WELDING RESEARCH COUNCIL

of the Engineering Foundation

Sponsored by the American Welding Society and American Institute of Electrical Engineers
American Institute of Mining and Metallurgical Engineers, American Society of Civil Engineers
American Society of Mechanical Engineers, and Society of Naval Architects and Marine Engineers

Supplement to The Welding Journal, March, 1950

Preliminary Results of Welding-Peening Investigation

A preliminary report on a comprehensive investigation to evaluate each of the many variables involved in peening. New measuring tools and equipment have been developed

by J. Lyell Wilson

INTRODUCTION

THE application of peening as an adjunct to the welding procedure, in certain circumstances, is not new and is almost as old a practice as that of metal-arc welding itself. The use of peening in this art appears to have evolved in a more or less haphazard manner and to have been credited as a benefit principally because some joints which otherwise could not be completed in one piece were found to be possible of satisfactory completion when peening was introduced as part of the welding procedure for the problem joints. Since the tendency toward cracking during the welding process, especially under conditions of high restraint, was attributed to the effects of shrinkage, loosely referred to as residual stress, and because the use of peening minimized such cracking, the practice of peening was assumed to be beneficial in reducing residual stresses.

While there are instances, as with very heavy weldments having extremely high geometry restraint, where interpass peening did not prevent cracking, the practice of peening in general has been satisfactory in this respect. The theories evolved to explain why such benefits accrue from peening are as diverse as the techniques thereby recommended and even required. Such methods range from the two extremes, that of peening only the external weld passes, and that of peening only the internal passes. Other equally important factors, such as optimum temperature, size (weight) of hammer, size (weight) of tool, shape of tool and relative degree of "riding" the hammer, etc., have been less clearly defined or established than have the general procedures of the peening operations.

Whatever the reason may be for any observed beneficial effect of peening, however, at least one careful investigation disclosed that practically negligible differences in residual stresses resulted from the application of one recognized peening technique compared with that of an unpeened comparable sample.[1]

From these tests the conclusions drawn by the authors are summarized as follows:

1. In butt welds hot peening does not reduce residual stresses unless the last passes are peened.
2. The longitudinal residual stresses of welds may be reduced to less than 25,000 psi. by peening the weld after it has been completed and cooled nearly to ambient temperature. This procedure will not produce appreciable reduction of the transverse compression at the ends of the weld, or reduce the transverse tension in welds under transverse restraint.
3. Peening, to obtain maximum reduction (below 21,000 psi.) of longitudinal residual stresses, to reduce the transverse compression at the ends of welds or to reduce the transverse tension in welds having high-transverse restraint, must be applied to the weld and adjacent plate metal for at least 2 in. on either (both)

J. Lyell Wilson formerly Research Director, American Bureau of Shipping, New York, N. Y., is now a Consulting Naval Architect, New York.

Presented at Thirtieth Annual Meeting, A.W.S., Cleveland, Ohio, week of Oct. 17, 1949.

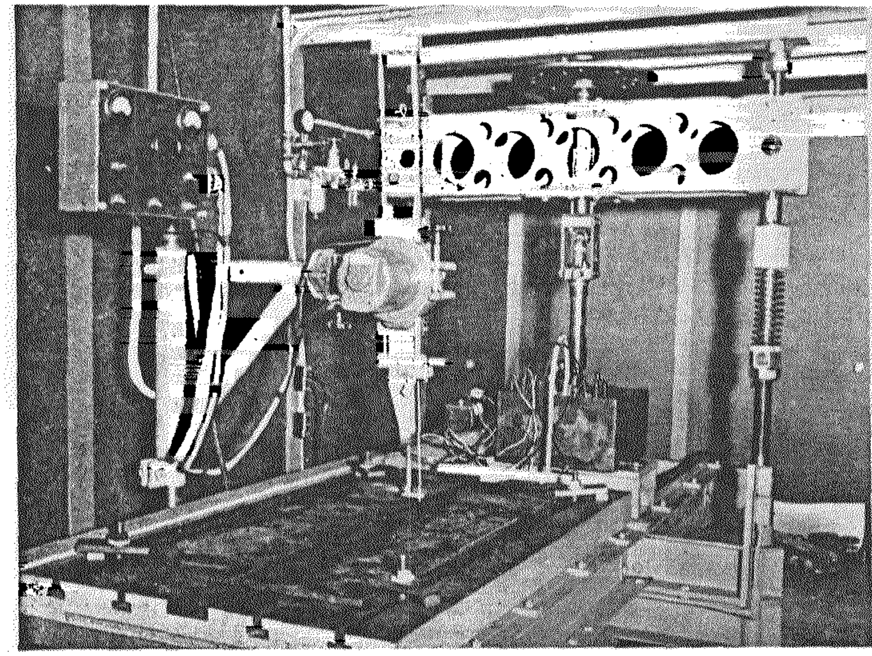

Fig. 1 Welding peening machine

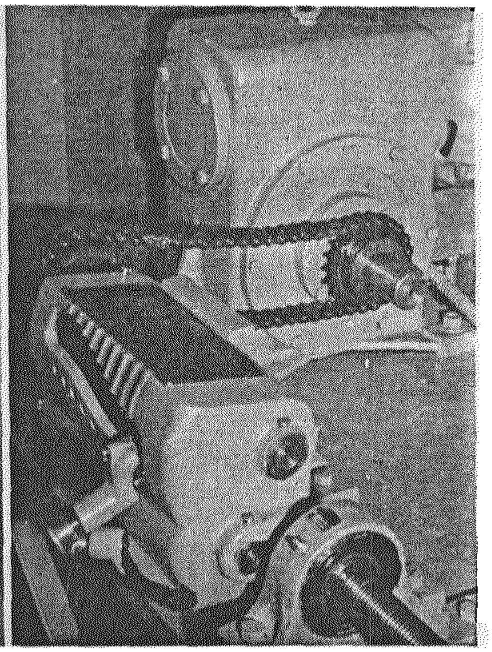

Fig. 2 Driving mechanism

side of the weld after it is completed and has cooled nearly to ambient temperature.

4. Deposition of the last passes of a weld after all stresses from previous passes have been eliminated will produce residual stresses of approximately the same magnitude as would have existed had no stress relief taken place on previous passes.

Such findings appear to be seriously contradictory to the theory upon which interpass peening was predicated. However, it should be noted that the implied major premise for this project was that residual stress is the sole criterion for the establishment of final quality. It is therefore a significant observation that the same investigators subsequently reported other findings in residual stress studies on ship plate panels and related structures which formed the principal foundation for the conclusion that residual stress, as such, had very little if anything to do with failures (i.e., were not a major cause for fracture). Under the circumstances it seems advisable to suggest that the peening problem may not be solved through a study of resultant residual stresses alone and that other criteria must be explored for a more complete picture.

In the aforementioned project every effort was made to attain good reproducibility which incidentally poses many difficult problems which have discouraged some investigators from pursuing the problem of peening. Apparently, however, the air pressure was controlled at between 95 to 105 psi. and the several air hammers ranged from 2300 to 5200 blows per minute. These characteristics are apparently manufacturers ratings. The rate of peening (tool travel) and the amount of loading (riding load) were controlled, as well as could be, manually and, since one standardized procedure was developed and used, sufficed for all practical purposes to produce relative values.

Although the results were not published in The Welding Journal until about 18 months later, an investigation was being carried out on weld peening at the University of Washington[2] almost concurrently with that previously mentioned at the University of California.

While further effort was made in this second study to develop a holding jig for the hammer for greater control and better reproducibility of peening, the criterion of residual stress (effect in stress relief) is specifically the major premise. Data regarding air pressure, hammer size and frequency of blows are not included but it is assumed that only one size of air hammer was used in this investigation. Some of the answers to the questions indicated as the scope of this second thesis must therefore be assumed to be based on academic reasoning. The conclusions are summarized as follows:

1. Cold peening is purely a surface-working effect. The depth of crystal deformation for a given tool will depend on the impact of the hammer and size and shape of tool. The larger hammer with greater impact

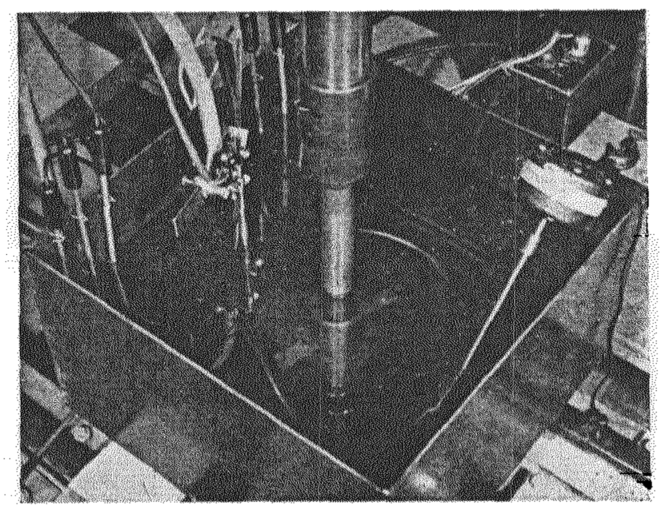

Fig. 3 Oil bath and jig

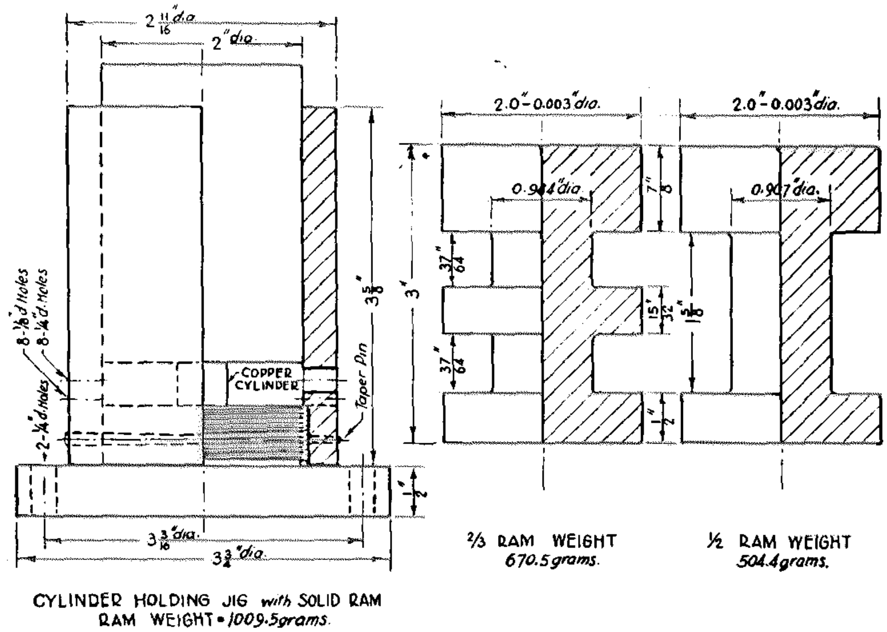

Figure 4

strength will produce more depth of indentation and plastic flow. A tool of smaller area in contact with the metal being peened will produce greater depth of plastic flow than one of larger area.

2. For field work using electrode sizes suitable for all-position application (E6010 Classification) peening to the extent of 1.5 min. per square inch of exposed bead area will give plastic flow and full stress relief with tools and hammer described in this paper. (It has been noted that the data regarding hammer and tools are not included in the published discussion.)

3. Flaking may serve as an indication for extent of peening. This condition appears to occur at the point where the weldment no longer responds to peening. No harmful effects from flaking were observed if subsequent passes were applied.

4. No appreciable reduction in ductility was observed. (It is assumed that ductility here refers only to the orthodox characteristic since only standard joint tests are mentioned in the text.)

5. Increasing or decreasing the "hold-on" pressure has no influence on the amount of work accomplished by a hammer, if the shoulder of the tool is, at the beginning of each stroke of the ram, properly engaged by the barrel of the hammer. This requires only a nominal amount of effort from the operator.

6. A small, spherically shaped peening tool will give more rapid crystal deformation than a larger tool which is more nearly flat on the face. It appears that where a very flat tool is used, the peening effect is superficial. A spherically shaped tool of smaller size will be conducive to greater indentation and deeper plastic flow.

Since the foregoing investigations were both based upon the same criterion, residual stress, and as previously stated because residual stress is now considered relatively of minor significance, it appears that the entire problem regarding the relative benefits and deleterious effects, if any, of the peening of welding remains to be solved. Even though we admit that peening appears to be desirable under some circumstances there is very little real evidence as to whether such peening results in effects of such nature as to balance or unbalance benefits and detriments, if both exist after peening. As indicated in the foregoing summary of two outstanding investigations into one phase of the problem there are at present two diametrically opposite conclusions derived from different techniques aimed in the same direction. On the one hand it is demonstrated that no appreciable change in residual stress results from peening except by a specific and unusual method and on the other hand it is stated as a result of comparable study that a generally accepted peening technique "will give plastic flow and full stress relief."

This sort of a situation merely emphasizes the fact that the effects of peening must be explored under conditions which will permit more accurate evaluation of not only those effects which more accurately reflect the most critical characteristics of the welded joint but also of the variable characteristics of the very pneumatic tools which are almost universally used for peening. Accordingly the American Bureau of Shipping proposed to the Welding Research Council that a welding-peening project be sponsored through the appropriate Committee along substantially the following lines.

Welding Research Council and American Bureau of Shipping—Welding-Peening Project

OBJECTIVES

At the very outset, the Peening Committee of the Welding Research Council decided that the following possible objectives of the investigation should be considered as the project developed:

1. Furnish scientific data as to the correctness of code requirements relative to the elimination of the peening of the first and last layers.

2. Information as to the variables of peening which might be used by codes as a matter of control.

3. Effect of peening on transition temperature of weld metal and the welded joint as a whole.

Within the scope of these objectives and by using automatically controlled welding and peening operations, it was proposed that the following principal variables should be explored:

(*a*) Size (weight) of hammer.

(*b*) Adjustment (stroke frequency) of air pressure.

Fig. 5 Typical cylinders

(*c*) Temperature (time) at which peening is applied.

(*d*) All variables, (*a*), (*b*) and (*c*) to be explored under two peening conditions, viz:

1. Peening all but first and last or the both outside layers of weld deposits.
2. Peening only the outside layers of weld deposits.

PROCEDURE

In order to carry out the objectives properly, the project was planned in three major phases, (1) the development of equipment and instrumentation, (2) the calibration and (3) the making and testing of samples. These three phases are outlined as follows:

Phase I

1. Development of mechanical equipment necessary for automatically controlling:
   (*a*) Ambient conditions.
   (*b*) All welding characteristics and operation.
   (*c*) Air pressures and timing.
   (*d*) All thermal conditions of samples being worked.
2. Development of a universal machine for the automatic operation in welding and peening.
3. Development and application of the instrumentation.

Phase II

1. Calibrate pneumatic hammers to establish relative energy levels with the following variables:
   (*a*) Three hammers, light, medium and heavy
   (*b*) Four air pressures, 60, 75, 90 and 105 psi.
   (*c*) Four riding loads, 0, 50, 100 and 150 lb.
2. The first series of calibrations was to be with copper cylinders (pure CCC electrolytic copper), 0.50 in. diameter by 0.425 in. length, which were completely annealed, quenched and pickled before being used. The basis for energy comparisons was to be the stress-strain measurement data of identical cylinders (3) calibrated in a standard tensile machine under compression.
3. For comparative purposes a second set of cylinders from the base or prime plate was to be similarly tested under the hammers.
4. A third set of cylinders from the weld metal was to be similarly tested.

Phases III and IV

When completed results of calibration are available, Phase III will comprise the work of preparing welded samples for peening under the various conditions considered appropriate as determined from a study of the calibration test results. Following these operations, Phase IV will include the cutting, preparation and the testing of the samples to determine transition temperature data and probably some of the following characteristic studies:

(*a*) Tension tests across joint

HAMMER	LOAD - LBS.	AIR PRESSURES									
		45 PSI.		60 PSI.		75 PSI.		90 PSI.		105 PSI.	
		NO.	COMP.	NO.	COMP.	NO.	COMP.	NO.	COMP.	NO.	COMP.
		COPPER CYLINDERS 0.425" lengths × 0.50" dias. AT 210° F OIL BATH									
LIGHT	0	2240		2526	0.129	2716	0.162	2856	0.183	3000	0.201
	50	2219		2455	0.114	2670	0.159	2785	0.190	3043	0.211
	100	2185		2445	0.117	2660	0.184	2804	0.193	2985	0.208
	150	2187		2442	0.136	2596	0.188	2797	0.202	2954	0.214
MEDIUM	0	1431		1643	0.146	1731	0.207	1816	0.235	1858	0.258
	50	1506		1731	0.148	1952	0.197	2096	0.225	2250	0.244
	100	1504		1720	0.142	1998	0.193	2190	0.222	2376	0.238
	150	1593		1789	0.153	1998	0.203	2211	0.220	2392	0.239
HEAVY	0				0.233		0.253		0.273		0.288
	50				0.233		0.266		0.278		0.284
	100				0.259		0.282		0.317		0.329
	150				0.244		0.275		0.314		0.309
		COPPER CYLINDERS 0.75" length × 0.75" dia. AT 210°F & 70°F OIL BATH									
MED	50	210°			0.080		0.126		0.173		0.181
	50	70°			0.086		0.124		0.154		0.187
		COPPER CYLINDERS 0.425" length × 0.50" dia. AT 70° F OIL BATH									
L	150								0.206		
M	0				0.130		0.196		0.229		0.233
H	100								0.262		
		PLATE & WELD METAL CYLINDERS 0.5" × 0.5" ALL AT 90 PSI.									
		MAT	TEMP.	WITH AS-ROLLED PLATE				WITH NORM. PLATE			
L	150	WELD	70°	VERT.	0.010	LONG.	0.003	VERT.	0.003	LONG.	0.005
M	0	WELD	70°	VERT.	0.046	LONG.	0.046	VERT.	0.042	LONG.	0.047
H	100	WELD	70°	VERT.	0.096	LONG.	0.090	VERT.	0.078	LONG.	0.140?
210°	90 PSI.	WELD	L-150*	L-.015	V-.011	M-0*	L-.045	V-.045	H-100*	L .082	V .074
L	150	PLATE	70°			LONG.	0.030			LONG.	0.036
H	100	PLATE	70°			LONG.	0.126			LONG.	0.110
		MAT.	TEMP.	WITH AS-ROLLED PLATE				WITH NORM. PLATE			
M	0	PLATE	210°	L-0.081		T-0.087	V-0.097	L-0.090		T-0.079	V-0.101
M	0	PLATE	70°	L-0.083		T-0.077	V-0.084	L-0.083		T-0.086	V-0.077

Fig. 6 Summary of data—averages of observed calibration values

(*b*) Tension tests of all-weld metal
(*c*) Guided bends
(*d*) Tukon hardness surveys
(*e*) Macro and micro studies

However, the purpose of the present paper is to describe the work carried out under Phases I and II and, in presenting the data derived from the calibration work of Phase II, indicate the factors which appear to

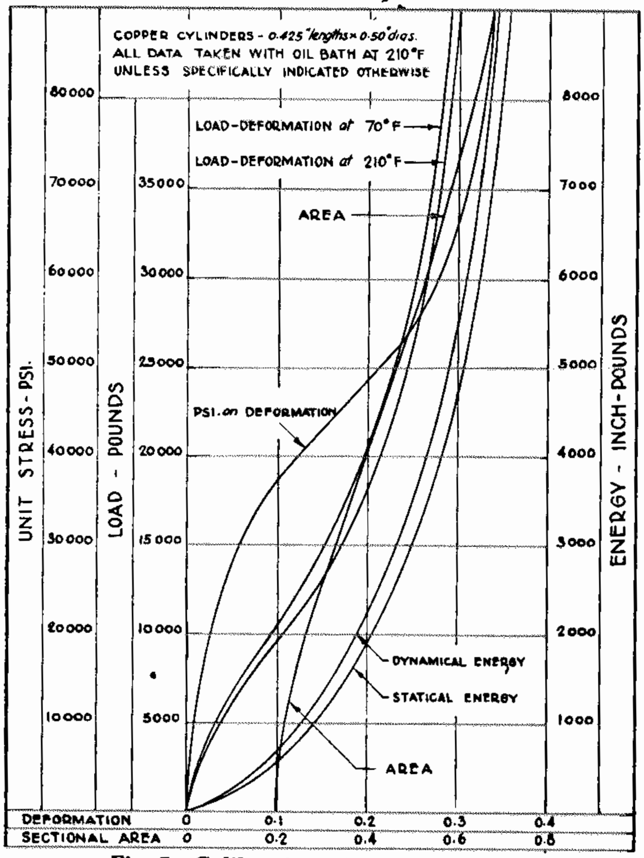

Fig. 7 Calibration of copper cylinders

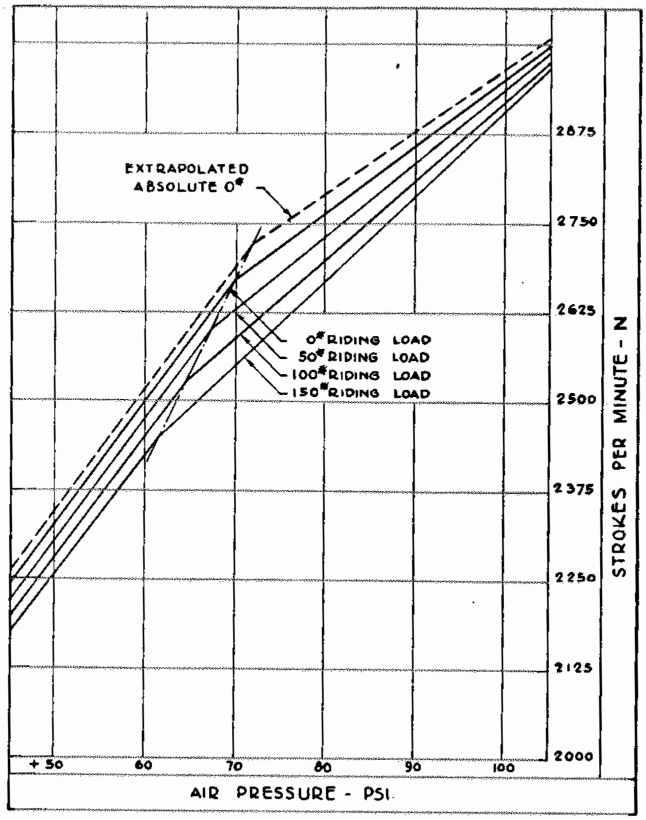

Fig. 9 Light hammer calibration

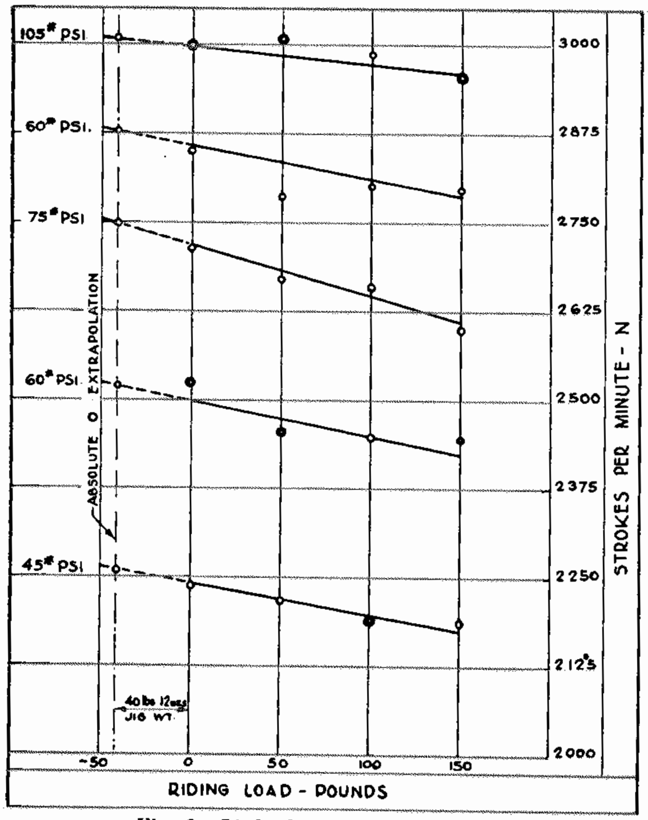

Fig. 8 Light hammer calibration

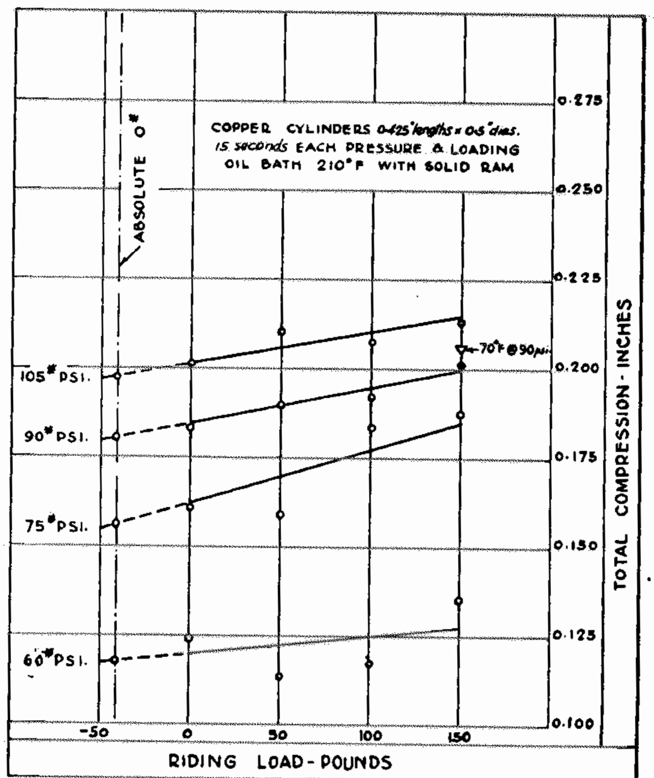

Fig. 10 Light hammer ca

contradict some previous findings and certainly to differ from certain preconceived ideas regarding the characteristics of pneumatic tool performance. The results thus far obtained seem to indicate that the careful approach to the establishment of fundamental factors as recommended by the Peening Committee is fully justified and what is more important that the application of peening to the welded joints should be fully explored perhaps even beyond the scope which has been blueprinted.

WELDING-PEENING EQUIPMENT

The development of mechanical equipment and of automatic controls was of necessity one over-all problem and was carried out as such. It included the construction of a special soundproofed room, thermally insulated, within the laboratory. This double-walled room, completely air conditioned, is sufficiently large to contain the operating machine with all necessary operating and control adjustment switch gear and valves while the compressor, control panel boxes, welding machine and similar equipment were located conveniently outside the special room.

In order to provide generous inertia, the welding-peening machine, intended to perform all welding and peening automatically, was constructed of relatively heavy members, as illustrated in Fig. 1. As completed, therefore, its total weight is approximately between $2^1/_2$ and 3 tons, the moving stage alone being 3000 lbs. This machine consists essentially of two heavy 8-in. wide flanged I-beams, 15 ft. long, on each of which is mounted and secured a miniature steel rail, accurately aligned and on which the heavy cast-iron stage rides very much as a planer.

This stage, slotted for securing the work samples, rides on six solid-steel roller wheels machined to fit the rail heads and its travel is actuated by a lead screw driven at the desired speed by means of a ratiomotor and screw-cutting gear box. With such change gears and drive mechanism, shown in Fig. 2, the speed of travel can be adjusted accurately to values within a range of from about $^1/_2$ to 24 in. per minute with not more than one sprocket change. The range of travel on the lead screw is about 11 ft. and since the stage is 5 ft. long the rails are fitted with mechanical stops in addition to limit switches.

By mounting the main 8-in. beams on top of three cross members of the same section, which in turn were each mounted on two spring-box vibration dampeners there is practically no vibration transmitted to the concrete floor. The most important result, however, is that the entire machine comprises a heavy mass with ample solidity as a foundation and yet one having no rigid attachments to anything outside of itself, even to the floor—it really floats on dampeners.

Uprights are attached to the machine by way of independent cross members hung to the main beams between those carrying the load to the floor mountings. As shown in Fig. 1, the cantilever support carries the adjustable bracket for the automatic welding head while the symmetrical pair of uprights act as guides to the floating cross box beam in the center of which the air hammer holding jig floats as a piston in a cylinder. The

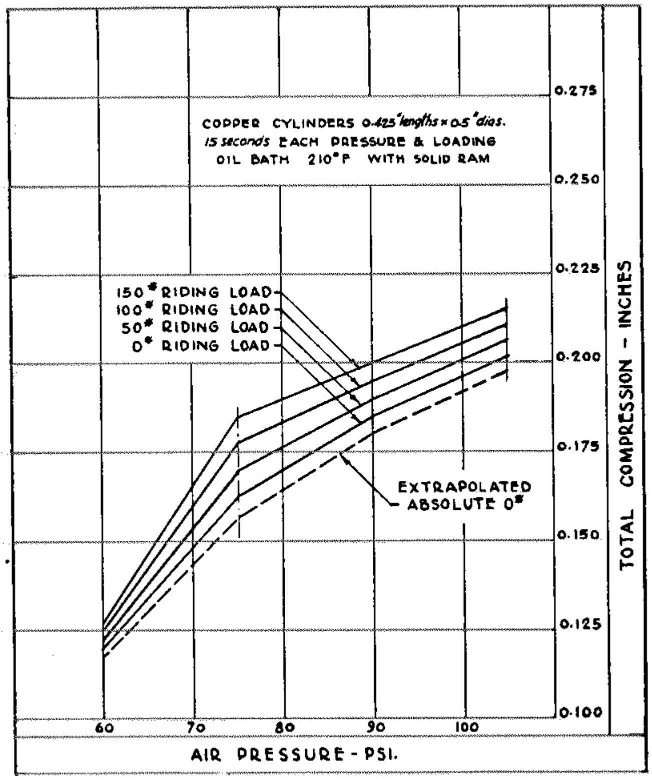

Fig. 11 Light hammer calibration

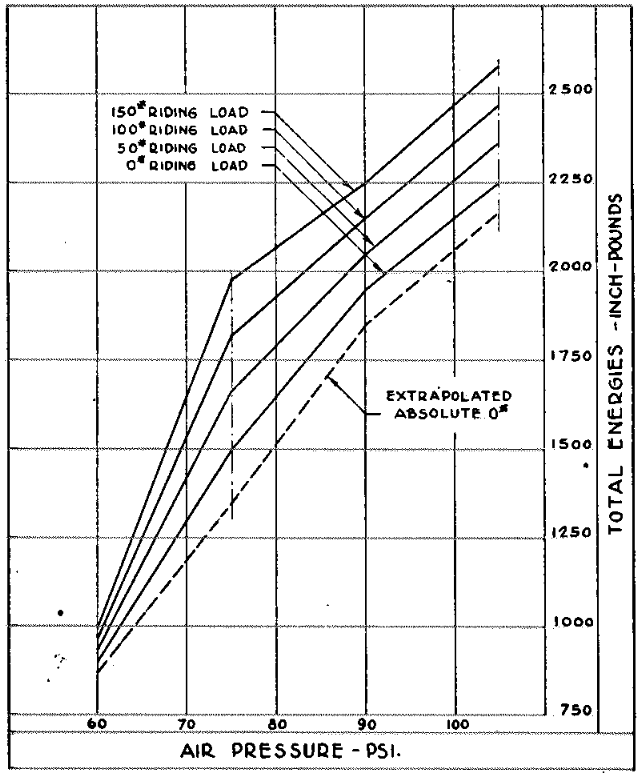

Fig. 12 Light hammer calibration

uprights are located 5 ft. apart and are each 5 ft. from the ends of the machine.

Each of the three air hammers is fitted with its own special clamp type yoke for attachment to the holding jig in such a manner as to permit the normal positions of the tool points to impinge at a common level when at rest. Two auxiliary slide rods are fitted on opposite sides of the holding jig's main stem acting as slide keys to keep the jig and hence the hammers from turning. Similarly each hammer is provided with a retainer for the tool and the tool blanks are specially socketed in square, hexagonal, etc., shapes to prevent turning.

The three air hammers with tool blanks and accessories, together with the electrically driven air compressor, storage tank and control equipment, have been furnished for use on the project through the generous cooperation of the Chicago Pneumatic Tool Co., and their assistance in this respect has been most valuable.

The compressor has a 10-hp. motor drive and just enough over capacity and air storage to keep the heavy hammer operating continuously. In order to minimize the noise in the laboratory the compressor equipment is located in the machinery room of the building and the air supply line is carried to a manifold in the project room. Included within this room at the manifold are the reducing valve, control valves, filters and gages together with the solenoid control valve used for actual operation, the hand throttle on each hammer being clamped in the fully open position.

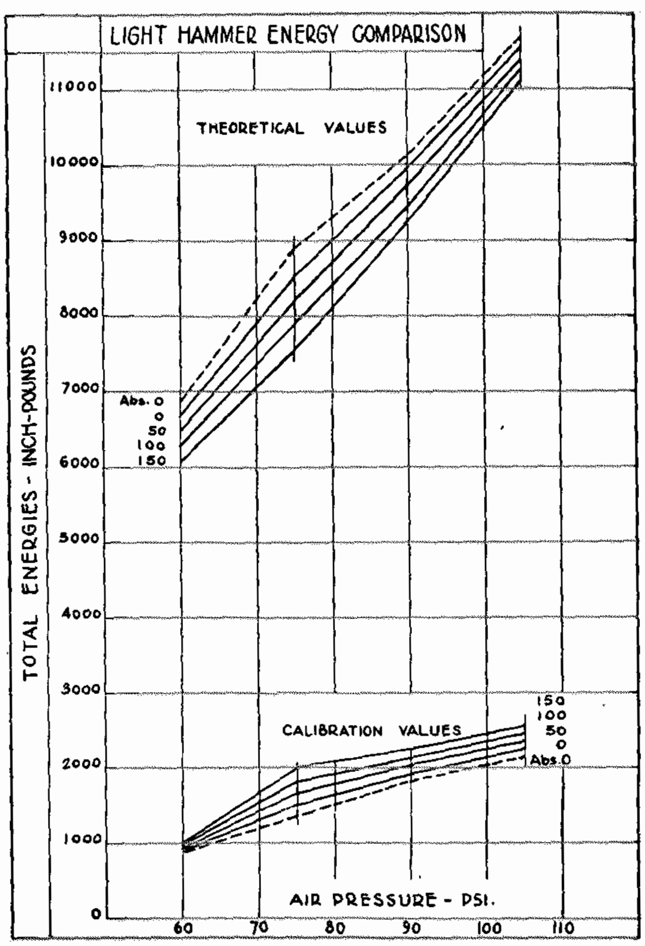

Fig. 13 Light hammer energy comparison

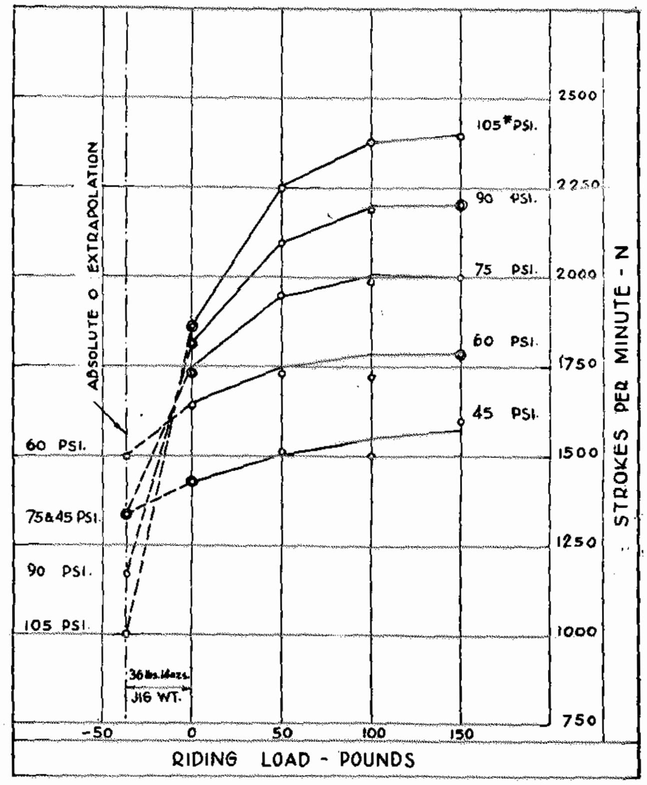

Fig. 14 Medium hammer calibration

Operation is controlled through the solenoid valve by way of an electrical timing switch so that the actual operation of the hammer may be timed accurately in seconds and with the most important feature of absolute reproducibility on timing. In order to minimize "over-riding" or coasting after the main solenoid stop valve closes, the rubber hose pendant to the hammer handle is as short as possible, the solenoid valve being mounted on the flange of the cross box beam near the hammer for this reason.

HAMMER STROKE FREQUENCY CALIBRATION

In order to determine the number of blows per minute for each of the three hammers, experiments were made with several different forms of pickups for registration on the oscilloscope. Interferences, in the form of outside pickups, were so troublesome with all of the induction coil arrangements that these were abandoned in favor of the electric-resistance-wire strain gages on the tool. By using two of these strain gages axially on opposite sides of the tool blank, clear well-defined blips could readily be seen on the oscilloscope screen. The dynamical type, high-resistance gages also permitted the application of impulses directly to the oscilloscope and simplified the hookup.

While the preliminary experimental phase of this particular calibration was very troublesome there were no problems with the strain gages in this application more unusual than the all too frequent fractures in the pigtail connections. However, there still remains a question, of not too great significance, with respect to just what the number indicated by the blip frequency on the scope screen really means. Naturally this was assumed to be the number of blows per minute, but because of the tremendous differences between the corresponding theoretical values of energy and those actually measured by calibration it seems more reasonable for the present to refer to these as the number of strokes per minute pending further review of these and the theoretical analysis. Since they must be multiples of blows per minute, whatever they are called, these numbers are listed in the tabular form of summary, Fig. 6, as numbers and are used in subsequent calculations as stroke frequency. However, as these values enter into calculations only for the theoretical energy output of the hammers their amount is of minor significance and effects only the relative efficiency of the hammer and the accessories used for applying the impact load.

Even a cursory review of the data shown in Fig. 6 will suffice to show that both air pressure and riding load have a considerable effect upon stroke frequency for all hammers and that this variation increases with hammer size. Considerations of this characteristic will be discussed subsequently, however, and for the present it should be noted that, contrary to assumptions previously held, the stroke frequency is definitely not constant and may be considerably less than commercial ratings when measured under actual working conditions carefully controlled.

In calibrating the hammers for stroke frequency, a substantial, heavy plate, box-girder type of anvil was fitted across and locked to the rails directly under the air hammers. The same anvil support also served a similar purpose in calibrating the hammers for energy output except that a tank for the oil bath was added as shown in Fig. 3. This oil bath tank was equipped with heating elements and circulating mechanism together with a cylindrical holding jig and plug piston type rams for holding the copper cylinders as illustrated by Fig. 4. The use of this latter equipment is described in the following discussion.

STATICAL ENERGY CALIBRATION WITH COPPER CYLINDERS

Using copper cylinders as "compression plugs" in ordinary static press calibration applications is not unusual but similar applications in the dynamical field have been somewhat limited to balistical studies or work of a similar nature where rather high-strain rates are involved. Since the purpose for the statical energy data in this project was to arrive at a proper base line on dynamical energy, existing data on such a relationship between statical and dynamical values was of paramount importance. Accordingly the information and references made available through physicists in both Navy and Army experimental work of this nature was of considerable value in the preliminary studies for this phase of the calibration work. While the work was not necessarily shortened thereby, it helped considerably to have comparable results not merely as check data but for the important relationship between "one-shot" impacts as compared with repeated cycles of much smaller impact loads of uniform value.

There were also minor problems in the initial stages of the statical calibration in the testing machine where much trouble resulted from the dimensional propor-

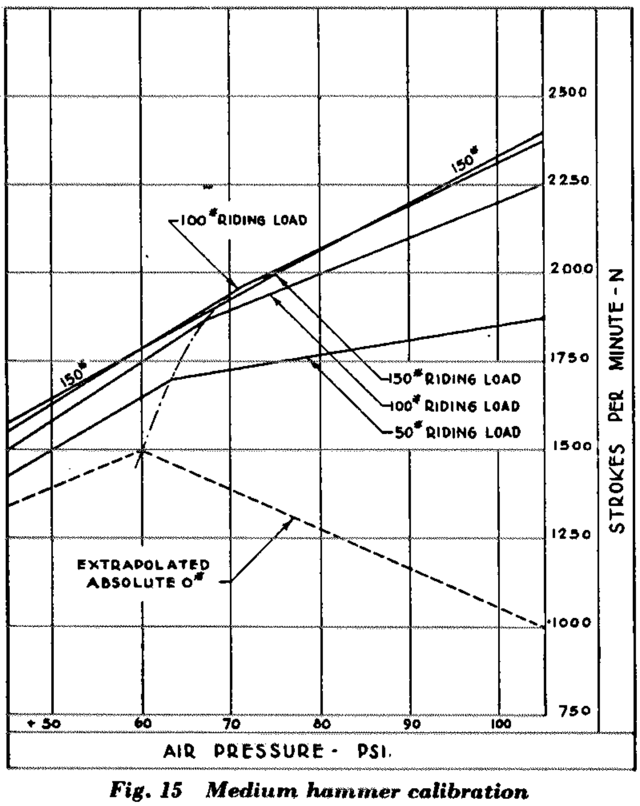

Fig. 15 Medium hammer calibration

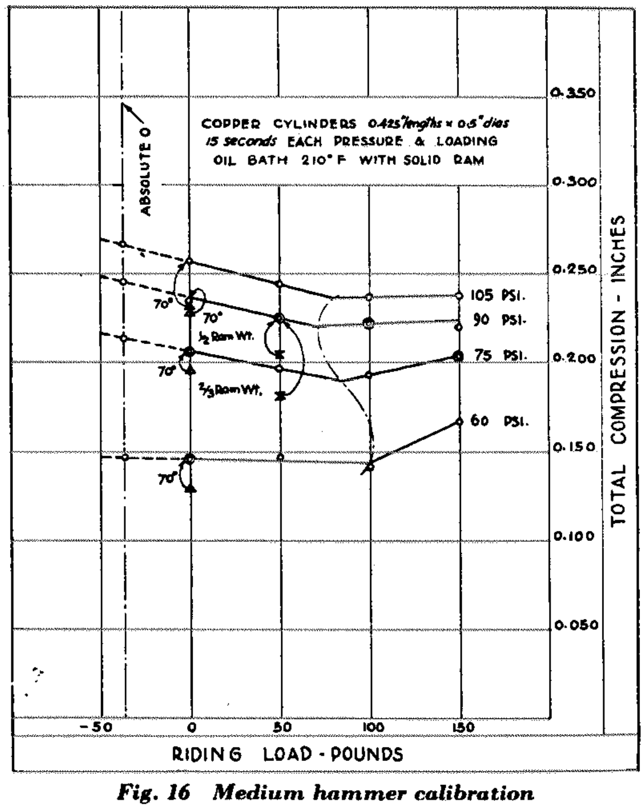

Fig. 16 Medium hammer calibration

tions of the copper cylinders. Careful checking confirmed the fact that the quality and grade of copper, the annealing, quenching, pickling and temperature control during compression, were satisfactory but the results were not. The characteristic curves derived from stress-strain data seemed appropriate and comparable with previous findings but the "Tower of Pisa" look of the cylinders after compression indicated a possible slip discrepancy on final deformation. Finally, by changing the length of the cylinders to about half the former amount (1.00 to 0.425 in.), thereby conforming more closely to proportions used in other investigations, the ultimate results were quite normal in both appearance and as technical data.

Copper cylinders were machined from pure electrolytic copper (CCC grade) to a final length of 0.425 ± 0.0005 in. and to a diameter of 0.50 ± 0.0005 in. All of the copper bar stock was furnished by the American Brass Co. through the courtesy of John R. Freeman, Jr., Technical Manager, and it is of stock commercially known as hard-drawn electrolytic tough pitch copper rod. To insure proper bearing surfaces the ends of the cylinders were ground parallel in a special jig to the final dimensions. All copper cylinders were annealed in an electrically heated furnace at a temperature of 1150° F. The temperature was maintained for 1 hr. and the cylinders were then quenched in water at 100° F. and finally pickled.

An oil bath was provided during testing to hold the temperature of the copper to a minimum of 200° F. in order to avoid as much work hardening as possible. A light gage mild-steel square container having a heavy bottom plate was used for the oil bath. This was fitted with a hardened steel block in the bottom center and the block contained a ground, slightly oversize, center depression to keep the copper cylinders from slipping out of an approximately central position. The same oil bath container, as previously mentioned and as shown in Fig. 3, was also used for the dynamical calibration under the hammers. It will be seen that this container is also fitted with an electrical thermostat control in the heater circuit and an agitator.

After the load-deformation data, shown in Fig. 7, were carefully checked several times with different cylinders, with practically identical results, the statical calibration was considered satisfactory and, through comparison with comparable independent data, it was felt that the procedure must also be correct up to this point. The equipment was therefore set up under the hammer station in a similar manner for the dynamical work.

DYNAMICAL ENERGY CALIBRATION WITH COPPER CYLINDERS

The same procedure was then followed with copper cylinders under the hammers except that it became necessary under dynamical conditions to prevent the displacement of the cylinders which otherwise became distorted and useless. The tool of an air hammer is perhaps the most difficult thing to control in precision work and it was considered impossible to confine the tool as by guides because of the uncertain friction thereby introduced. Accordingly, within the oil bath a cylindrical holding jig, illustrated in Fig. 4, was developed with several different weights of piston-like rams. This latter feature was introduced in an effort to detect any effect from the ram mass between the tool

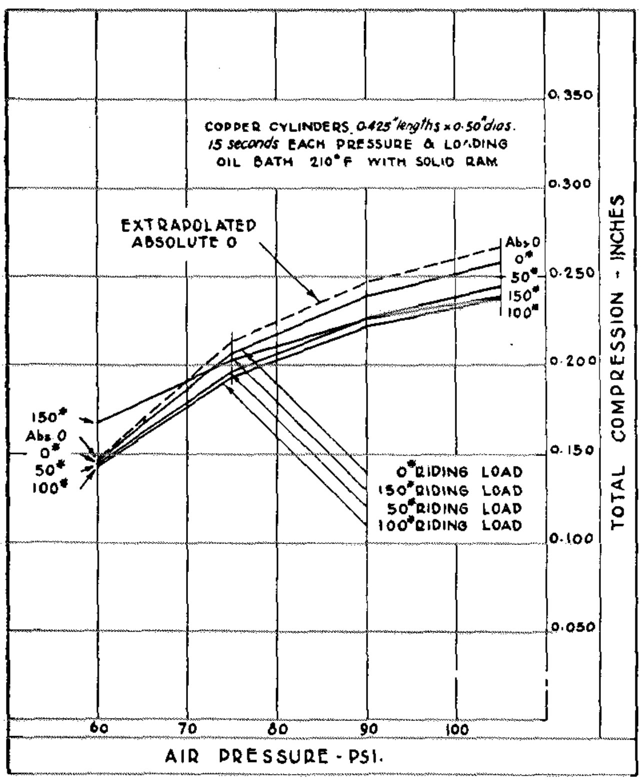

Fig. 17 Medium hammer calibration

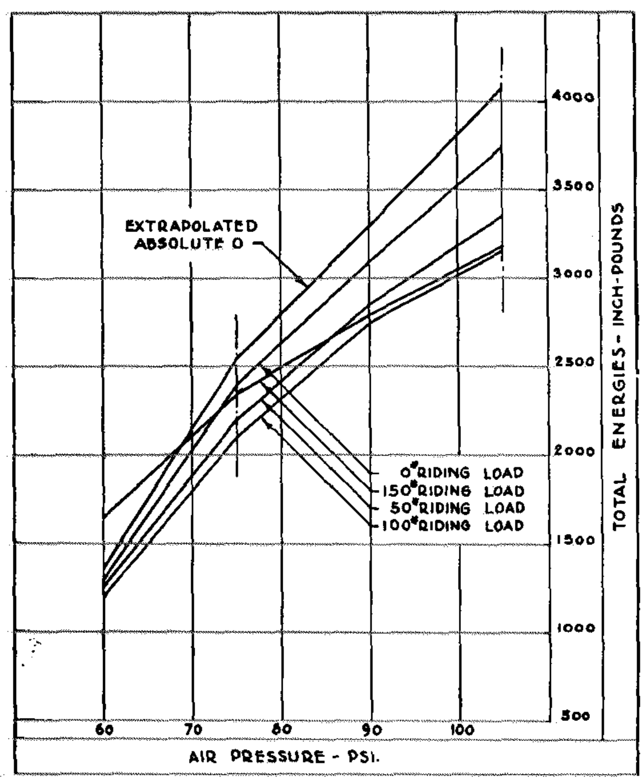

Fig. 18 Medium hammer calibration

and the copper. The cylindrical shell was relieved by holes drilled in the sides at the bottom to allow for free flowing of the oil. By means of this holding arrangement it was possible to compress the cylinders (copper) quite readily without any appreciable (measureable) distortion or marking by impact of the cylinder ends so that it was comparatively easy to make accurate micrometer measurements. An enlarged photograph, Fig. 5, illustrates the two typical extremes of resulting shapes. A brief discussion of these contrasting results, which are of no serious significance, is included in reference 3 of the bibliography.

All parts of the cylindrical holding jig were hardened after machining and ground for accuracy. The hardness values aimed for were the same as those found for the tool blanks. Check hardness readings for the copper indicate that practically all work hardening occurs at the first pressure or stroke, is nearly all surface effect and is comparable in both statical and dynamical conditions. However, the most important check on the results obtained is that furnished by comparison with other data from the most reliable sources.

Outstanding among available data seems to be that by E. T. Habib, Physicist, David Taylor Model Basin, Navy Dept., Washington, D. C.,[3] and the one major difference between that work and the peening project is that the impact in the former is furnished by one single blow while in the peening it is by a large number of repeated blows. Since the data check very well indeed it appears reasonable to conclude that within the range of values explored there is no appreciable difference in total energy effect as between comparable energies delivered by single blows and by uniform repeated blows.

The relationship between statical and dynamical energy values, as shown in Fig. 7, corresponds to that derived from Habib's work at the appropriate strain rate which in the case of the air hammers averages not more than the lowest values used in the ballistic studies. In an over-all sense this ratio of dynamical to statical energy averages about 1.175 and appears to be fairly constant within the range of values pertinent to the peening study.

RESUME OF DATA

I. Hammers—Chicago Pneumatic Tool Co.

(a) Yoke, same for all hammers, 21 lb. 2 oz. weight

(b) No. 1, heavy, mfrs. designation, No. 60 large hammer

Weights:

No. 1 hammer (including piston)	26 lb. 2 1/2 oz.
Holder clamp	12 lb. 6 1/2 oz.
Tool blank	6 lb. 2 1/2 oz.
Piston (274.2 gm.)	0.604 lb.

Dimensions of piston and stroke:

Piston length	2.5075 in.
Piston diameter	1.061 in.
Piston stroke	6.00 in.
Manufacturer's BPM*	1340 at 90 psi.

(c) No. 2, medium, mfrs. designation, CP 411

Weights:

No. 2 hammer (including piston)	18 lb. 0 oz.
Holder clamp	15 lb. 12 oz.
Tool blank	1 lb. 13 oz.
Piston (stepped—446.9 gm.)	0.985 lb.

* Blows per minute.

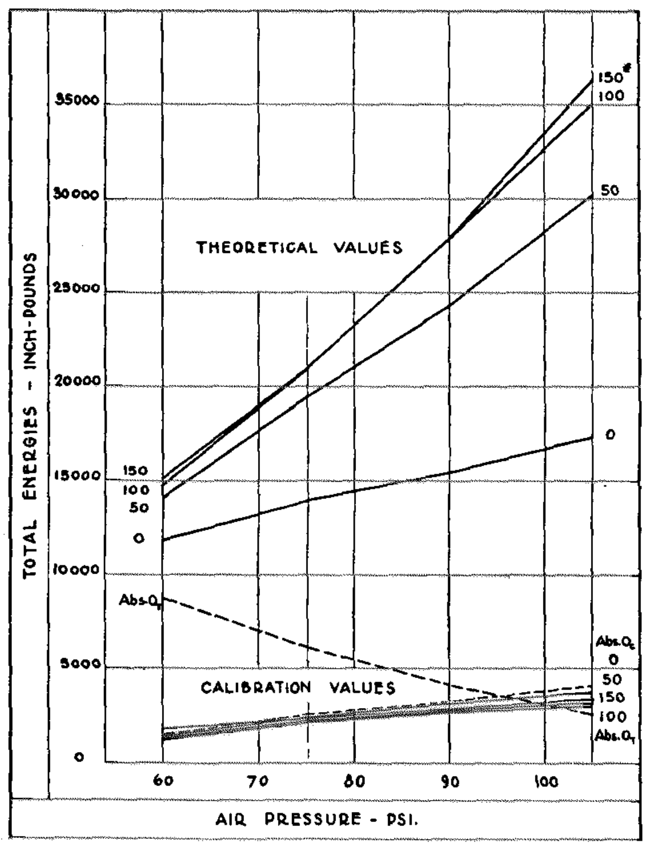

Fig. 19 Medium hammer energy comparison

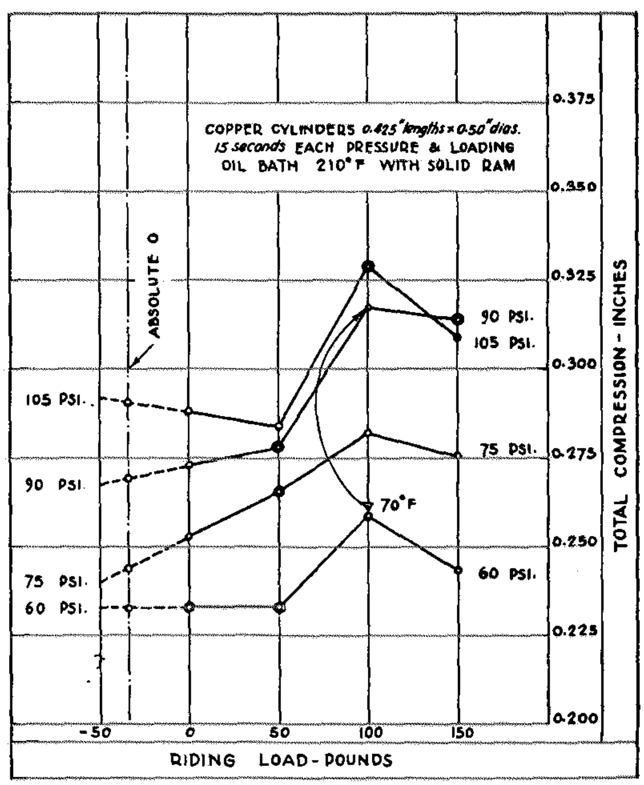

Fig. 20 Heavy hammer calibration

Dimensions of piston and stroke:

Piston length	5.625 in.
Piston diameter	1.124 and 0.810 in.
Piston stroke	1.25 in.
Manufacturer's BPM	3150 at 90 psi.

(*d*) No. 3, light, mfrs. designation, No. 1 chipping hammer

Weights:

No. 3 hammer (including piston)	13 lb. 14½ oz.
Holding clamp	19 lb. 10 oz.
Tool blank	2 lb. 3 oz.
Piston (226.4 gm.)	0.496 lb.

Dimensions of piston and stroke:

Piston length	1.979 in.
Piston diameter	1.123 in.
Piston stroke	2.250 in.
Manufacturer's BPM	3050 at 90 psi.

II. Oil Bath Cylindrical Holder and Rams, see Fig. 4.

III. Theoretical Energy Analysis.[4]

$$E \text{ per stroke} = \frac{\overset{\#}{Wp}}{2g}\left(\frac{S'' \times \text{BPM}}{185}\right)^2 \times 12 \text{ in in.-lb.}$$

$$E \text{ per 15 sec.} = \frac{\overset{\#}{Wp}}{2g}\left(\frac{S'' \times \text{BPM}}{185}\right)^2 \times 12 \times \frac{\text{BPM}}{4} \text{ in in.-lb.}$$

$$= \text{for No. 1 heavy hammer } \frac{\text{BPM}^3}{33{,}750} \text{ in.-lb.}$$

$$= \text{for No. 2 medium hammer } \frac{\text{BPM}^3}{475{,}000} \text{ in.-lb.}$$

$$= \text{for No. 3 light hammer } \frac{\text{BPM}^3}{293{,}000} \text{ in.-lb.}$$

IV. Stroke Frequency of Hammers, see columns indicated as "No." in the tabular Summary of Data, Fig. 6.

(*a*) The values of stroke frequency (N) are plotted and cross-faired as follows:

1. Light hammer No. 3.
   N plotted on riding load, Fig. 8.
   N plotted on air pressure, Fig. 9.
2. Medium hammer No. 2.
   N plotted on riding load, Fig. 14.

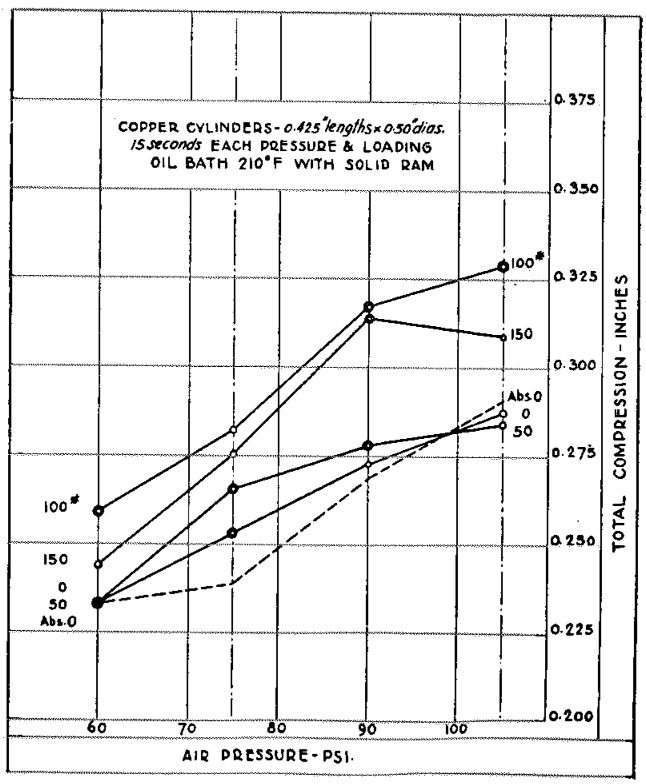

Fig. 21 Heavy hammer calibration

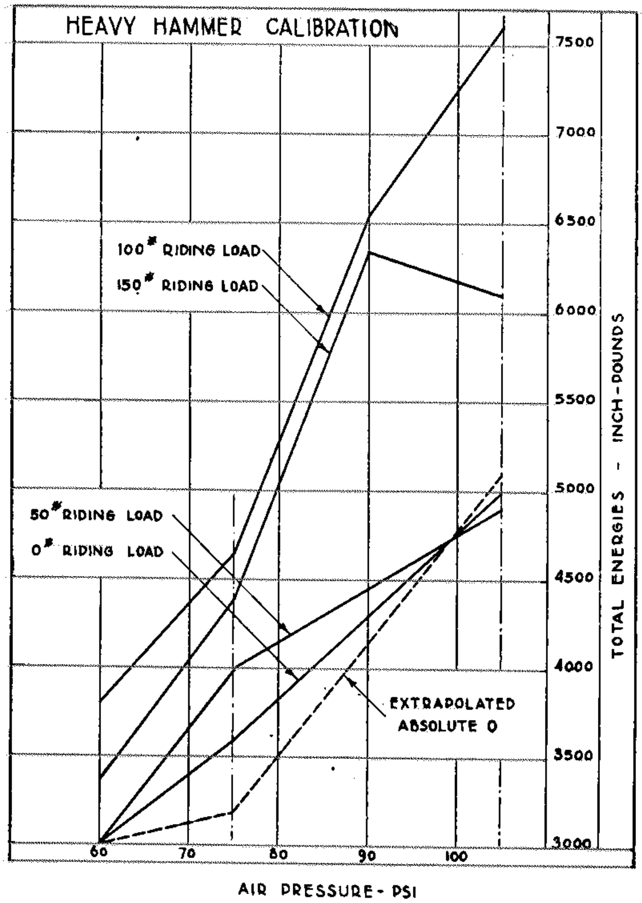

Fig. 22 Heavy hammer calibration

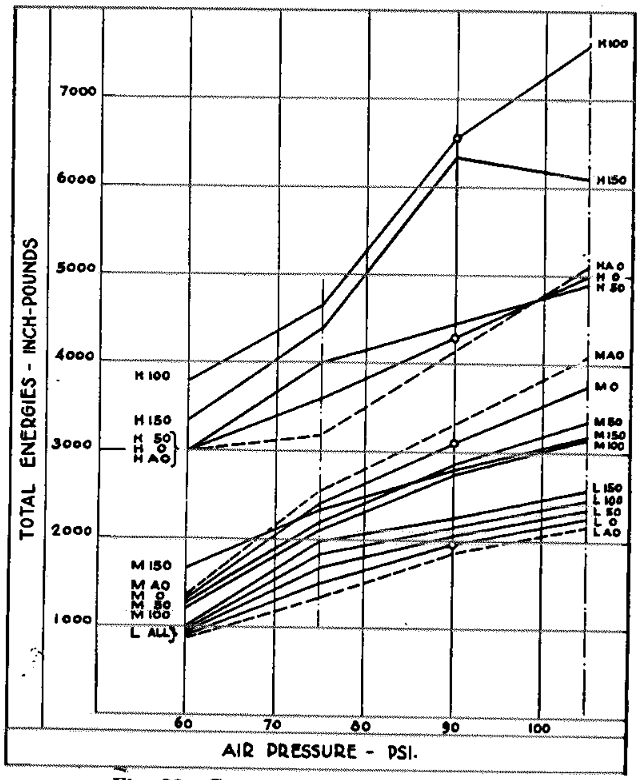

Fig. 23 Complete energy comparison

N plotted on air pressure, Fig. 15.

3. Heavy hammer No. 1, not yet available but may be added as supplementary data.

V. Compression Values for Copper Cylinders (15 sec.), see columns indicated as "comp." total compression in inches in the tabular Summary of Data, Fig. 6.

(*a*) The values of total compression are similarly plotted and cross-faired as follows:

1. Light hammer No. 3.
   Total compression on riding load, Fig. 10.
   Total compression on air pressure, Fig. 11.
2. Medium hammer No. 2.
   Total compression on riding load, Fig. 16.
   Total compression on air pressure, Fig. 17.
3. Heavy hammer No. 1.
   Total compression on riding load, Fig. 20.
   Total compression on air pressure, Fig. 21.

VI. Total Energies from 15 Sec. Hammer Operation.

(*a*) Converted from dynamical energy curve shown in fundamental data, Fig. 7

(*b*) The values of total energy are plotted for each hammer as follows:

1. Light hammer No. 3, Fig. 12.
2. Medium hammer No. 2, Fig. 18.
3. Heavy hammer No. 1, Fig. 22.

VII. Complete Energy Comparison for all three hammers under all conditions of loading and air pressures are shown in Fig. 23.

SUMMARY OF FINDINGS

As previously intimated the data for the several hammers used in this project demonstrate the fact that "riding load" has a marked effect upon the hammer performance characteristics. In certain conditions "riding load" has an effect comparable with that resulting from varying air pressure. Generally, however, air pressure is the major factor in hammer performance and the accurate control of air pressure is an important essential for all such studies.

The relationship between the masses of hammer, piston and riding load is significant as a factor. For the present it is assumed that apparent reversals of effect between hammers may therefore be found related through characteristics dependent upon synchronous or natural frequencies of the hammer systems, i.e., masses of hammer, piston and riding load. The mass of the ram in the cylindrical holding jig seems not to be significant.

From observation the body of the hammer seems to work as well as the piston the impact being received at the shoulder on the tool blank. All previous statements contradict this observation, however, and it should be observed that theoretical energies are far in excess of actual values. However infinitesimal such blows from the hammer body may be, it is this possibility that leads to the assumption that stroke frequency is a multiple of the oscilloscope screen indications rather than a direct reading. The point is of minor significance, however, because of the fact that hammer preformance efficiency is not being studied since it does not yet seem to be a factor.

The primary purpose of this phase of the project was to verify the effects of riding load and air pressure as applied to the several hammers of known characteristics, and finally to establish by calibration an appropriate energy baseline for the hammers and thus have fairly accurate pilot conditions for peening the welded joint. For the present therefore, it appears that such values have been established rather clearly and the choice might appropriately be those suggested by the circled points on the 90 psi. ordinate and the corresponding curves of the Complete Energy Comparison shown in Fig. 23. In other words, if all three hammers are used at 90 psi. and with 0 riding load (no weight added) the respective total energies for 15 secs. of operation would be:

Light hammer, in.-lbs.	1950
Medium hammer, in.-lbs.	3100
Heavy hammer, in.-lbs.	4300

A further check value for the fourth set would be with the heavy hammer at 90 psi. and 100 lbs. riding load with a 15 secs. energy total of 6567 in.-lbs.

APPRECIATION

It is possible to express grateful appreciation only in group fashion to so numerous a group of friends and associates who have generously helped in this effort with advice and counsel. At the same time it is felt that the infinite patience and helpful collaboration should be specifically acknowledged to the author's colleagues on the laboratory staff of the American Bureau of Shipping, also the helpful cooperation of the Bureau's executive staff and the painstaking and continuous interest and helpful consideration of members of the Peening Committee of the Welding Research Council, Leon C. Bibber, Chairman, William Bunn, Clarence E. Jackson, Dr. Robert D. Stout and, especially, William Spraragen.

Bibliography

1. De Garmo, E. Paul, Jonassen, Finn, and Meriam, J. L., "The Effect of Peening upon Residual Welding Stresses." Paper presented at the Annual Meeting, AMERICAN WELDING SOCIETY, November 1946, and published in THE WELDING JOURNAL, 25 (10), Research Suppl., 616-s to 623-s (1946).
2. Morris, Joe Lawrence, "Extent of Peening Weld Deposits for Stress Relief," thesis in the Department of Mechanical Engineering, University of Washington, 1946, and published in THE WELDING JOURNAL, 27 (3), Research Suppl., 148-s to 158-s (1948).
3. Habib, E. T., "A Method of Making High-Speed Compression Tests on Small Copper Cylinders," presented as part of a Symposium on Flow and Fracture of Metals at the National Meeting of the Applied Mechanics Division, The American Society of Mechanical Engineers, June 1948, and subsequently published in the *Jl. Applied Mechanics*.
4. Abkowitz, D. E., "Dynamic and Static Compression Testing of 3/8 Inch Copper Balls," Report R-240, July 1947, David Taylor Model Basins, Navy Dept., Washington, D. C.
5. Spraragen, W., "Peening—Its Effect on Relief of Residual Stresses, Distortion and Mechanical Properties of Welds," THE WELDING JOURNAL, 23 (3), 121–144 (1944).