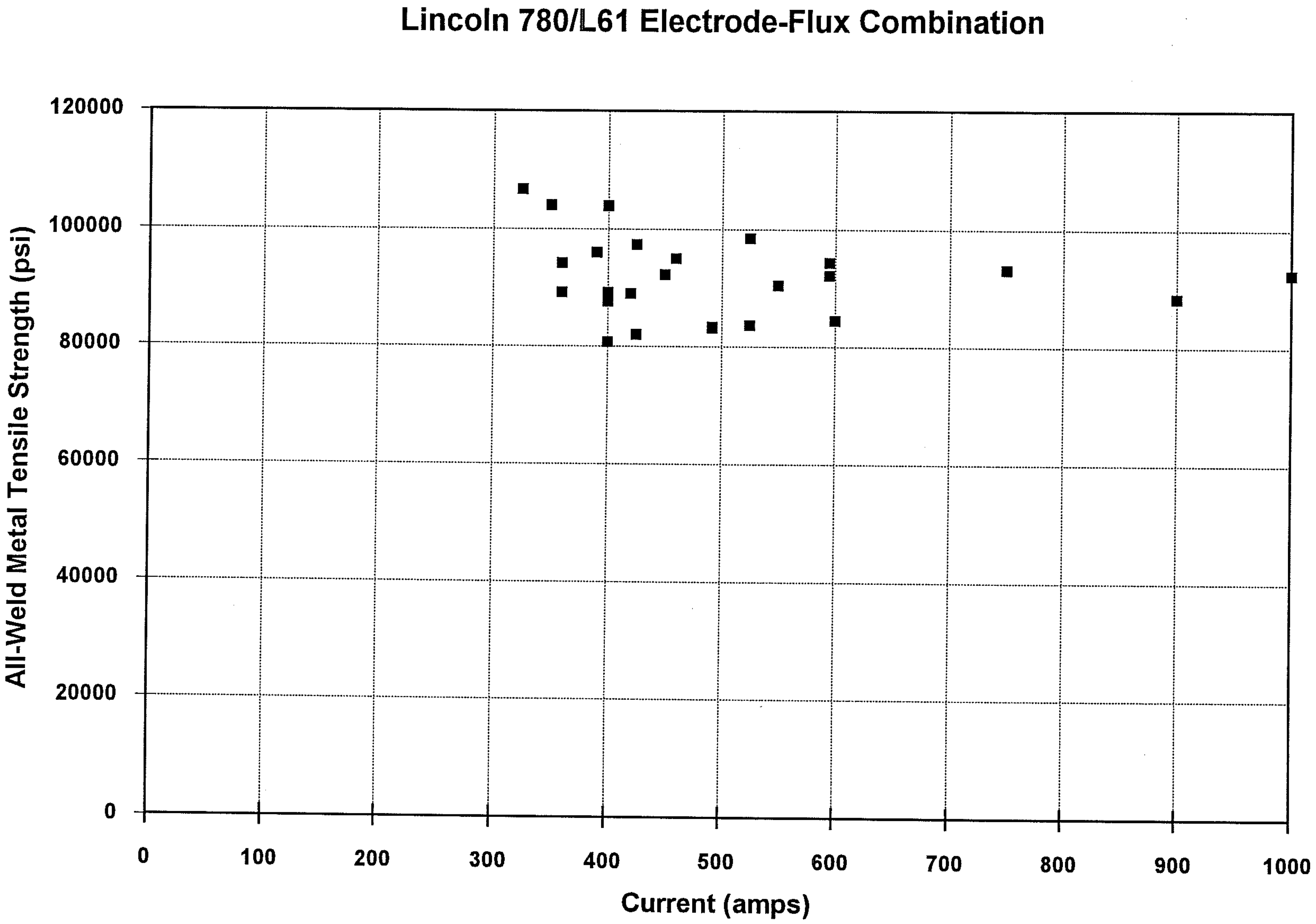


Figure 54 - All-weld tensile strength vs. current for Lincoln 780 flux and L61 electrode.

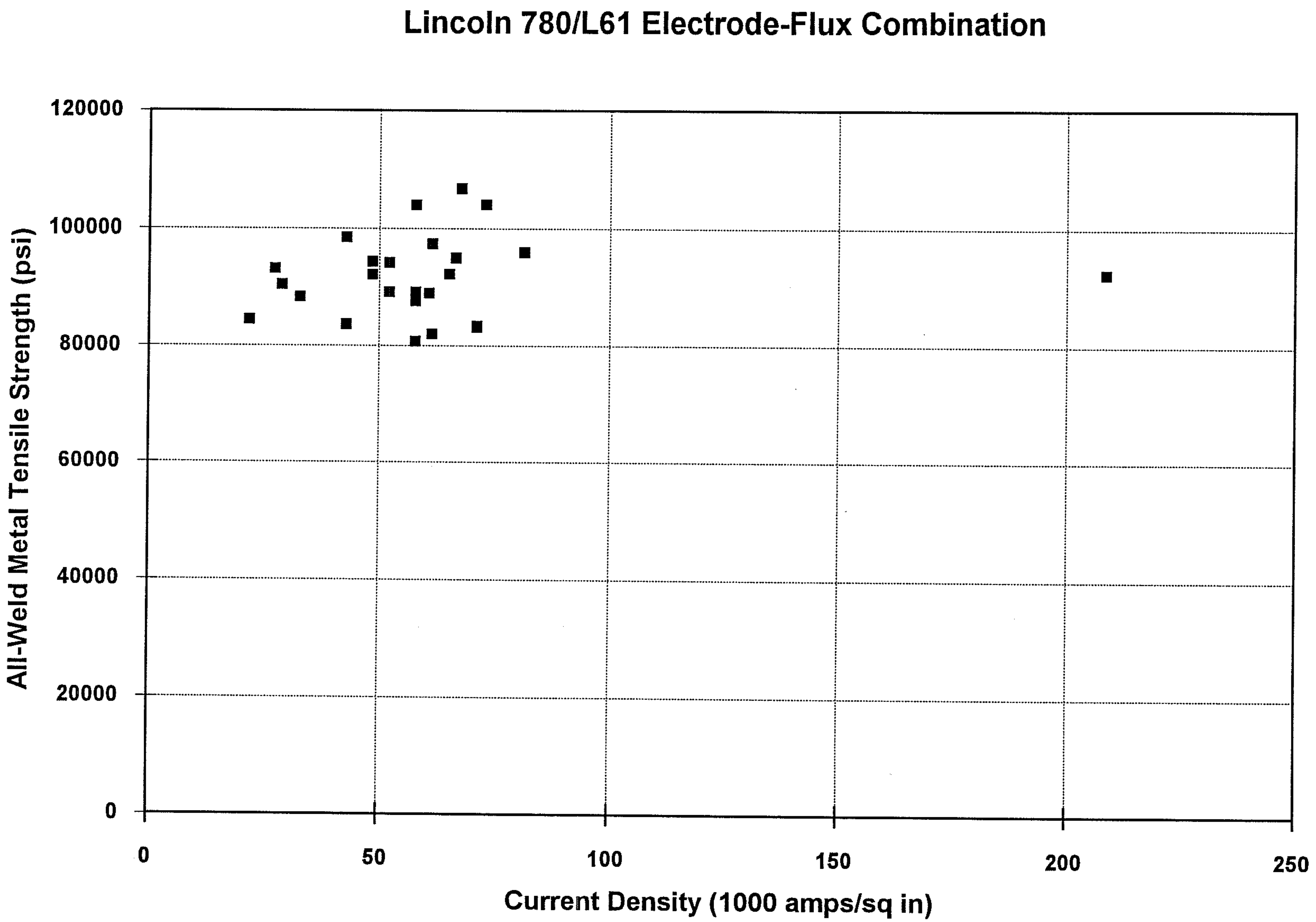


Figure 55 - All-weld tensile strength vs. current density for Lincoln 780 flux and L61 electrode.

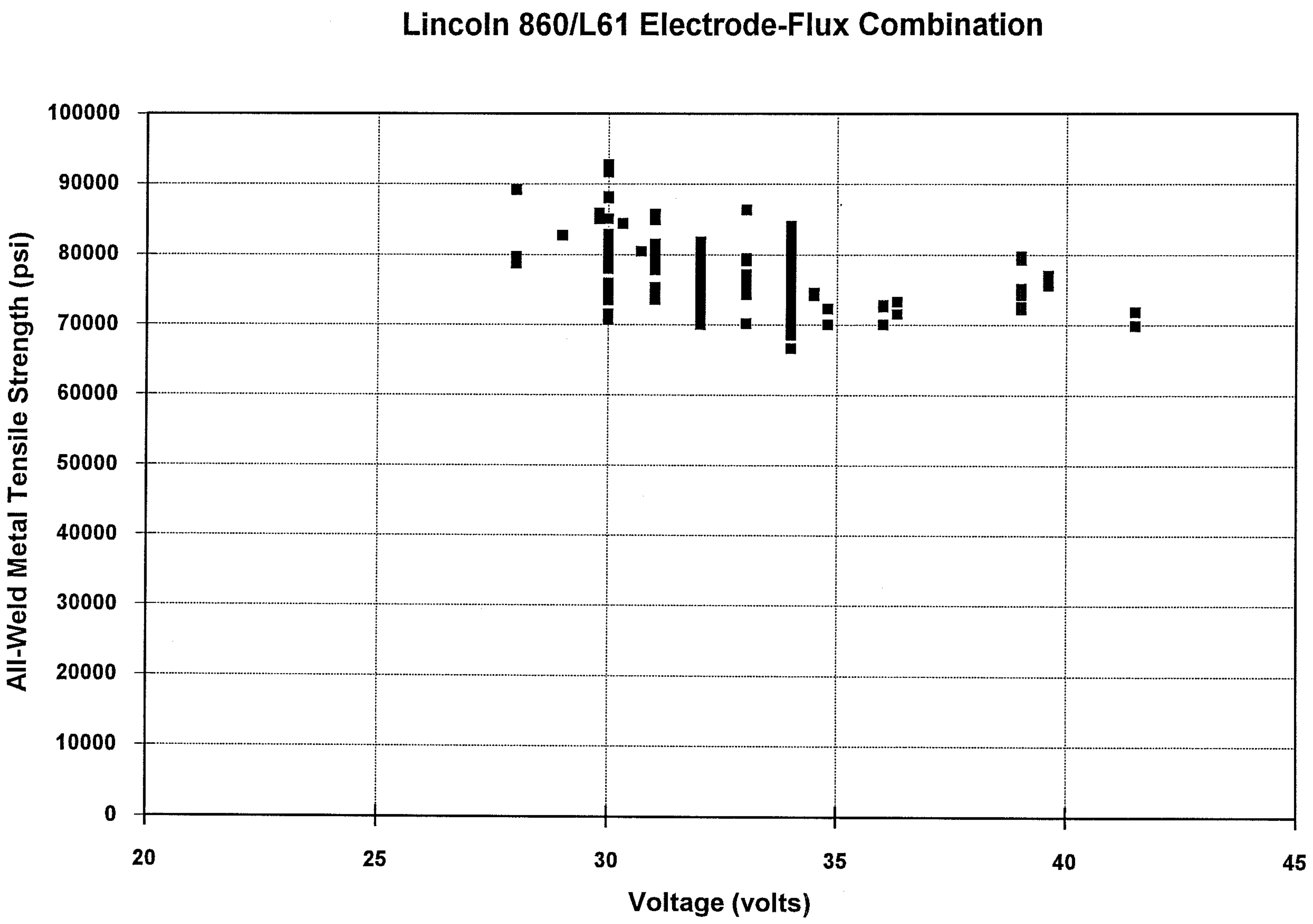


Figure 56 - All-weld tensile strength vs. voltage for Lincoln 860 flux and L61 electrode.

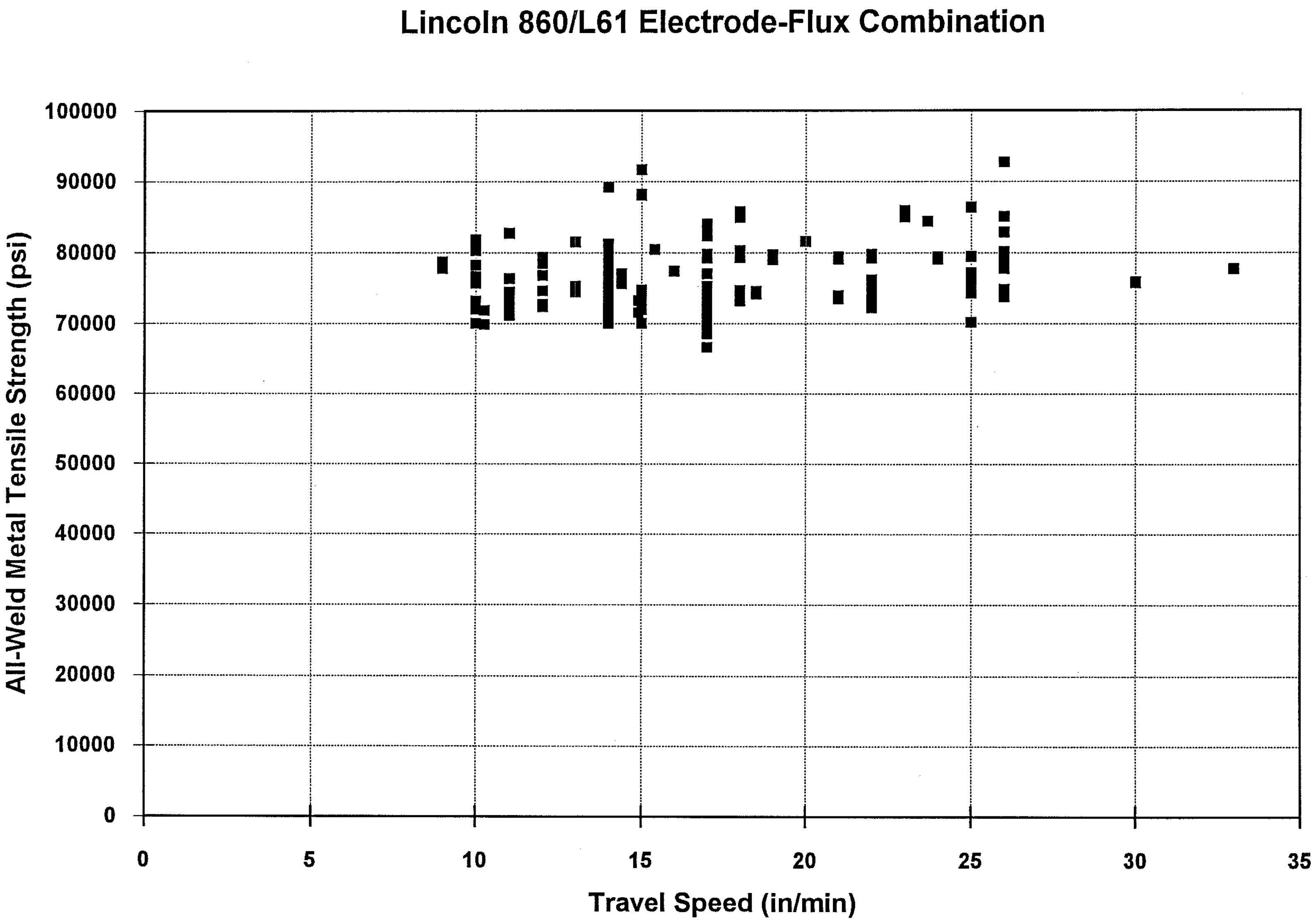


Figure 57 - All-weld tensile strength vs. travel speed for Lincoln 860 flux and L61 electrode.

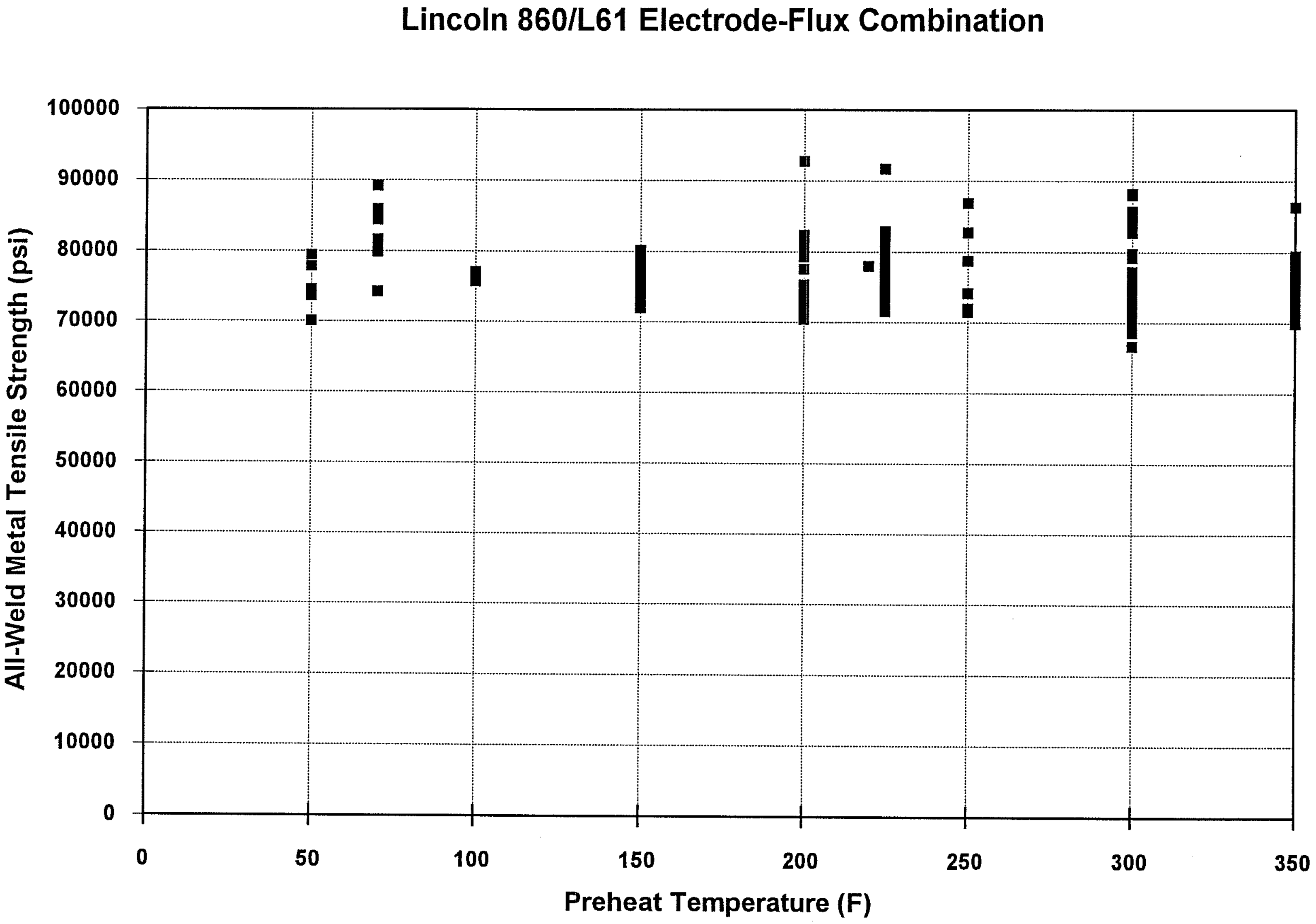


Figure 58 - All-weld tensile strength vs. preheat temperature for Lincoln 860 flux and L61 electrode.

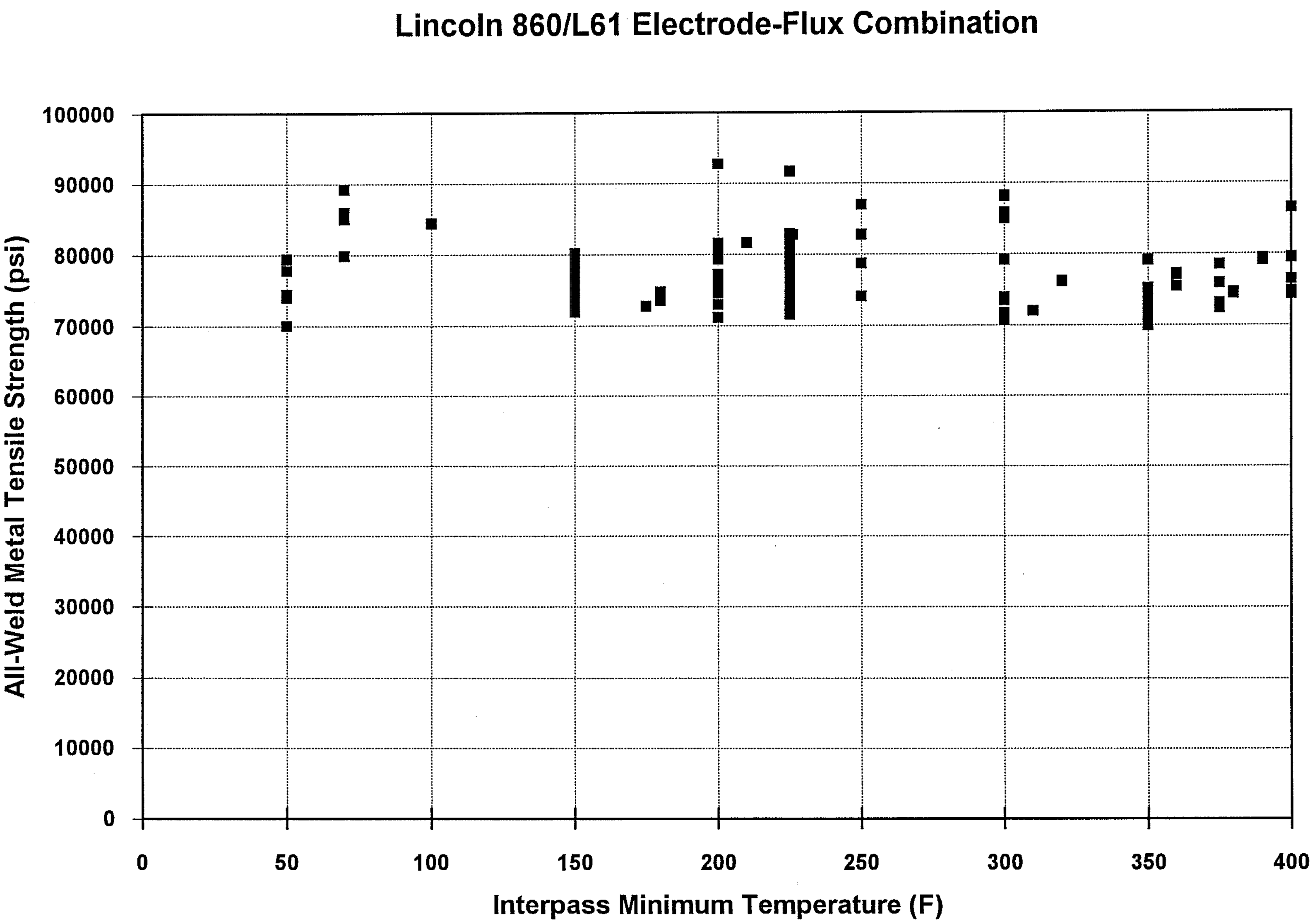


Figure 59 - All-weld tensile strength vs. minimum interpass temperature for Lincoln 860 flux and L61 electrode.

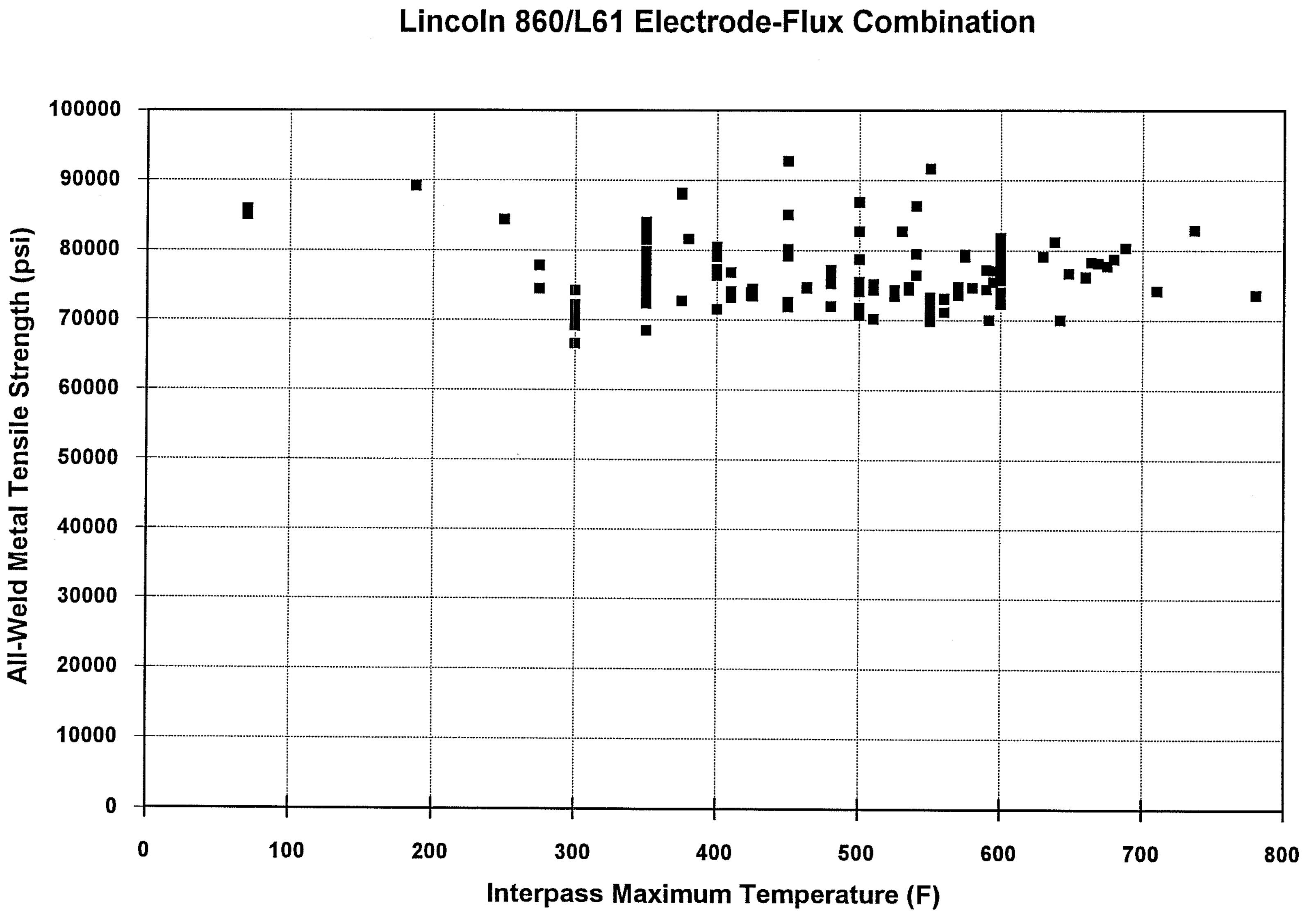


Figure 60 - All-weld tensile strength vs. maximum interpass temperature for Lincoln 860 flux and L61 electrode.

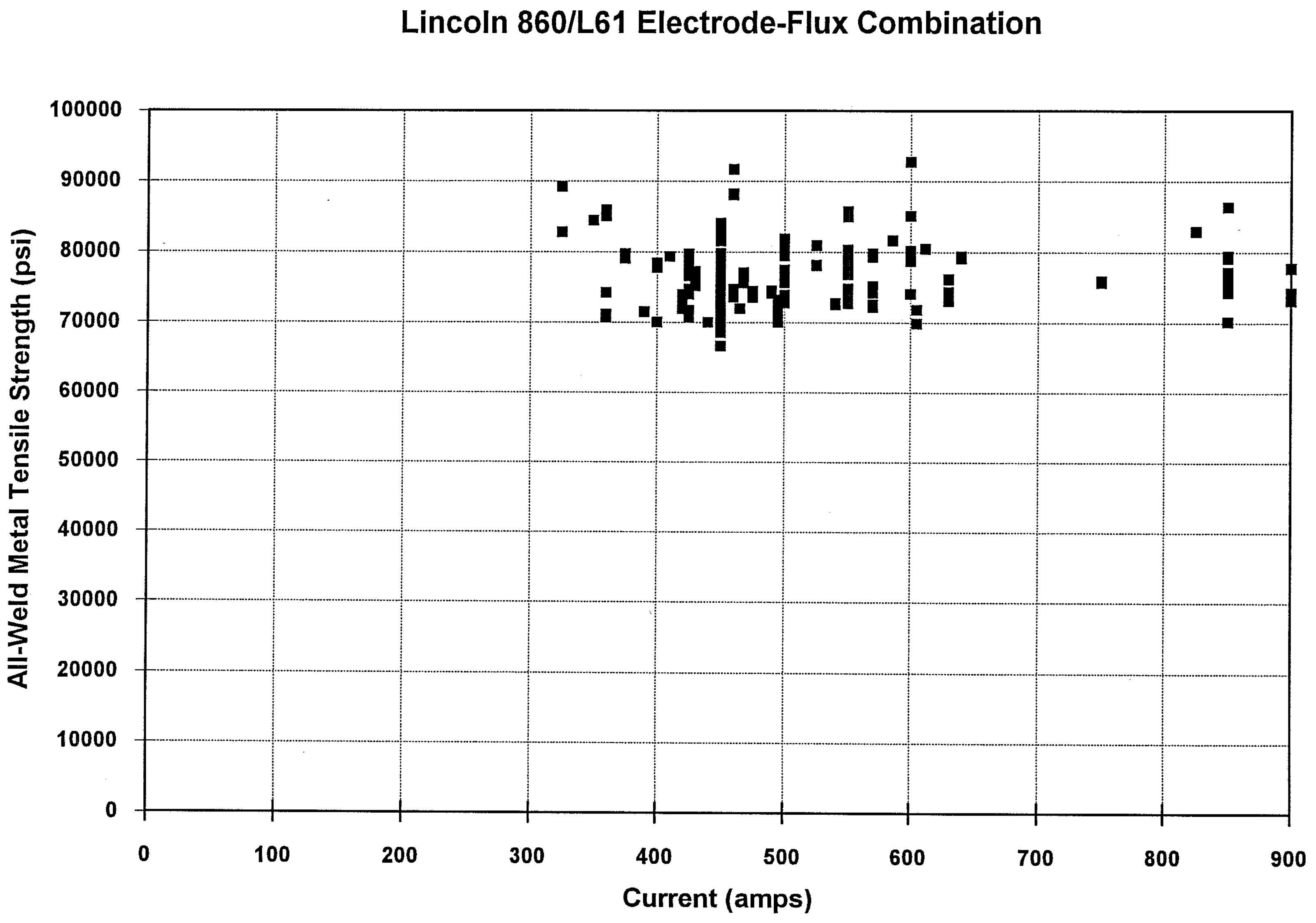


Figure 61 - All-weld tensile strength vs. current for Lincoln 860 flux and L61 electrode.

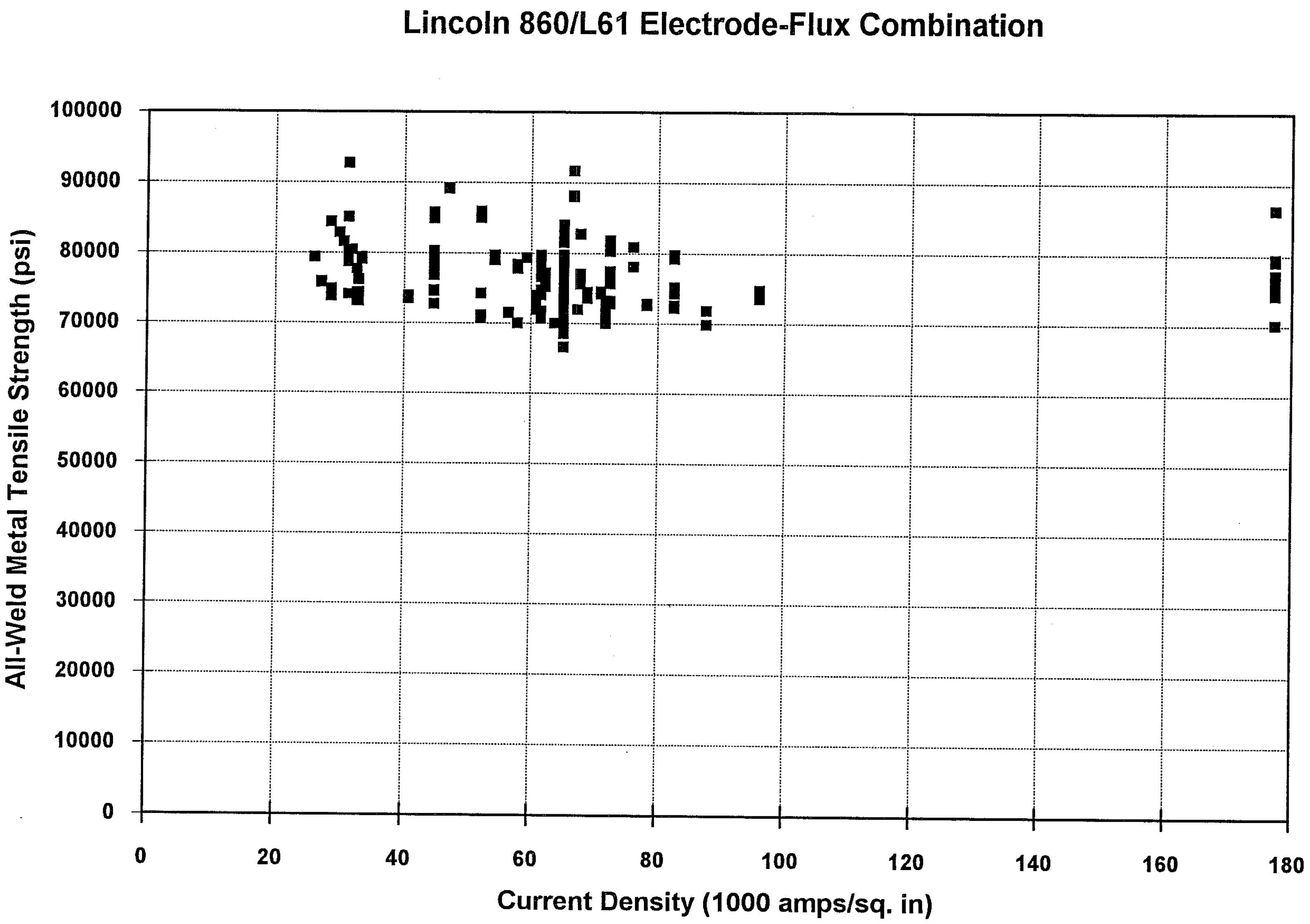


Figure 62 - All-weld tensile strength vs. current density for Lincoln 860 flux and L61 electrode.

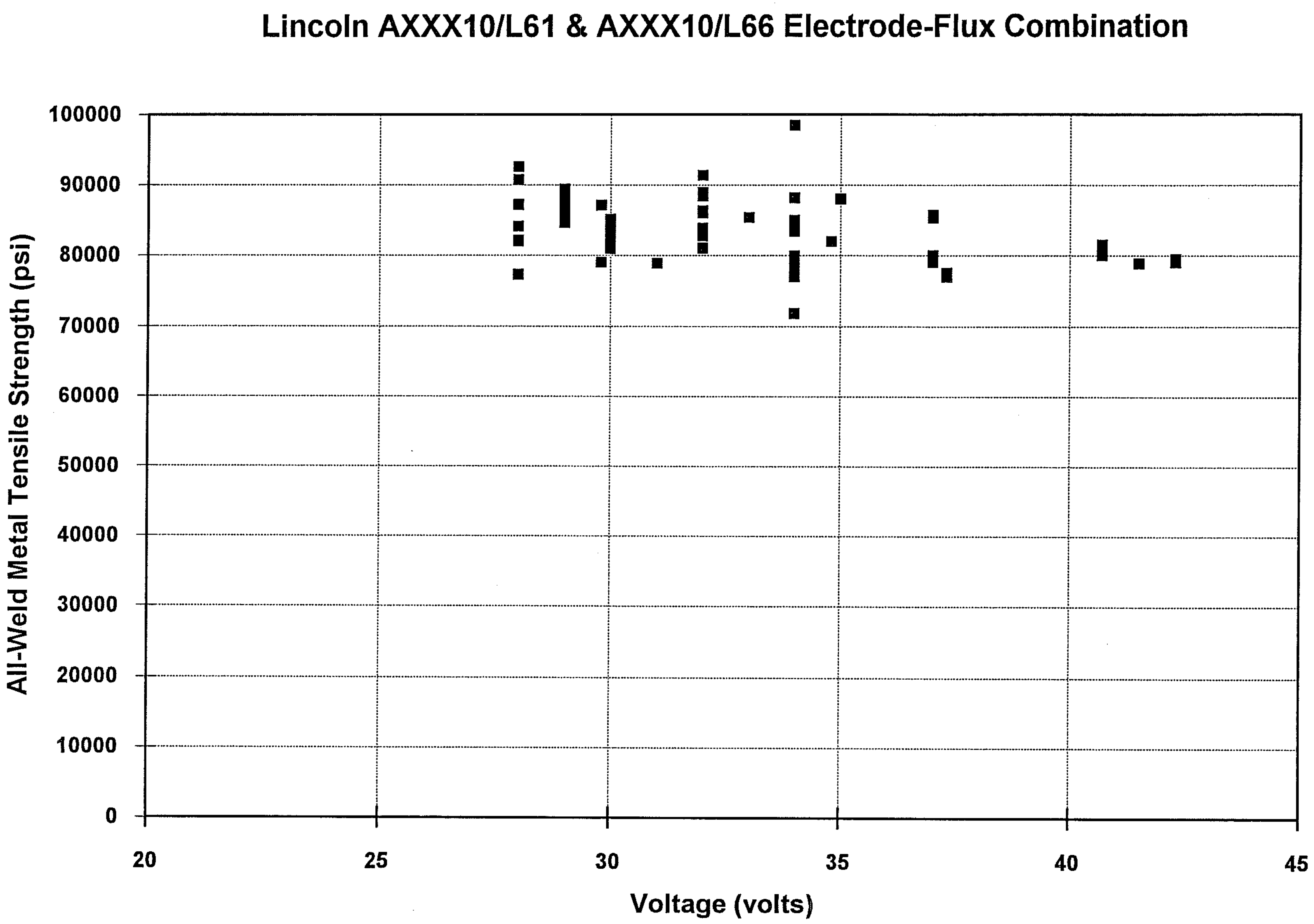

Lincoln AXXX10/L61 & AXXX10/L66 Electrode-Flux Combination

Figure 63 - All-weld tensile strength vs. voltage for Lincoln AXXX10 flux and L61 and L66 electrodes.

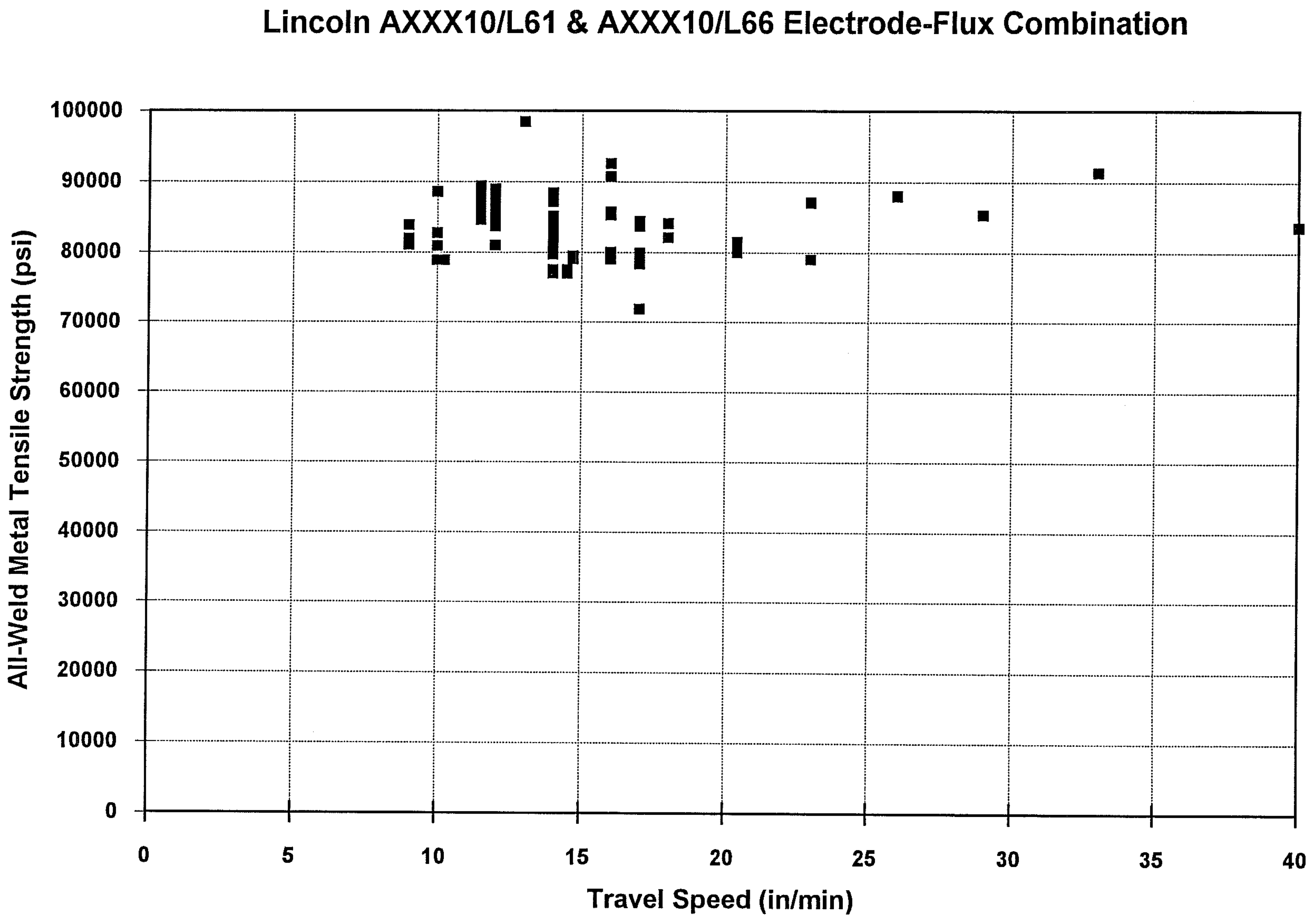


Figure 64 - All-weld tensile strength vs. travel speed for Lincoln AXXX10 flux and L61 and L66 electrodes.

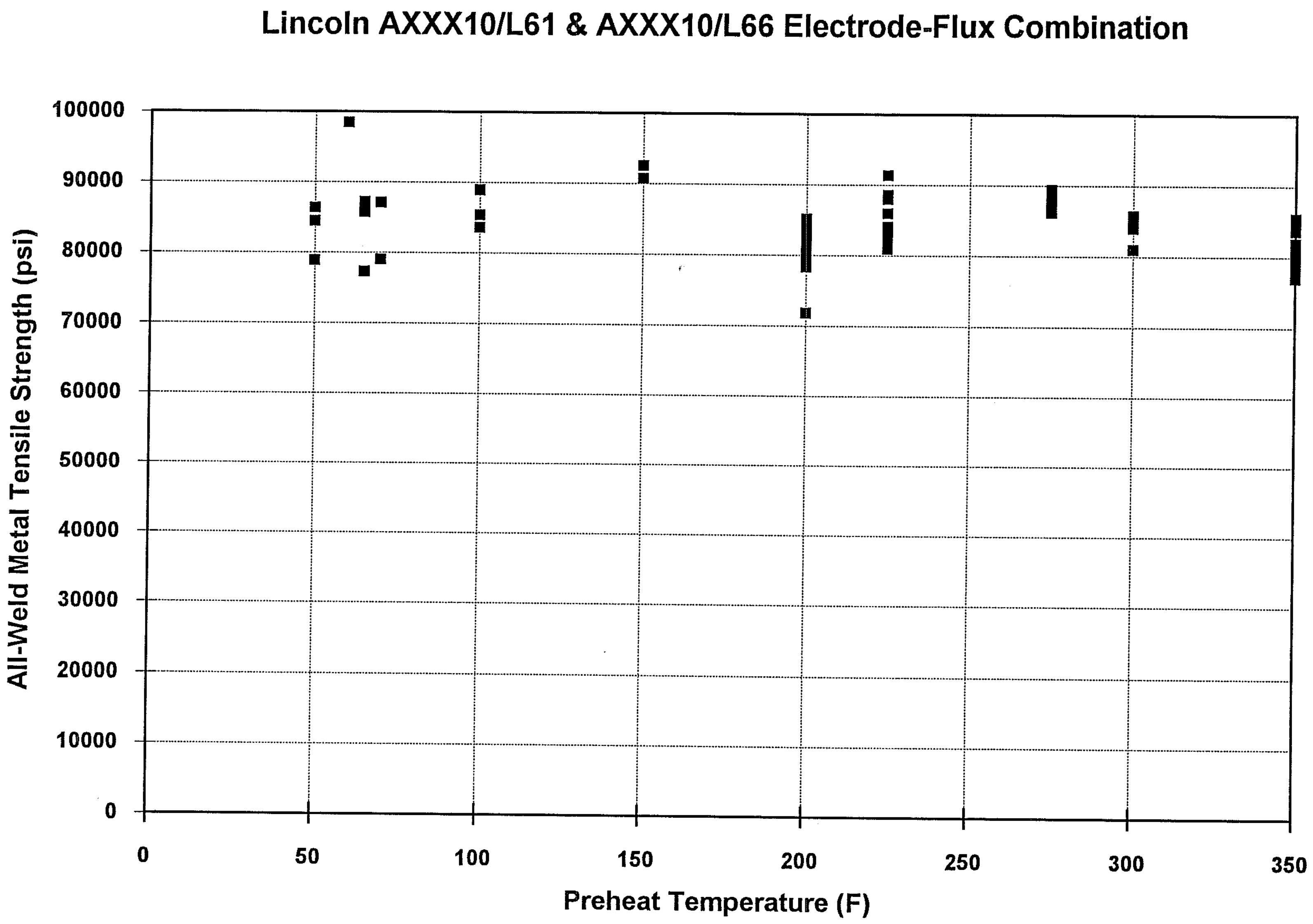


Figure 65 - All weld tensile strength vs. preheat temperature for Lincoln AXXX10 flux and L61 and L66 electrodes.

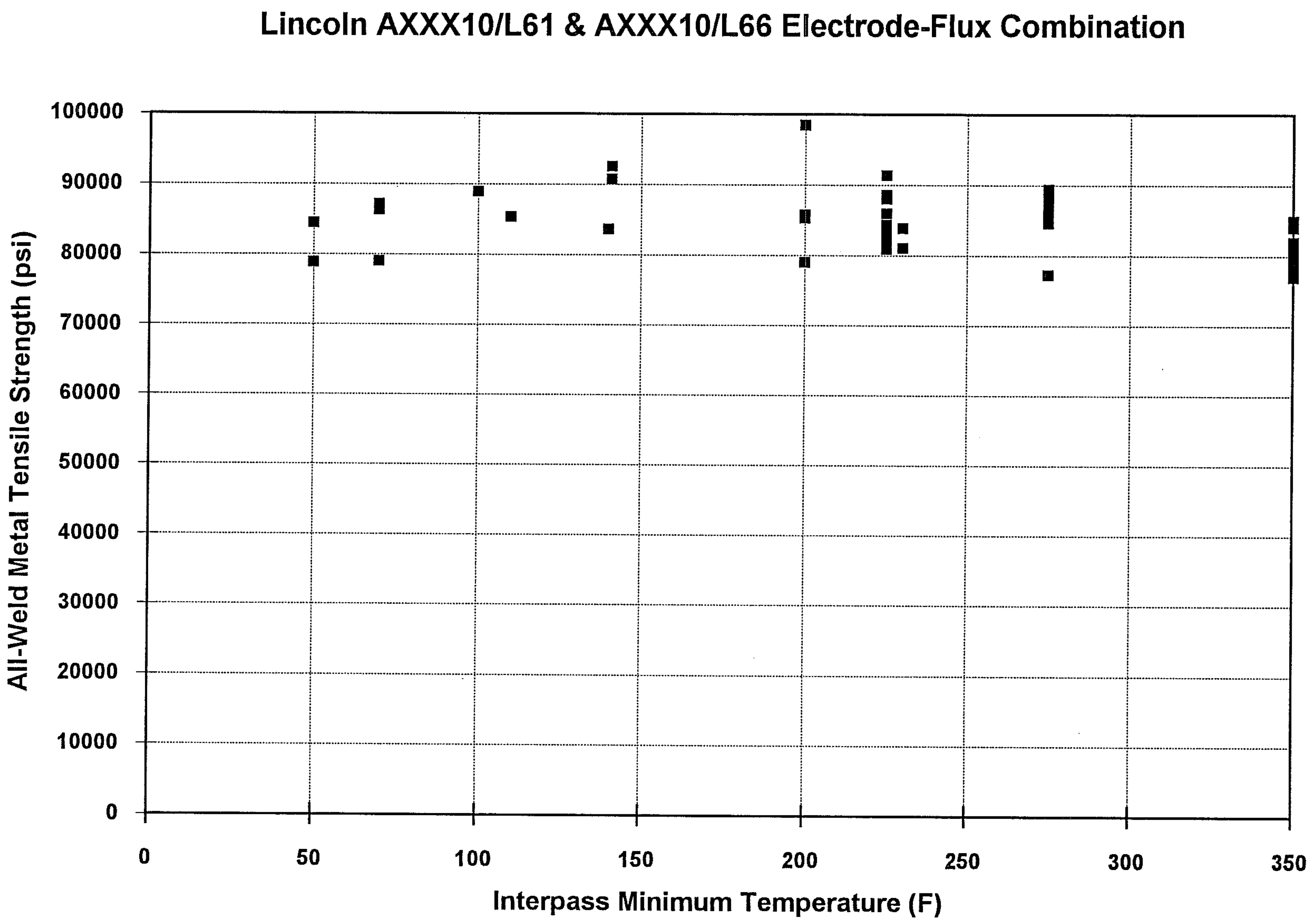


Figure 66 - All-weld tensile strength vs. minimum interpass temperature for Lincoln AXXX10 flux and L61 and L66 electrodes.

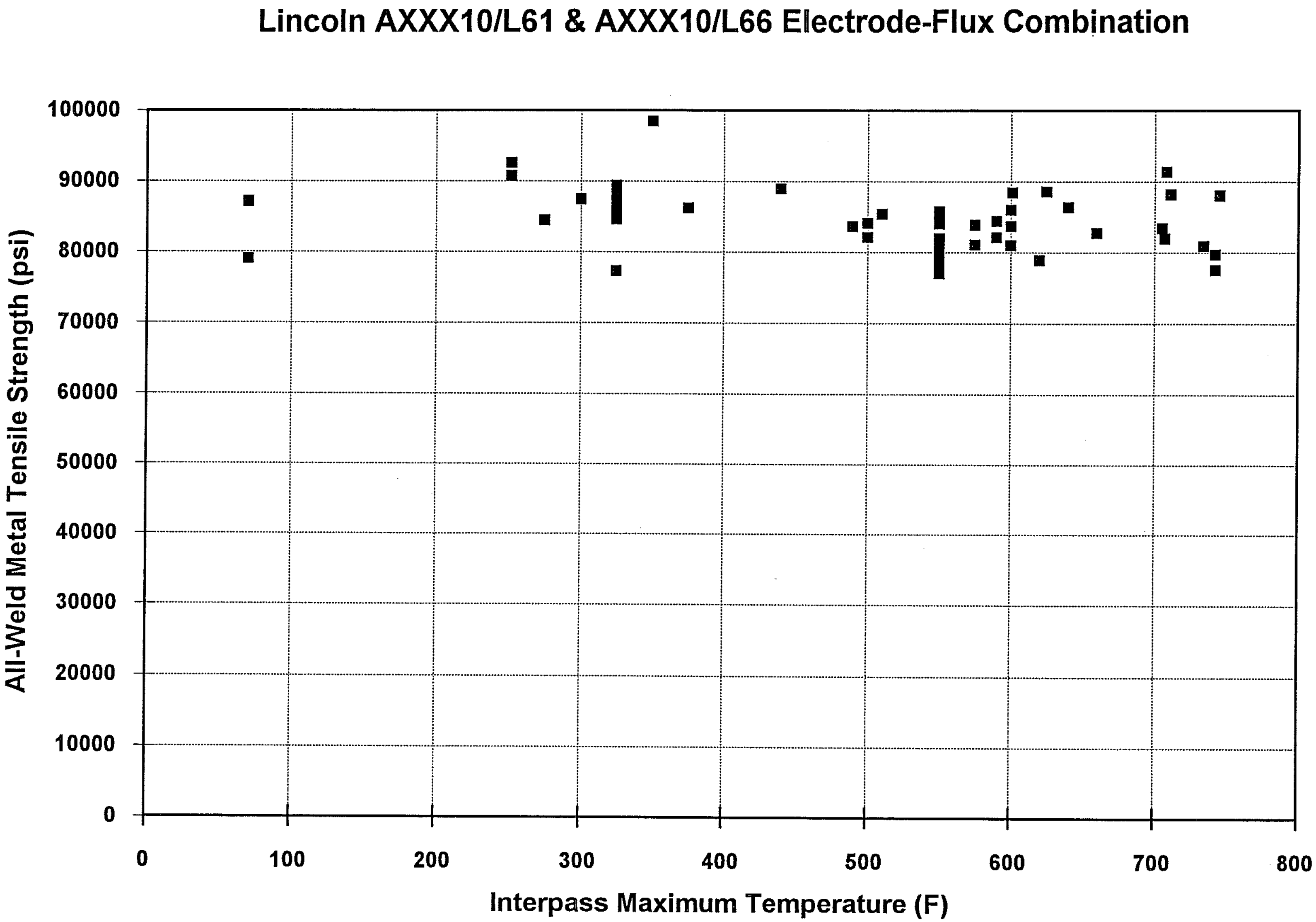


Figure 67 - All-weld tensile strength vs. maximum interpass temperature for Lincoln AXXX10 flux and L61 and L66 electrodes.

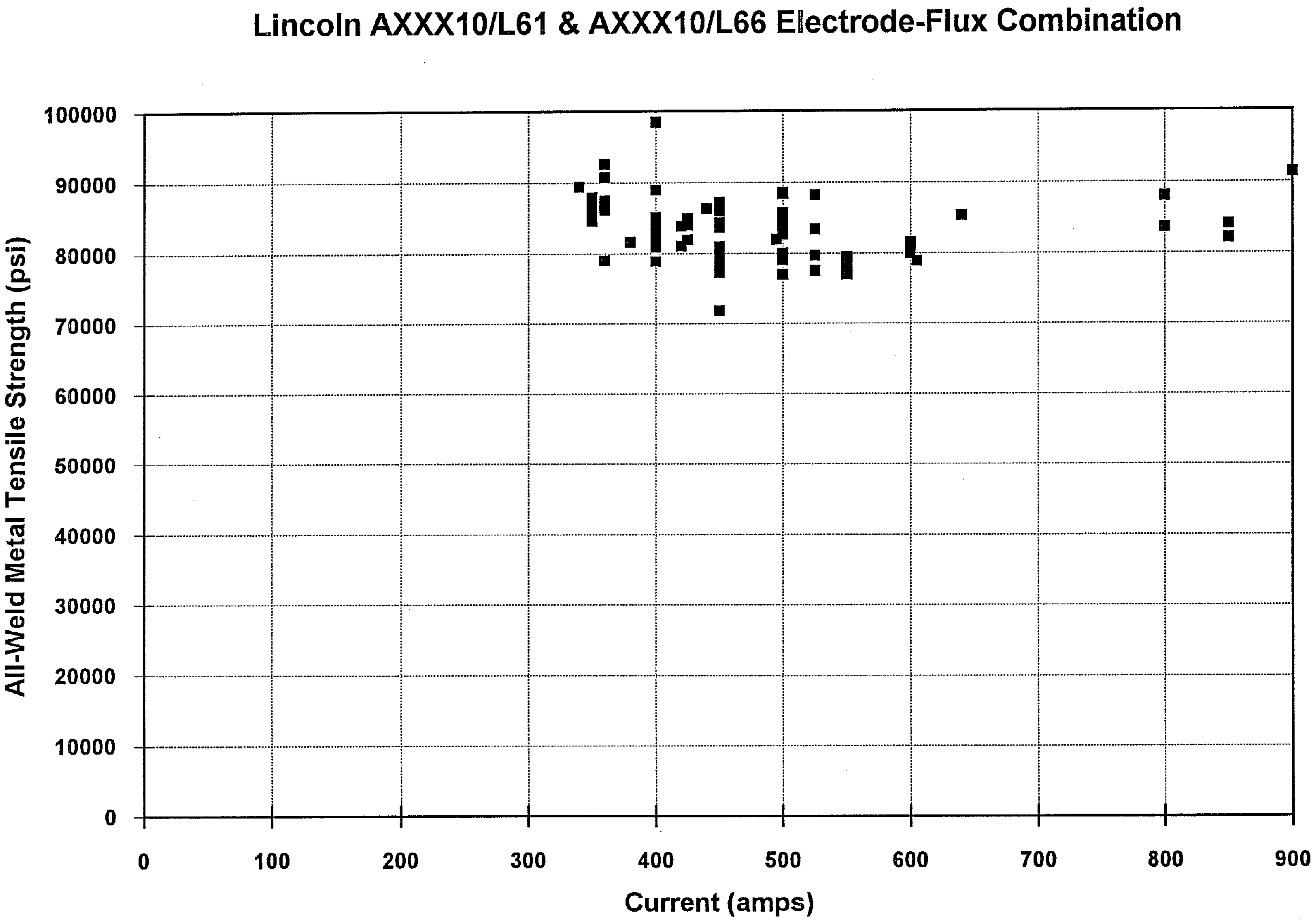


Figure 68 - All-weld tensile strength vs. current for Lincoln AXXX10 flux and L61 and L66 electrodes.

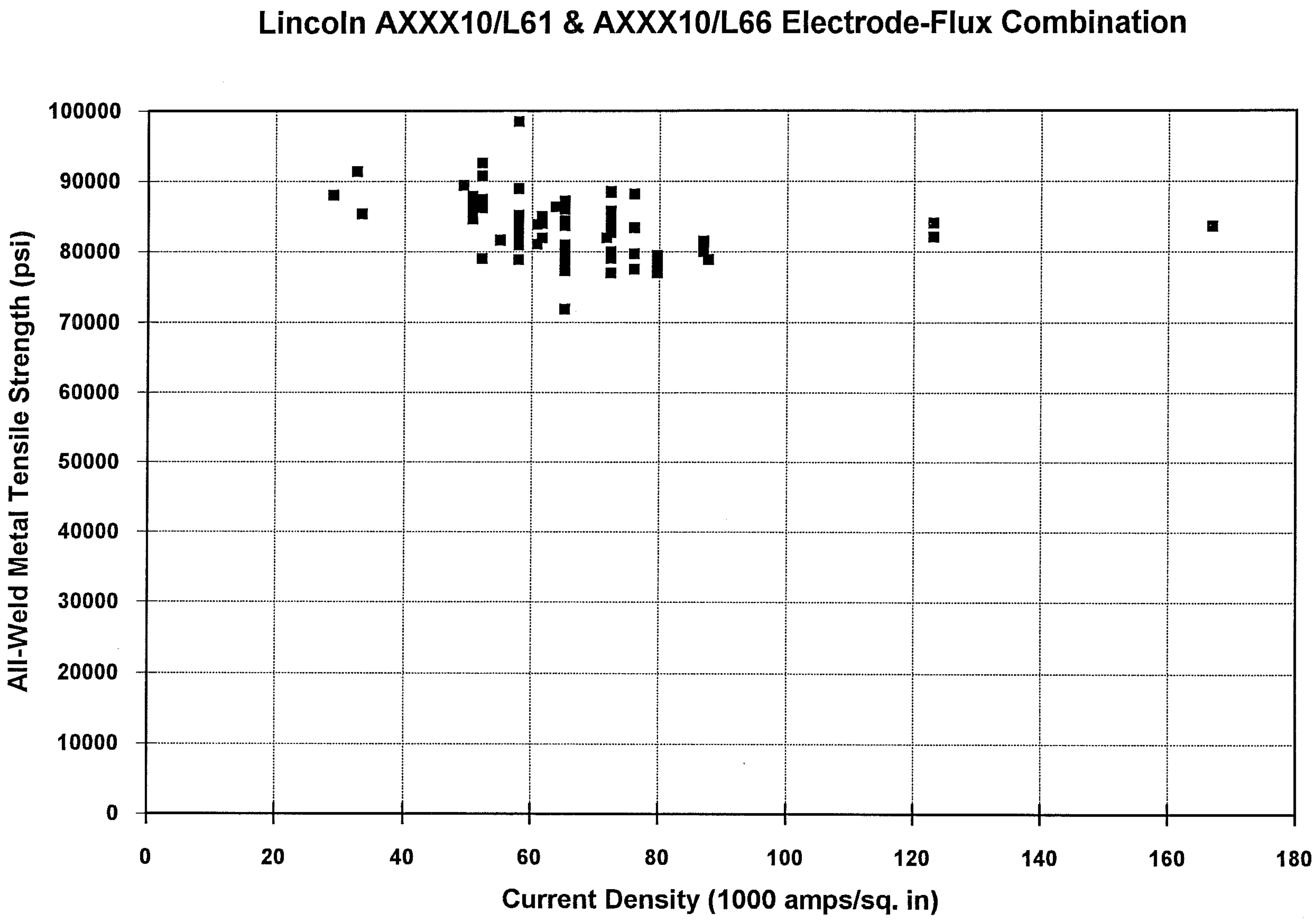


Figure 69 - All-weld tensile strength vs. current density for Lincoln AXXX10 flux and L61 and L66 electrodes.

In addition to these displays of a lack of an overall relationship between heat input and weld mechanical properties, instances were found where identical procedures performed by the same fabrication shop produced widely differing notch toughness and tensile strength values. In one particular instance, a number of welds made by the same fabricator in 1 inch thick A36 plate, using Lincoln 882 flux and L61 electrode operated with a heat input of 54 kJ/in and identical reported preheat and interpass temperature limits exhibited notch toughness averages ranging between 79.9 and 146.8 ft-lb. Obviously, the variables being currently reported do not suffice as a suitable controls of weld quality when cases such as these are considered.

If, indeed, the most significant factor determining the strength and toughness of a SAW weld is flux type rather than heat input, then a fabricator should be able to repeatedly produce welds with good mechanical properties by simply using the flux recommended by the manufacturer for the application. The question of which values to use for current, voltage, and travel speed then falls to ensuring that the weld penetrates sufficiently into the base metal and that the weld is free from physical defects. If a test weld is inspected and found to have adequate penetration into the base metal and is free of voids or inclusions which could affect the quality of the weld, the strength and toughness can be predicted within a reasonable range using manufacturer's data. It is important to note, though, that the actual production joint geometry may differ from the B-U2-S joint used for the test plates, and thus may not be as conducive to the formation of a good weld.

What the aforementioned strength and toughness range is, however, is not as clear. Lincoln test data from certificates of conformance give values of notch toughness which exhibit the same sort of mechanical property-flux type correlation as do fabricators' values from qualification tests, though as Table 3 shows, average toughnesses fabricators were able to obtain centered around 70% of Lincoln's. (Note: The data in Table 3 are only from -20 °F Charpy tests, and thus do not include all PQR's.) Individual fabricator test values range from about 20% to 130% of Lincoln's results. This spread is not a problem if the welds which fall in the lower end of the range still can meet the qualification standards of 20 ft-lb minimum at -20 °F for A36, A572 and A588 steels. For the most frequently used Lincoln fluxes, including the 800 series and AXXX10, meeting the 20 ft-lb minimum has not been a problem for the fabricators in the past. For the 700 and 900 series fluxes, not enough information was available to adequately determine the expected range of toughness values, though that evidence available shows that notch toughness for the 700 series may routinely fall below the 20 ft-lb minimum, regardless of technique. One caveat regarding the 700 series data, however, is that production welds using any active flux are restricted by the code to single- or two-pass welds, such that the multi-pass test procedure welds may not be indicative of actual production weld properties.

Table 4 gives minimum, average, and maximum heat input values used by fabricators in their procedure qualifications, as well as the Lincoln values used to obtain the toughness values given in Table 3 from certificates of conformance. The data in Table 4 show the wide range of heat input values which fabricators used, though overall, the average heat input values fabricators used were very close to Lincoln's.

Flux	Minimum Reported Average (ft-lb)	Fabricator Average Value (ft-lb)	Lincoln Average Value (ft-lb)	Ratio of Fab. Average to Lincoln Average	# of PQR's Represented
AXXX10	22.8	47.3	50	.95	35
761	3.4	13.1	35	.37	5
780	20.2	43.9	27	1.63	12
860	13.4	54.5	87	.63	61
865	28.8	58.6	53	1.10	16
882	16.5	83.1	108	.77	69
960	49.2	54.2	67	.81	3
980	18.6	18.6*	33	.56	1

* Data obtained from only one test series

Table 3 - -20 ° F Charpy notch toughness values from fabricators and from Lincoln Electric Company for Lincoln fluxes.

Flux	Minimum Fabricator Heat Input (kJ/in)	Average Fabricator Heat Input (kJ/in)	Maximum Fabricator Heat Input (kJ/in)	Lincoln Heat Input (kJ/in)	Ratio of Fab. Avg. to Lincoln Values
AXXX10	28.0	65.2	147	57.1	1.14
761	28.0	58.4	80.9	57.8	1.01
780	23.4	63.7	120	57.8	1.10
860	26.8	61.7	147	57.8	1.07
865	31.7	61.9	84.4	57.8	1.07
882	20.3	52.2	90.0	57.8	0.90
960	51.0	61.7	83.0	57.8	1.07
980	24.2	54.7	96.3	53.7	1.02

Table 4 - Heat inputs used by fabricators and Lincoln Electric with Lincoln fluxes.

To allow a procedure to become prequalified, that procedure must be able to consistently deliver adequate weld quality with a minimum of variability about the mean. Because there is no absolute guideline as to what is an acceptable variability, it was decided to compare the spread of values obtained from SAW procedures to the spread from SMAW procedures, which are normally prequalified. The database of SMAW procedures used for this comparison, which is shown in Table 5, was made up of qualifications performed under various FCM guidelines, since D1.5 allows SMAW procedures to be prequalified. That comparison reveals that there is no trend in difference in variance, which is standard deviation multipiled by the average, between processes for either notch toughness or tensile strength when all SAW procedures are considered, though SAW procedures with neutral fluxes, which in Table 5 is comprised only of Lincoln 800 series flux data, do show a noticeably lower variability in weld metal tensile strength. Overall, however, procedures using SMAW processes have significantly higher notch toughnesses and slightly higher tensile strengths than do SAW procedures. The reader should not be concerned about the mismatch in report numbers between the Charpy tests and tensile tests. The difference stems from the fact that some fabricators performed 0 ° F Charpy tests instead of the -20 ° F tests. Additionally, not all fabricator reports gave equal numbers of Charpy and tensile strength results.

	-20° F Charpy Notch Toughness			All Weld Metal Ultimate Tensile Strength		
	SMAW	SAW - All	SAW - Lincoln Neutral	SMAW	SAW - All	SAW - Lincoln Neutral
Mean	83.2	59.6	69.4	83,600	81,100	77,300
Standard Deviation	31.6	31.4	31.2	7,400	7,620	5,620
Variance	996	987	972	5.47×10^7	5.80×10^7	3.16×10^7
Number of Reports	70	246	167	72	364	310

Table 5 - Comparison of statistical strength and toughness values for SMAW and SAW test welds. "SAW - Lincoln Neutral" data considers only Lincoln 800 series fluxes.

From these observations, two stances could be taken on the idea of prequalifying SAW welds. First, it may be argued that because SAW procedures have a possibility of failing qualification by producing either too low a notch toughness or a tensile strength which is outside of the acceptable envelope, that qualification of SAW procedures continue as in the past with no revisions. The second argument uses the same evidence to arrive at the opposite conclusion, namely, that since some SAW procedures would fail qualification regardless of technique used, SAW procedures should be prequalified. This second view assumes that the same sort of variability which is found between tested welds will likely appear between the tested weld and the actual production weld made using that procedure, and that there is no known method of controlling that variability.

V. Conclusions and Recommendations

Given the overwhelming evidence linking flux type with weld mechanical properties, the most reasonable recommendation which can be made based on the evidence from this study is to allow welds made with Lincoln 800 series or AXXX10 fluxes and L61 electrode wire to be considered prequalified with some input variable limits for strength and toughness, while retaining the less costly workmanship related tests, including visual inspection, radiographic inspection, and side bend tests in place of the more extensive test battery now necessary. These three tests do not require the same level of machine work to be done to the test plate as do the tensile and Charpy tests, and would thus significantly reduce the cost to the fabricator. Because of the lack of data available to study failures due to workmanship, complete prequalification without any testing at all cannot be recommended.

Of all of the SAW procedures studied, about 70% used fluxes from the Lincoln 800 and AXXX10 series with L61 or L66 wire. This disproportionately large volume of procedures indicates two things: first, that fabricators would best benefit from the elimination of these fluxes from qualification; and second, that fabricators feel most confident using these fluxes for their welds. Because of the extensive experience which fabricators have using and qualifying welds with these fluxes, it can be said with confidence that they will be safe for use with reduced qualification requirements.

Because fluxes from the 700 and 900 series lacked data sufficient to determine whether they conform to the conclusions reached for the 800 and AXXX10 fluxes, it cannot yet be recommended that they be considered prequalified. Additionally, because the 700 series fluxes are active fluxes, a strong possibility does exist that a correlation between heat input and weld mechanical properties should be present which is not found in the 800 and AXXX10 fluxes.

Although the only flux series recommended for reduced qualification are the Lincoln 800 and AXXX10 fluxes, it would be desirable to give other manufacturers the opportunity to participate in this partial prequalification. This report cannot endorse the same reductions in qualification requirements for welds made with consumables from manufacturers other than Lincoln because of the relatively small numbers of procedures qualified using products from those manufacturers. If, however, others can demonstrate that their products are capable of achieving strength and toughness values equal to or better than Lincoln's, then their products should be allowed to considered prequalified as well.

The final step towards prequalifying welds made with Lincoln 800 series and AXXX10 fluxes used with Lincoln L61 electrode wire, as well as subsequent prequalification for other combinations, will be to determine what envelope of variable values should be allowed in production welds. Table 6 provides some statistical breakdown of the operator-controllable variables now limited by the code to show the range over which fabricators were able to operate and still qualify procedures using Lincoln 800 series and AXXX10 fluxes. Although this study has found no correlation between weld quality and any variable other than flux type, it would be imprudent to allow for operation outside of the tested data without any sort of controls or testing. When the determination is made as to the production limits, the actual values of the variables would then fall to the discretion of the fabricator, and would be limited by the ability to produce a weld with good penetration and workmanship.

One possible solution to this dilemma of finding an acceptable operating range is to revert somewhat to the provisions of the D1.1 code, wherein the consumable manufacturer is responsible for testing the strength of the welds and providing data for limiting production procedures. Under this plan, any manufacturer would be allowed to perform qualification tests similar to those outlined in D1.5-5.6.2, where maximum and minimum heat input values are used to produce a series of test welds to ensure that no undesirable effects appear at the extreme ends of the heat input scale. The full range of tests as prescribed under D1.5

would be performed on these welds, and only after displaying consistently good results would a manufacturer be able to approve the use of its consumables on a bridge structure without fabricator qualification other than for workmanship considerations.

Variable	Minimum	Maximum
Current (amps)	300	1000
Voltage (volts)	22	42
Travel Speed (in/min)	8	50
Heat Input (kJ/in)	20	147
Electrode Diameter (in)	5/64	3/16
Preheat Temperature (° F)	50	350
Interpass Temperature (° F)	50	950

Table 6 - Maximum and minimum values for input variables used with Lincoln 800 series and AXXX10 fluxes.

The envelope the manufacturer would approve would need to be limited by some target notch toughness and tensile strength averages which would allow a reasonable buffer above current code requirements, and which would ensure that production use of the consumables would form good quality welds in nearly all cases. Some suggestions for this target value might include:

1. Average SMAW values given in Table 5.
2. Overall average SAW values from Table 5.
3. Lincoln neutral SAW flux values from Table 5.
4. Typical SAW average values from independent research.

Alternatively, the fabricator might perform tests and specify the average achievable mechanical properties of his consumables using a given envelope. Market forces would then lead manufacturers to develop fluxes which can give higher strengths and toughnesses than his competitor's products.

This process, if properly implemented, would hold several advantages over the current D1.5 qualification process. First, it would greatly reduce the time and expense associated with weld qualification by requiring that the largest part of the testing procedure be performed once by the manufacturer, rather than by each shop. Second, it will encourage dissemination of data associated with the welding products from consumable manufacturer to fabricator, since fabricators would need to operate within boundaries established by the manufacturer. Finally, it will encourage product development, as manufacturers compete to make more versatile consumables which may be used over a wider operating range. Perhaps an added benefit of this plan would be an even greater expansion of the variable range on present products, as fabricators push the current limits to attempt to gain a competitive edge, leading to more flexibility in procedure specification.

The reader must be cautioned, however, that the findings of this study and the recommendation for partial prequalification is not a call to eliminate controls on welding variables. This recommendation merely acknowledges that these fluxes have worked consistently well with the techniques which fabricators are currently using. If a fabricator moves to a significantly different technique which does not fit with the data used in this study, if visual, radiographic, or side bend tests are suspicious, or if the fabricator is not experienced in producing welds using these consumables, then good judgement dictates that the fabricator run the full series of tests as prescribed by section 5.6 or 5.7 of D1.5 and to follow the guidelines of that section in making the production welds.

Once manufacturers have dictated the envelope for operation based on mechanical properties, fabricators must select the remaining values to give good workmanship characteristics to the weld. In order to give fabricators a range of values in which to operate based on the available database, it was thought that current density, which is:

$$CurrentDensity = \frac{Current}{(\pi/4)x(ElectrodeDiameter)^2} \quad (2)$$

would allow the fabricator to select a current range over which he should operate for a given electrode size. Data do not support using this relationship as a basis for selection of current, however, as fabricators did not choose current values based on a constant current density. On the contrary, as shown in Figure 70, fabricators tended to select lower current densities for larger electrodes.

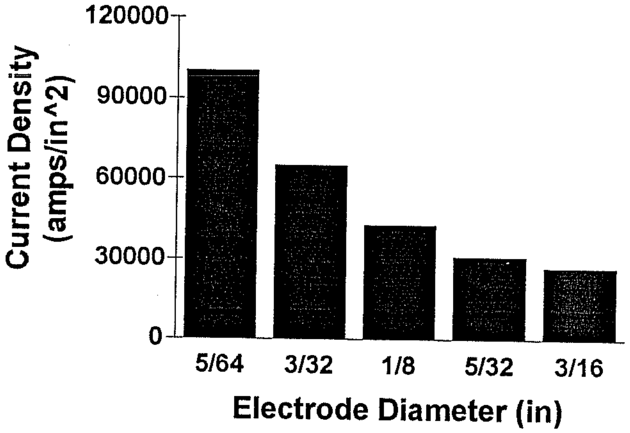


Figure 70 - Current density for each SAW electrode size.

Because of the trend of the current density-electrode diameter relationship, it was thought that a direct ratio between the two might provide a more constant value, even though this relationship has no physical meaning for an electrode with a round cross-section. If one considers this linear relationship between current and electrode size as shown in Figure 71, again data do not show a straight relationship, though the variability from a constant value is not as large in this case as it is for the current density relationship. Obviously, however, neither one of these criteria will suffice as guideline for limiting procedural variables.

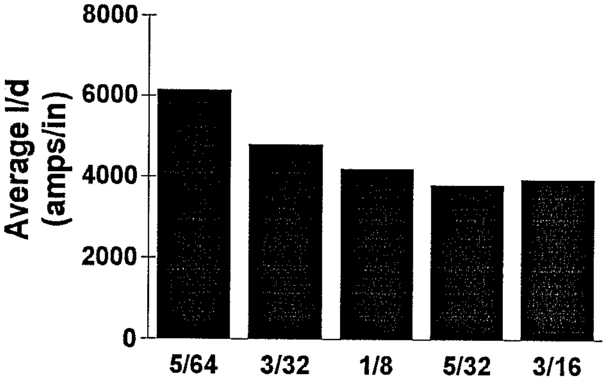


Figure 71 - Current-electrode diameter ratio for SAW electrode sizes.

Because no single variable arose as that which controls weld quality, fabricators should be encouraged to operate within the bounds found by this study as outlined in Table 6 even after prequalification takes effect. These values have been shown to produce welds which pass current qualification requirements, and therefore should be safe ranges of operation. Beyond any data presented here, though, the judgement of the welding engineer should be the foremost control on procedural variables.

For those procedures used on fracture critical members, which contributed 44% of all SAW qualifications investigated, it is would seem prudent for qualification and testing to remain as given in the codes simply to provide some assurance that workmanship problems do not go unnoticed. If, after implementation of a new qualification system for redundant members, the evidence shows that weld quality is not compromised and costs to fabricators are reduced, then a similar reduction of the testing requirements should be seriously considered for FCM's. Because nearly half of the data used for this study were from FCM qualifications, however, it is obvious that the more extensive tests required of non-redundant members do not reveal hidden effects on mechanical properties of the test weld which are not apparent from those tests conducted under D1.5.

The reduction of qualification requirements should not excuse one important fact, which is that none of the variables which were investigated in this study, which included all those currently controlled by the code, seem to provide the necessary correlation between welder effort and weld mechanical properties. Without this crucial link, there is little impetus for welders and welding engineers to control their work and to stick to specified operational values, which may eventually lead to compromised safety. With this warning stated, the next logical step in this investigation is to perform research wherein a systematic investigation of the effect of operator-controlled variables is conducted, such that the specific control or set of controls emerge. This particular study has suffered in many cases because of inadequacies of fabricators' reporting styles, inability to directly investigate the effect of variable manipulation, and the lack of a single source of data free of scatter due to human error. With these faults addressed, the "golden variable" may well show itself very readily.

Appendix

Statistical Overview of SAW Consumables

This appendix contains numerical data not directly relevant to one's understanding of the preceding material, but nonetheless valuable for those interested in the behavior of the consumables used by fabricators contributing to this study. It is intended to provide a reference which was not before available to those interested, but which, because of the scope of this study, is easily gleaned from the database which was assembled for the project. It is not meant as a recommendation of certain products over others, as each set of consumables is designed for specific uses. In case of any doubt, the manufacturer should be contacted for advice.

For those fields where information is left out (most often results from 0°F Charpy notch toughness tests), fabricators did not provide results for those tests. In addition, the reader should no be alarmed by seemingly inconsistent numbers of reports for the different consumable types, as some fabricators included either deficient or excessive information in their reports. Every effort has been made to include every applicable record, and no information was intentionally excluded.

Lincoln AXXX10/L61&L66	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	98500	71817	83400	1.78E+07	80
All-Weld Yield Strength (psi)	89200	58300	69700	3.75E+07	80
0 F Charpy Notch Toughness (ft-lb)	65.4	26.6	49	112	19
-20 F Charpy Notch Toughness (ft-lb)	83.6	22.8	47	221	42
Transverse Tensile Strength (psi)	92570	73948	84000	1.11E+07	98

Lincoln 761/L61	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	106001	82410	93600	5.46E+07	11
All-Weld Yield Strength (psi)	79719	63865	71300	3.16E+07	11
0 F Charpy Notch Toughness (ft-lb)	31.2	5.4	18	75	7
-20 F Charpy Notch Toughness (ft-lb)	22.4	3.4	13	78	5
Transverse Tensile Strength (psi)	95072	80100	87800	2.77E+07	18

Lincoln 780/L61	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	106700	80800	91800	5.06E+07	24
All-Weld Yield Strength (psi)	102500	63900	71300	7.47E+07	24
0 F Charpy Notch Toughness (ft-lb)	74	19.9	18	287	13
-20 F Charpy Notch Toughness (ft-lb)	131.2	20.2	44	1250	12
Transverse Tensile Strength (psi)	94592	67093	85100	3.25E+07	46

Lincoln 860/L61&L66	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	92700	68530	76200	2.03E+07	102
All-Weld Yield Strength (psi)	79600	51200	63400	3.35E+07	102
0 F Charpy Notch Toughness (ft-lb)	105.8	11.3	60	431	36
-20 F Charpy Notch Toughness (ft-lb)	145.4	13.4	55	563	71
Transverse Tensile Strength (psi)	94400	67500	80000	1.91E+07	216

Lincoln 860/LA-75	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	91701	82700	87700	1.38E+07	4
All-Weld Yield Strength (psi)	80423	74700	76500	7.27E+06	4
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	57.4	36.6	50	82	4
Transverse Tensile Strength (psi)	80856	79516	80200	4.91E+05	4

Lincoln 865/L61	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	92965	81840	88700	1.06E+07	20
All-Weld Yield Strength (psi)	98595	63731	81000	4.58E+07	20
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	72.8	N/A	1
-20 F Charpy Notch Toughness (ft-lb)	100.2	28.8	59	361	13
Transverse Tensile Strength (psi)	95476	80519	86200	2.41E+07	26

Lincoln 865/LA-75	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	97602	92772	95200	5.28E+06	4
All-Weld Yield Strength (psi)	90602	84211	87000	8.67E+06	4
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	75.6	37.2	55	279	4
Transverse Tensile Strength (psi)	94700	80929	86100	4.10E+07	6

Lincoln 880M/LA-75	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	83500	79000	82000	3.21E+06	5
All-Weld Yield Strength (psi)	72500	66000	68500	6.15E+06	5
0 F Charpy Notch Toughness (ft-lb)	113.2	86	100	187	3
-20 F Charpy Notch Toughness (ft-lb)	N/A	N/A	88.7	N/A	1
Transverse Tensile Strength (psi)	87600	76100	82600	1.13E+07	8

Lincoln 880M/LA-100	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	111300	109100	111000	1.54E+06	3
All-Weld Yield Strength (psi)	103800	98400	101000	8.25E+06	3
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
Transverse Tensile Strength (psi)	93300	91400	92300	4.66E+05	6

Lincoln 882/L61	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	103200	63100	76900	2.79E+07	124
All-Weld Yield Strength (psi)	83000	52600	64800	2.80E+07	123
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	168.4	16.5	83	1033	84
Transverse Tensile Strength (psi)	90150	70800	80100	2.03E+07	127

Lincoln 882/Ni 2	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	95700	80400	89900	2.75E+07	8
All-Weld Yield Strength (psi)	83800	72800	78300	1.59E+07	8
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	103.6	87.8	94	53	4
Transverse Tensile Strength (psi)	88500	84200	86300	1.77E+06	12

Lincoln 960/L61	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	82600	73000	79100	2.20E+07	6
All-Weld Yield Strength (psi)	68100	56900	63600	2.50E+07	6
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	62.6	49.2	54	54	3
Transverse Tensile Strength (psi)	80600	77100	78600	1.76E+06	6

Lincoln 980/L61	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	92500	79000	84000	4.06E+07	4
All-Weld Yield Strength (psi)	84200	62500	73300	1.05E+08	4
0 F Charpy Notch Toughness (ft-lb)	60.4	38.6	50	80	4
-20 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
Transverse Tensile Strength (psi)	89500	81000	84700	8.89E+06	8

Lincoln 980/LA-75	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	91000	83100	88400	6.34E+06	11
All-Weld Yield Strength (psi)	84000	73200	80200	1.26E+07	11
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	33	N/A	1
-20 F Charpy Notch Toughness (ft-lb)	41.3	25.8	36	36	5
Transverse Tensile Strength (psi)	87200	67000	76800	7.02E+07	12

L-Tec 429/81	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	86500	72465	80000	1.03E+07	49
All-Weld Yield Strength (psi)	80000	56300	66400	2.76E+07	49
0 F Charpy Notch Toughness (ft-lb)	77.4	22	55	419	6
-20 F Charpy Notch Toughness (ft-lb)	93.4	21.8	38	218	24
Transverse Tensile Strength (psi)	88500	71700	80300	1.59E+07	56

L-Tec 429/WS	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	93400	79700	85900	1.63E+07	14
All-Weld Yield Strength (psi)	83000	59900	71400	3.29E+07	14
0 F Charpy Notch Toughness (ft-lb)	46.2	24.4	34	89	5
-20 F Charpy Notch Toughness (ft-lb)	55.5	36.5	45	52	6
Transverse Tensile Strength (psi)	94000	80500	86700	1.82E+07	22

L-Tec 651VF/ENi4	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	92190	83940	88600	1.56E+07	4
All-Weld Yield Strength (psi)	83490	76145	80500	1.12E+07	4
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	77.8	49.4	64	403	2
Transverse Tensile Strength (psi)	93470	87050	90400	8.95E+06	4

Linde 585/36	High	Low	Mean	Variance	# of Reports
All-Weld Tensile Strength (psi)	86200	75100	80800	1.13E+07	19
All-Weld Yield Strength (psi)	77600	61200	69800	2.69E+07	19
0 F Charpy Notch Toughness (ft-lb)	N/A	N/A	N/A	N/A	N/A
-20 F Charpy Notch Toughness (ft-lb)	37.9	16.7	30	35	15
Transverse Tensile Strength (psi)	85100	77400	81100	5.00E+06	30