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RESEARCH PROGRAM TO DEVELOP A TECHNOLOGY IMPROVEMENT PROGRAM FOR CLOSED DIE FORGING

Final Report

Prepared under Contract No. NAS8-20093
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Torrance, California

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FOREWORD

This report was prepared by Harvey Engineering Laboratories for Research and Development, a division of Harvey Aluminum (Incorporated), under Contract Number NAS8-20093, Control Number DCN 1-5-30-12531(1F), for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of Mr. Charles N. Irvine, Manufacturing Engineering Laboratory, as the Contracting Officer's authorized representative during the administration of this contract.

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ABSTRACT

A series of upset forging tests were run to demonstrate the improvement possible through the use of high temperature dies. Three materials were used: 7075 aluminum alloy, 811 titanium alloy, and 250 maraging steel.

For 7075 aluminum the material was heated to 800°F and the dies heat to 400-800°F. Increasing die temperatures produced thinner discs with greatly reduced unit forging force.

The 811 titanium and 250 maraging steel material was heated to 1950°F and the dies heated 400-1400°F in 200 degree increments. The 811 titanium data show significant and consistent lowering of the unit forging force and production of thinner discs up through 1200°F die temperature. The 1400°F die temperature data is inconsistent due, it is believed, to oxidation and lubrication problems.

The data for maraging steel is incomplete but shows a consistent trend of lower unit forging force and thinner discs possible with increasing die temperatures.

Hot work die steel used for aluminum forging performed very satisfactorily. Inconel 713C used for titanium and maraging steel also performed quite well but showed some shallow thermal cracking attributed to rapid open flame heating methods used, but the work is not extensive enough to estimate die life. Lubrication problems became serious at temperatures above 800°F and particularly so at 1200 and 1400°F.

Dies were designed and manufactured for similar elevated temperature tests to produce cup forgings. Preliminary tests were performed with these on 7075 aluminum.

Dies were also designed for a ribbed bracket forging intended for demonstration of the benefits possible through the use of high temperature dies.

SECTION 1

INTRODUCTION

The objective of this program is to develop advanced closed die forging techniques which are applicable to producing more sophisticated and closer tolerance shapes from high strength space materials such as 7075 aluminum alloy, 8Al-1V-1Mo titanium alloy and 250 maraging steel. In such forgings there is a continual need for more complex shapes with thinner webs, higher ribs, sharper transitions between thick and thin sections, closer tolerances, and closer finish to the desired dimensions to reduce machining. All of these are related to the flow of metal in the die and control of this flow so that the metal will completely fill the die cavity.

The metal flow is related to the characteristics of the metal, the temperature at which it is forged, the lubrication, and the chilling of the metal by the die. Not much can be done about the first two factors since the metal characteristics are fixed and fairly well defined, and the forging temperatures have already been raised to the practical limits. Lubricants for forging have been the subject of many investigations, a number of which are still active, so it would appear that this factor will be improved by other programs. Therefore, the program was aimed at improvement through the use of higher than normal die temperatures. It is axiomatic that as the die temperatures approach the metal forging temperature, heat loss from the metal to the die is reduced and flow characteristics are improved.

In the normal forging operations, die temperatures are limited by the ability of the die steels to retain their strength and hardness with increasing temperature. The practical limit is generally considered to be the tempering temperature for the steel used. Most dies are made of hot-work die steels which are tempered in the range of 1000 to 1100°F. This presents no problems for aluminum alloys which are forged at 600 to 950°F, but titanium alloys forged at 1700 to 2000°F do present problems. For these, if the dies are to be heated to reduce the chilling effect, the hot-work die steels will not be adequate. However, there are a number of high temperature alloys which are essentially solid solution alloys and not dependent on heat treatment to attain their strength and hardness. Some of these have properties which made them likely candidates for high temperature forging dies. Among them are the Inconel alloys, the most promising of which are Inconel 713C and 100. Both of these have been recommended for this type of application. They are produced by investment casting, have excellent high temperature strength, and also have excellent oxidation resistance. The 713C alloy is the most promising of these and was used in this program. It performed quite well and its use should be explored further.

SECTION II

LITERATURE REVIEW

The published literature and reports consulted in the course of this project are listed in Appendix I. These have been scanned for basic information on lubricants, particularly those suitable for high temperature applications; for die materials which have shown promise for use at higher than usual temperatures; and for general information on hot-working metal processing. Several of these references are noteworthy because of their comprehensive covering of the general field of forging and their summary of the "state-of-the-art." Some of these are briefly noted below.

A Manual on Fundamentals of Forging Practice prepared for the Manufacturing Technology Division, Air Force Systems Command under contract with Battelle Memorial Institute.(1)

This is a state-of-the-art type of summary. It presents descriptions of various kinds and types of forging equipment noting the principles of their operation and common usage, discusses basics on metal flow in dies, some important factors in die and forging design, and also presents significant information on forging of sixteen alloy types. Among these are aluminum alloys, titanium alloys, and maraging steels which are of special significance to this program. Appendix A to this Manual is also noteworthy in its coverage of fundamental physical metallurgical concepts of importance to the deformation of metals. This manual should be of considerable interest and help to forging shops and those concerned with the theory and practice of forging of a wide variety of metals and alloys.

Technical Evaluation of the Forging Industry,(2) Principles of Forging Design,(3) Heat Treatment of Ferrous Forgings,(4) Mechanical and Physical Properties of Ferrous Forgings,(5) and Metallurgy of Ferrous Forgings.(6)

These are a series of six booklets prepared under the sponsorship of the AISI Committee of Hot Rolled and Cold Finished Bar Producers, and have been prepared by IITRI. They treat primarily with the forging of ferrous metals and are highly recommended to those concerned with forging of ferrous metals. Their coverage of the field is extensive and they treat the various areas with remarkable clarity and scope. Their treatment of the metallurgy and properties of steel forgings is particularly lucid.

Lubrication During Hot Forging of Steel.(7) This is a report of research sponsored by the Forging Industry Educational and Research Foundation conducted at Case Institute of Technology. It covers investigations of a large series of forging lubricants and materials suggested for such use. Among these are borates, phosphates, bromides, chlorides, fluorides, iodides, sulphides, silicates, carbonates, and oxides. Small scale laboratory tests were used for screening purposes and out of these tests six likely candidates were chosen for plant tests. Of these, five were graphite plus solid additions in a water base, and the sixth was a silicone resin base paint. Plant tests indicated all of them could show improvement over current plant practice but that methods of application could have a greater influence than the type of lubricant. Spraying as contrasted to swabbing provided the most uniform and effective coating.

Metal Deformation Processing, Vol.I and II(8) and Status Reports on Government Metalworking Processes and Equipment Program.(9)-(14) These are DMIC reports and are of special interest in their coverage of recent and active programs conducted by the various government agencies. The information on fundamental treatment of the deformation of metals, lubrication, and current works on processes are of particular interest to this program.

High Temperature Extrusion Lubricants, Progress Reports 4 through 7.(15) These are notable for the wide range of substances investigated and the laboratory-type test method designed to evaluate them. The method is well suited to high temperature testing and, in general, consists of determining the rate of deceleration of a disc coated with the lubricant when suddenly subjected to a fixed vertical load. A series of reactivity tests were also used to screen out substances which would be too corrosive to the dies and material extruded. The work was primarily aimed at lubricants for hot extrusion but the results should be of interest for forging as well. A number of graphite-metal oxide mixtures show up well in these tests.

The Mechanical Properties of 18% Maraging Steel,(16) Mechanical and Physical Properties of Three Super Alloys - MAR-M200, MAR-M302, and MAR-M322,(17) An Investigation of 18NiCoMo(300) Maraging Steel Forging.(18) These three references are concerned with maraging steels, their compositions, thermal treatments, and their physical metallurgy. They provide an excellent summary of maraging steels.

Development of 2400F Forging Die System.(19) This report is of particular value to this program in that it also has the objective of investigating the effect of elevated die temperatures. They have also investigated the Inconel alloys as die material, notably 718, 100, and 713. They conclude that 713 shows the greatest promise. The choice of 713 as a die material for the present program is based on this work and personal discussions with the authors.

The remaining references are of general interest, giving some general concepts of the programs conducted in examination of lubricants during forging programs on steel and titanium, and some of the high temperature metal working processes.

SECTION III

CONSULTATION WITH FORGING INDUSTRY

At the beginning of this program ten representative organizations were visited to discuss the nature of the project and to obtain their recommendations and suggestions. These organizations included suppliers of die materials, producers of forgings, and research groups. In general, the industry was interested in the project and of the opinion that much benefit would result from research and development effort on the forging processes. However, the industry is highly competitive and specific information as to practices and processes are in most instances considered proprietary. The details of lubricants applied, stock temperatures used, die temperatures attained, and similar details could be discussed in general terms only. Within such limits, the attitude was one of cooperation and interest and a number of useful suggestions and recommendations were made.

Regarding the die steels for use on the aluminum work, the normal grades of pre-hardened and tempered steels of the 6F, 6F2, and 6F3 were recommended and were considered to be capable of satisfactory operation at temperatures approaching the stock temperatures. For the work on titanium and the maraging steels, the high nickel alloys such as Inconel 713C and Inconel 100 were recommended. Hard facing of H-11 types of die steels was also suggested as a possible means of extending the working range of these die steel types.

Graphite base lubricants were strongly recommended and application by spray methods considered to be the most satisfactory. Specific details as to grade and proportions of graphite with fillers and dispersion agents were considered proprietary and therefore were not available.

While spray methods of applying the lubricant were highly recommended, it was noted that this became difficult with increasing die temperatures. The water or oil carriers tend to form a vapor layer at the die surface and prevent the solids from reaching the die. They also form clouds of vapor which are a considerable nuisance and require extensive ventilation. It was also noted that swabbing was sometimes more effective in coating the die because the lubricant could be placed at the areas where maximum flow of metal was needed. Another point that was made was the need to carefully watch the possible accumulation of solids in die cavities. The general substance of these comments point to the fact that no one method of applying the lubricant has yet been universally satisfactory.

Another point that was made by a number of those consulted was that the competitive nature of the industry usually leads to the use of the simplest and most economical method of producing a forging and that such methods do not necessarily result in the development of the highest property levels of which the material may be capable. The use of higher temperatures, lubrication methods aimed at the needs of a specific forged part, or the use of additional forging steps to arrive at the desired configuration, can often be of help and provide improvement in the properties obtained. However, when these result in increased forging costs, they may not be feasible because of the intense competitive nature of the industry.

A number of industry people also strongly recommend research on the fundamentals of metal flow in dies and continued emphasis on lubrication of dies and forging stock. However, those making such recommendations had no specific suggestions but seemed to believe that the complex nature of the metal flow in any particular forging would make it difficult to generalize.

SECTION IV

GENERAL PLAN OF ATTACK

The general plan of attack on this program called for two series of forging tests. The first consisted of upset forging of cylindrical pieces, varying the die temperature and measuring the forging forces and the thickness of the discs produced. These tests simulate the forming of thin, flat webs in forgings and provide data on the forging forces required to produce them as the die temperature is varied. The second series consisted of the formation of cups from a cylindrical slug, measuring the wall thickness, the height of the wall, and the forging forces required with varying die temperatures. This series simulates the formation of ribs in forging and provides information on the forging forces required to produce thin, high ribs as the die-temperature is increased.

For economy, the die designs were kept as simple as possible with maximum interchangeability. The design contemplated heating the dies in a separate furnace and quickly transferring them to the press and locking them in place. Other means of heating the dies were discarded as excessive in cost, complex in design and requiring too much time to bring to temperature. The die temperatures were monitored by thermocouples inserted in the dies with the hot junction as close to the working surface as feasible. A 500-ton hydraulic forging press was available for this program and the dies were designed for this press.

Since this program was limited in scope, no special efforts were made to undertake the development or investigation of forging lubricants. Instead, efforts were made to utilize existing and standard lubricants. In particular, graphite forging lubricants in water or oil carriers were used for the lower temperature work and glass wool and glass powders for the higher temperatures.

The forging stock purchased was as-extruded bar for the 7075 aluminum and as-rolled rod for the 811 titanium alloy and maraging steel. The cylinders for upset forging were machined to 2.00" diameter, 1.5" long; and to 2.50" diameter and 1" long for the cup forging.

Hydraulic pressure measurements were made by inserting a BLH Pressure Cell in the hydraulic line of the press and recorded on either an Offner Dynograph Amplifer Recorder or on a Sanborn two channel recorder. The cell and recorders were previously standardized by calibration in a standard hydraulic pressure system. One such calibration chart is shown in Figure 1. The normal line pressure of the press is 2400 to 2500 psi; and while this can be read on a dial gauge, the response of the gauge is slow and pressure surges make it difficult to read accurately.

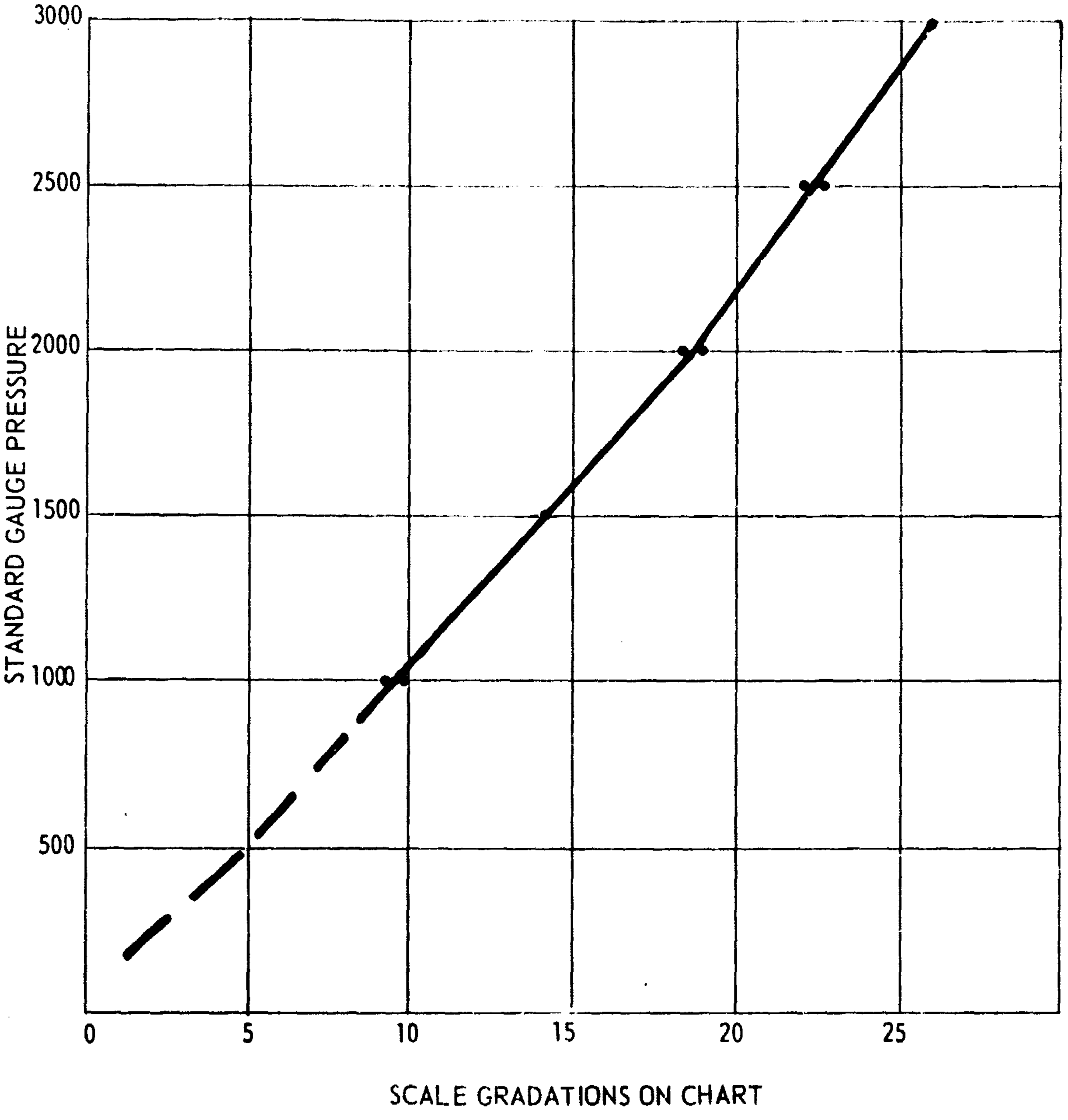

Figure 1. Calibration of Pressure Recording System

SECTION V

DESCRIPTION OF FORGING DIES

Flat Dies for Aluminum

These dies, as shown in drawing 20-09201, are made of pre-hardened hot-work die steel (FX) normally used for aluminum forging. They are capable of operating satisfactorily for forging aluminum alloys at die temperatures up to 900°F. Since the 7075 alloy is forged at 800°F, this steel is quite adequate for the purpose of the program.

As can be seen from the drawing, the dies were designed as simply as possible and with the intent of making them easy to move in and out of the press. The working face of the dies was made 12 x 12 inch to provide ample pressing area and the thickness made 4 inch to provide a high heat capacity so that the loss of heat on transfer from the furnace to the press would be minimum. The dies are retained in the holders by tapered shanks and keyed in place by driving a tapered wedge between the die and the holder in much the same manner as used for hammer forging dies.

The holders were made of mild steel with the gibs machined from separate pieces to reduce the machining required. The drawing calls for the holder to be made of 2-inch plate but it was actually made of 4-inch plate because of the immediate availability of this material. To minimize the heat flow from the die through the holder and to the press ram, a 1/2-inch thick piece of transite faced with expanded metal sheet was fastened to the die holder. The expanded metal protected the transite from damage during the transfer of the dies in and out of the holder and also provided some restriction to the flow of heat.

Thermocouple wells are provided for temperature control. These are placed so as to locate the couple hot junction 1/2-inch below the center of the working face of each die. These arrangements were very satisfactory for the temperature range explored in forging aluminum. Trial runs indicated that the dies could be moved out of the furnace and locked in the press ready for forging in 2 to 4 minutes with very little loss in temperature.

Flat Dies for Titanium Alloy and Maraging Steel

The flat dies for the titanium alloy and maraging steels are shown in drawing 20-09302. As shown in the drawing, they were designed to fit the same die holders as used for the aluminum forging dies. Because of the higher temperatures to be used, these dies are made of Inconel 713C. This alloy is a nickel base alloy with a nominal analysis of Cr 13%, Mo 9.5%, Ti 0.75%, Al 6.0%, Fe 2.5% max., Cb+Ta 2.3%, C 0.14%, Mn 0.25% max., Si 0.5% max., balance Ni. It is a casting alloy normally produced by vacuum melting and investment casting and largely used for impellers, scrolls, exhaust ducting and similar application because of its excellent high temperature properties and its resistance to oxidation at temperatures in the range of 1900°F. It has been recommended for high temperature forging dies because of its high hot hardness, good high temperature strength and oxidation resistance. Since it is ordinarily produced in relatively small thin cast pieces, the size of these dies was reduced to keep the weight within the capabilities of the supplier who advised that about 85 lbs was their maximum limit. To bring the dies within this weight, the working face was reduced to an 8.5-inch diameter circle and the bottom half was designed with slots to reduce the weight still further. The supplier later found that he could cast the dies without the slots and still get a sound piece. The dies furnished were therefore solid rather than slotted at the bottom. They were X-rayed for soundness after delivery and found to be sound and free of shrink holes and gas porosity. One die face showed a slight concavity due to shrinkage but could be ground flat to produce a good solid working face. The thermocouple wells were produced by elox machining without difficulty. Machining of the alloy was also accomplished without incident by using carbide tools and taking slow cuts.

It is of interest to note that these dies weighing 91 lbs each were the heaviest pieces cast in 713C by the supplier. Their nominal thickness of 4 inches is also the thickest to be made to that time. The alloy is normally made in thicknesses under 1/2-inch and about 80 lbs maximum weight. The vacuum melt equipment and characteristics of the alloy usually limit the total weight of the melt to 175 lbs, about 50 percent of which is required for gating and risers. The simplicity of these dies made it possible to utilize a greater portion of the metal for the casting.

Cupping Dies

The design of these dies is shown in drawing 20-09303, Sheets 1 to 4. Sheet 1 shows the assembly of the complete die. It is drawn in two positions; that is, with the press closed and the cup as-formed on the punch, and with the press open and the cup resting on the stripper plate after being stripped from the punch. These dies are designed to make cup forgings with wall thicknesses from 0.100" to 0.250" in steps of 0.050" and to permit variable bottom thicknesses as required. The slug size is a nominal 2.50" in diameter and 1.00" in length. The punches and the cylinder inserts are both designed for quick and simple placement. Like the flat dies, the working parts (punches, cylinder insert, and top plug) are intended to be heated in a furnace adjacent to the press and quickly transferred to the press and locked in place with a minimum loss in temperature.

Sheet 2 shows the base plate and the toggle actuated slides which can quickly clamp the punch and hold it in place. The base ring is made of 4340 steel and has an insert of Inconel 713C for the tapered seat of the punch.

Sheet 3 gives the details of the punches, the cylinder inserts, the base insert and the punch insert. For forging the aluminum cups, these parts are made of Hardtem FX hot-work die steel and for titanium alloy and maraging steel these parts are made of 713C Inconel. Like the flat dies, these parts are investment cast with an allowance of 1/16" for machining to size. Thermocouple wells and grooves shown permit monitoring of the punch temperature at a point 1/2" under the working face of the punch and at the upper center of the cylinder insert wall.

Sheet 4 gives the details of the retainer ring, pressing head and stripper plate. All of these parts are made of 4340 steel.

SECTION VI

FLAT DIE WORK ON 7075 ALUMINUM ALLOY

These tests were run first in order to check out procedures, establish the best methods of conducting the test, determine the data to be collected, and the most suitable means of evaluating and presenting it.

The dies were heated in a furnace immediately adjacent to the press and transferred to the press, locked in position and ready for forging in a matter of three to four minutes. They were heated to the maximum temperature required for the run with an over-allowance of 25 to 50 degrees to take care of the drop during transfer. This drop was generally in the neighborhood of 10 to 15 degrees. Lower forging temperature ranges were obtained by allowing the dies to cool in the press between groups of samples. For this purpose the temperature of the dies was continuously monitored through thermocouples placed in the wells below the working face of each die. This also permitted a determination of the average top and bottom die temperatures at the time of forging each sample.

The die temperatures used ranged from a high of 875°F to a low of 350°F. The time required for forging each sample was approximately 20 to 25 seconds. During the forging, the dies cooled some 15 to 25°F between samples for the 800-700°F level; and less than 5°F for temperatures of 400°F and below. This cooling was generally quite regular for the higher temperature but at the low temperature the abrupt change in the slope of the cooling curve demonstrated that the dies were picking up heat from the 800°F slugs. This was quite apparent and, had the test been extended to a large number of slugs, an increase of die temperature would have resulted. In these tests, however, the small slug mass compared to the large mass of the dies and the use of a limited number of slugs in each condition simply reduced the cooling rate of the die.

The lubricant used for these tests was an oil based graphite containing some lead compound; it was applied as spray after dilution with kerosene. This lubricant was sprayed on the dies prior to heating and just before the forging of each sample. The working surfaces of the dies were placed together during the heating so that they and the initial lubricant coating were protected from excessive oxidation in the furnace. Spraying of the lubricant, as previously reported, and in agreement with previous experience in our own forging shop and also noted by others, is the most efficient method of application. However, the kerosene produces clouds of fog which is quite a nuisance and required extensive ventilation. In normal forging operations, the fog is largely prevented by ignition by die heating burners which were not used in these tests. It should be noted in passing that the extensive ventilation required to dissipate the fog contributed to rapid die cooling.

At the higher die temperatures, the rapid vaporization of the spray tended to keep the lubricant from sticking to the die surface and contributed to the scatter of results. At the lower temperature (400 to 500°F) the lubricant adhered to the surfaces much better and the data showed significantly less scatter. It was apparent that when the much higher die temperatures contemplated for titanium and maraging steel were used some improved method of applying the lubricant would be required.

Most of these tests were run with 2" diameter, 1.5" long slugs (volume 4.71 cu.in.), but a few 2.5" diameter, 1" long (volume 4.91 cu.in.) slugs were also used. In all cases they were heated to the forging temperature of 800°F. Three to four slugs were forged in each condition.

The forging was done on a 500-ton hydraulic press in which the forging pressures were controlled to produce a range of disc thickness.

The data logged for each sample included the following:

sample number and size
forging stock temperature
die temperature - top and bottom
hydraulic pressure
forged disc thickness
forged disc area
unit load applied

The forged sample thicknesses are averages of the minimum and maximum readings on each. The maximum range of thickness variation on the samples was approximately ±.010" with an average range ±.005". Most of this variation is believed to come from variable compression of the insulating material inserted between the dies and the holders to reduce loss of heat to the press and prevent excessive heating of the press parts. Normal clearances in the press guides and factors related to die placement account for the rest.

The area of the forged samples was determined from the initial slug volume and the thickness of the disc. Unit loads on the sample are based on the area of the forged sample. The press load was calculated from the hydraulic pressure used and the ram area of 452 sq.in. It is expressed in short tons per square inch of forged sample area.

The results of these tests are summarized in Figure 2 which is a plot of the forging force expressed in tons per square inch against the thickness of the resulting biscuits for die temperatures from 350 to 800°F. These curves are drawn through the minimum points for 50°F intervals of die temperature from data covering a series of test runs of which Tables I, II, and III are representative. As can be seen from a review of these tables, the scatter of the data in the individual tests is considerable. It is not excessive for this type of work and is believed due to variations in temperature, distribution of the lubricant on the die surfaces, and the relatively few samples forged per test. This scatter produces a considerable over-lap of curves drawn for the various die temperature intervals when all available data are plotted on a single chart. Curves through the minimum points for each temperature interval, however, allow a reasonable, although by no means perfect, separation of the data.

The choice of drawing the curve through the minimum points is justified on the basis that these points represent the best conditions found and, therefore, indicate the lowest forging force required for a given thickness. They show the greatest benefits that can be expected through the use of high die temperatures. In contract to this, the maximum points represent a breakdown of lubrication, non-uniform temperature and similar effects, and present a confused overlapping picture

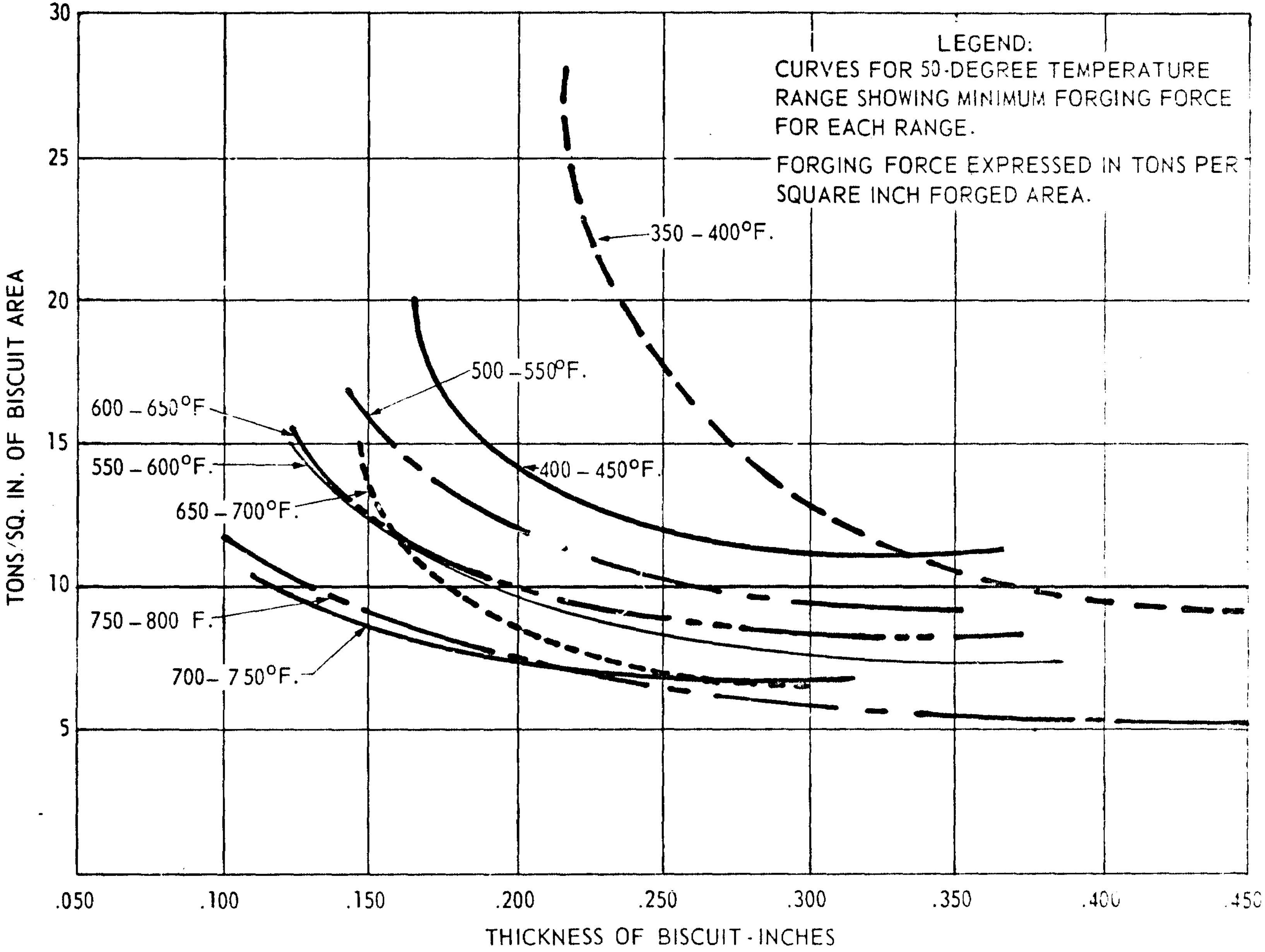

Figure 2. Forging Force vs. Thickness for 7075 Aluminum Alloy

of the effects of die temperature. It is believed that the use of a greater number of larger samples involving greater metal volume and larger surfaces would have reduced the scatter; however, this would have been more costly since they would have required larger dies and the use of a larger press.

TABLE I

Data from Test 13

Stock Size: 2" diameter, 1.42" long
Stock Temperature: 800°F
Press run against stops

Sample No.	Die Temperature (Degrees F)	Pressure (psi)	Biscuit Thickness (in.)	Area Sq.In.	Forging Force Tons per Sq.In.
1	825	600	.359	12.4	10.9
2	795	500	.355	12.6	9.0
3	785	450	.352	12.7	8.0
4	775	400	.350	13.3	6.8
5	760	500	.296	15.1	7.5
6	750	500	.295	15.1	7.5
7	745	500	.296	15.1	7.5
8	735	500	.296	15.1	7.5
9	720	650	.246	18.1	8.1
10	710	600	.246	18.1	7.5
11	705	650	.246	18.1	8.1
12	700	600	.246	18.1	7.5
13	695	900	.205	21.8	9.3
14	690	850	.204	21.8	8.8

TABLE II

Data from Test 14

Stock Size: 2" diameter by 1.42" long
Stock Temperature: 800°F
Press run against stops.

Sample No.	Die Temperature (°F.)	Pressure (psi)	Biscuit Dimensions Thickness (inches)	Biscuit Dimensions Area (sq.in.)	Forging Force Tons per sq.in.
1	778	2500*	.136	32.8	17.2
2	777	2500*	.126	35.4	16.0
3	772	2500*	.121	36.9	15.3
4	766	2500*	.116	38.5	14.7
5	759	1300	.133	33.5	8.7
6	754	1500	.134	33.3	10.2
7	749	1500	.131	34.1	9.9
8	737	1200	.159	28.1	9.6
9	733	1200	.161	27.7	9.8
10	728	1200	.161	27.7	9.8
11	724	800	.200	22.3	8.1
12	720	800	.198	22.5	8.0
13	710	800	.200	22.3	8.1
14	703	600	.245	18.2	7.4
15	700	600	.245	18.2	7.4
16	695	600	.245	18.2	7.4

*No stops. Full load of press used for these.

TABLE III

Data from Test 15

Stock Size: 2" diameter by 1.5" long
Stock Temperature: 800°F
Press limited by reversal.

Sample No.	Die Temperature (°F.)	Pressure (psi)	Average Biscuit Dimensions Thickness (in.)	Average Biscuit Dimensions Area (sq.in.)	Forging Force Tons per sq.in. area
1	805	2500*	.148	31.8	17.8
2	800	2500*	.138	34.1	16.6
3	790	2500*	.137	34.4	16.4
4	780	2330	.163	28.9	18.2
5	780	2100	.154	30.6	15.5
6	775	2160	.153	30.8	15.8
7	875**	2500*	-***	-	-
8	805	2500	.181	26.0	21.7
9	790	2500	.159	29.6	19.1
10	780	2500	.150	31.4	17.6
11	775	2150	.161	29.3	16.6
12	770	2000	.162	29.1	15.5
13	760	2000	.158	29.8	15.2
14	755	1200	.197	23.9	11.3
15	750	1250	.201	23.4	12.1
16	745	1230	.194	24.3	11.4
17	725	2500*	.138	34.1	16.6
18	720	2500*	.138	34.1	16.6

Table III - Continued

Sample No.	Die Temperature (^{o}F.)	Pressure (psi)	Average Biscuit Dimensions		Forging Force Tons per sq.in. area
			Thickness (in.)	Area (sq.in.)	
19	715	2500*	.139	33.9	16.7
20	710	2510	.148	31.8	17.8
21	705	2520	.144	32.7	18.7
22	705	2510	.147	32.1	17.7
23	700	2000	.158	29.8	15.2
24	690	1900	.153	30.8	13.9
25	690	1930	.155	30.4	14.4
26	690	2100	.159	29.6	16.0
27	690	2080	.153	30.8	15.3
28	685	2180	.154	30.6	16.1
29	605	2500*	.142	33.2	17.0
30	605	2500*	.146	32.3	17.5
31	605	2500*	.153	30.8	18.3
32	605	2500*	.153	30.8	18.3
33	605	2390	.162	29.1	18.6
34	600	2400	.166	28.4	19.1
35	600	2400	.163	28.9	18.8
36	595	2330	.166	28.4	18.5
37	595	2400	.172	27.4	19.8
38	595	2350	.170	27.7	19.2
39	590	1020	.224	21.0	11.0
40	590	1100	.223	21.0	11.0

Table III - Concluded

Sample No.	Die Temperature (°F.)	Pressure (psi)	Average Biscuit Dimensions		Forging Force Tons per sq.in. area
			Thickness (in.)	Area (sq.in.)	
41	590	1050	.224	21.0	11.0
42	580	1000	.230	20.5	11.0
43	580	1000	.234	20.1	11.2
44	580	1000	.237	19.9	11.4
45	440	2500*	.165	28.6	19.8
46	440	2400	.177	26.6	20.4
47	440	2400	.175	26.7	20.2
48	440	2400	.175	26.9	20.6
49	440	2320	.183	25.7	20.4
50	440	2290	.185	25.5	20.3
51	440	2400	.187	25.2	20.2
52	440	1230	.238	19.8	14.0
53	440	1150	.240	19.6	13.3
54	440	1150	.241	19.6	13.3

* Full load of press applied.
** Dies reheated in press at this point.
***This sample cracked.

The general conclusion that can be drawn from these forging tests is that substantial benefits can be shown in forging by the use of elevated die temperatures and that the methods used are reasonably satisfactory for demonstrating them.

SECTION VII

FLAT DIE WORK ON TITANIUM 811 ALLOY

The results of the work done on upset forging of the 811 titanium alloy are summarized in Figure 3, which is a chart of the forging force per unit area plotted against the thickness of the forged piece for four die temperatures (400, 800, 1200, and 1400°F). This chart presents the minimum relationships found for the various die temperatures. On review of this chart, the following significant conclusions may be drawn:

1) In the thickness range covered, the forging force per unit area has a straight line relationship with the thickness. However, at the greater thicknesses the line must bend to approach zero tons per square inch at the original slug thickness, but in the range of these tests the straight line holds. It is essentially the upper leg of the hyperbolic curve and the further decrease of thickness would become asymptotic to the vertical axis.

2) Again, within the thickness range of the tests, the forging force increases quite rapidly with decreasing thickness and hence, aptly illustrates the problem involved in producing thin webs in titanium forgings. It is apparent that to produce forged discs thinner than those obtained here, significantly increased forging loads would be required at a given die temperature.

3) Increase of die temperature shifts the unit forging force vs thickness relationship to the left making it possible to produce a given thickness at a lower forging load, or conversely, to produce a thinner piece with a given load. For example: with the 500-ton press used here, 400°F dies produced a piece 0.275" thick while 800°F dies produced a 0.190" thick piece and 1200°F dies produced 0.165" thick piece at maximum load.

4) The data for dies heated to 1400°F are not in agreement with that for the other three temperatures. It is believed that these data are at fault and further efforts to establish the true position of this line is recommended. The 400, 800, and 1200°F die temperature data are consistent and in good agreement with each

other as to the general trends; hence, it must be concluded that the 1400°F data are incorrect. The reason for their disagreement is not clear as yet; differences in lubrication of die surfaces and press operation are among the factors which could bring about the discrepancies. It is believed, however, that excessive oxidation of the slugs during heating is probably the major cause.

The tests reported here used forging slugs 2" in diameter, 1.5" high, with a generous 1/4" radius blending the end faces with the cylinder wall. They were heated to 1950°F for forging, using a glass slurry coating and flow of argon for protection from oxidation during heating. The appearance of the forged pieces, however, suggest that this protection should be improved in future work. For most of the tests run, three to four slugs were forged for each condition of die temperature and press load.

The dies were brought to temperature with torches, initially by simply playing the torches over the working face, and later by use of a refractory brick enclosure over the die and playing the torches in the space between. The first arrangement was satisfactory up to 1000°F but the heating rate was much too slow. The latter arrangement produced more rapid heating but also resulted in uneven heating because of the high flame temperature of the torch. The single thermocouple control situated in each of the dies about 1/2" below the center of the working face does not show these variations. Non-uniformity of temperature no doubt contributed to the scatter of the data obtained.

Prior to heating, the dies were coated with the same glass slurry used on the forging slugs. In several cases a slurry of "phosphotherm", a proprietary phosphate mixture, recommended for high temperature uses and for protection against oxidation, was used. This was not considered as good as the glass, particularly for 1200°F and above.

Glass wool pads were used for lubrication. These were approximately 4 to 6" square placed under and over the heated slug just before forging. At 400, 800, and 1000°F these were quite satisfactory with little or no sticking of the piece to the dies. At 1200 and 1400°F, however, the molten glass stuck the piece to one die and it would appear that a higher melting glass which would wet the billet at 1950°F but not the die at its operating temperature would be a more ideal combination.

The forging was done on a 500-ton press using the full hydraulic pressure of 2400 psi to produce the thinnest forged biscuit and reducing the pressure to get varying thicknesses for each die temperature. The operating conditions were such that the same hydraulic pressure adjustment could not be used for each case without extensive trial runs, and hence excessive use of the limited material available. The usual procedure was to run at full hydraulic pressure first and then reduce this in steps aimed at using 2/3 and then 1/2 or less of the full pressure. The actual load on the press ram was calculated from the pressure used, as recorded for each forging, and the ram area of 452 square inches. The load is expressed in the data tables in short tons.

400^{o}F Die Temperature

The data for these tests are presented in Table IV. The unit forging loads found are plotted against biscuit thickness in Figure 4. The general appearance of the biscuits produced is shown in Figure 5. For ease of comparison, the data are arranged in this and succeeding tables in groups of low ram load, intermediate load, and full press capacity, rather than in chronological order.

As will be noted from the table, the forgings made at full ram load are those of Run 19 where sharp cornered slugs and graphite lubricant were used; and, hence, are not fully representative of the well-radiused slugs lubricated with glass. Therefore, they are somewhat thicker than would be expected, but are used in this series rather than repeat the tests in order to conserve the available material for the higher die temperatures. In general, the data of Table IV lines up quite well showing decreasing thickness with increasing ram load.

The data are presented graphically in Figure 4 where unit forging force on the forged biscuit is plotted against biscuit thickness. In this chart, a line has been drawn through the minimum points for each set of data to represent the minimum forging force required to produce a given biscuit thickness. A companion line is drawn parallel to the minimum line and through the highest data point to represent the spread of the data. As might be expected, the maximum spread is found in the data from Run 19 where sharp cornered billets has restricted the metal flow. These are also the thinnest biscuits which can generally be expected to show the greatest spread of results.

The minimum line in this chart may be considered to summarize the results of the 400°F die temperature tests. It shows the lowest unit forging forces obtained for the thickness range encountered, and provides a base for comparison with higher temperature dies under similar conditions of forging and lubrication. The slope of this line is considerably steeper than was expected but is amply supported by the subsequent data obtained with dies heated to 800 and 1200°F. Looking at the extremities of this line, which is not extrapolated very far beyond the actual data points because it is clear that straight line portion is necessarily limited, it can be seen that the minimum unit forging force required to produce a biscuit thickness of 0.260" is 35 tons per sq.in., while that to produce a biscuit thickness of 0.360" is 19 tons per sq.in.

Figure 5 is a photograph of the forged biscuits produced with 400°F dies. It is intended to provide visual indication of the size, surface, general appearance and the overall shape of the biscuits as-forged. Only three of the samples from run 19 are shown here, but they are quite representative of the group. The rings from the sharp billet corners are shown clearly in these three biscuits. The absence of these rings in the other discs which were forged from well-radiused slugs is a striking demonstration of the effectiveness of the radius. In general, the surface of these biscuits is quite good, indicating that the overall metal flow has been smooth and regular.

TABLE IV

Upset Forging - 811 Titanium Alloy
Die Temperature 400°F

Run	Sample	Ram Load (Tons)	Die Temperature	Thickness	Area	Tons/sq.in.
27	28	262	400	.353	12.6	20.8
	29	254	"	.363	12.3	20.6
	30	254	"	.355	12.5	20.3
27	1	-	400	.312	14.3	29.0
	2	415	"	.304	14.7	28.2
	3	425	"	.306	14.5	30.0
19	1	543	400	.296	15.0	36.2
	2	"	"	.291	15.2	35.8
	3	"	"	.281	15.8	34.4
	4	"	"	.273	16.3	33.4
	5	"	"	.303	14.7	37.0
	6	"	"	.317	14.1	38.5
	7	"	"	.313	13.8	39.4
	8	"	"	.296	15.1	36.0

Notes:
(1) Forging stock: 2" disc, 1.5" high, 1/4" radius.
(2) Slugs dipped in glass slurry prior to heating.
(3) Forging Temperature: 1950°F.
(4) Phosphotherm on dies prior to heating (first six samples).
(5) Glass wool between slug and dies on forging.
(6) Last eight samples used square cornered slugs and graphite film lubricant.

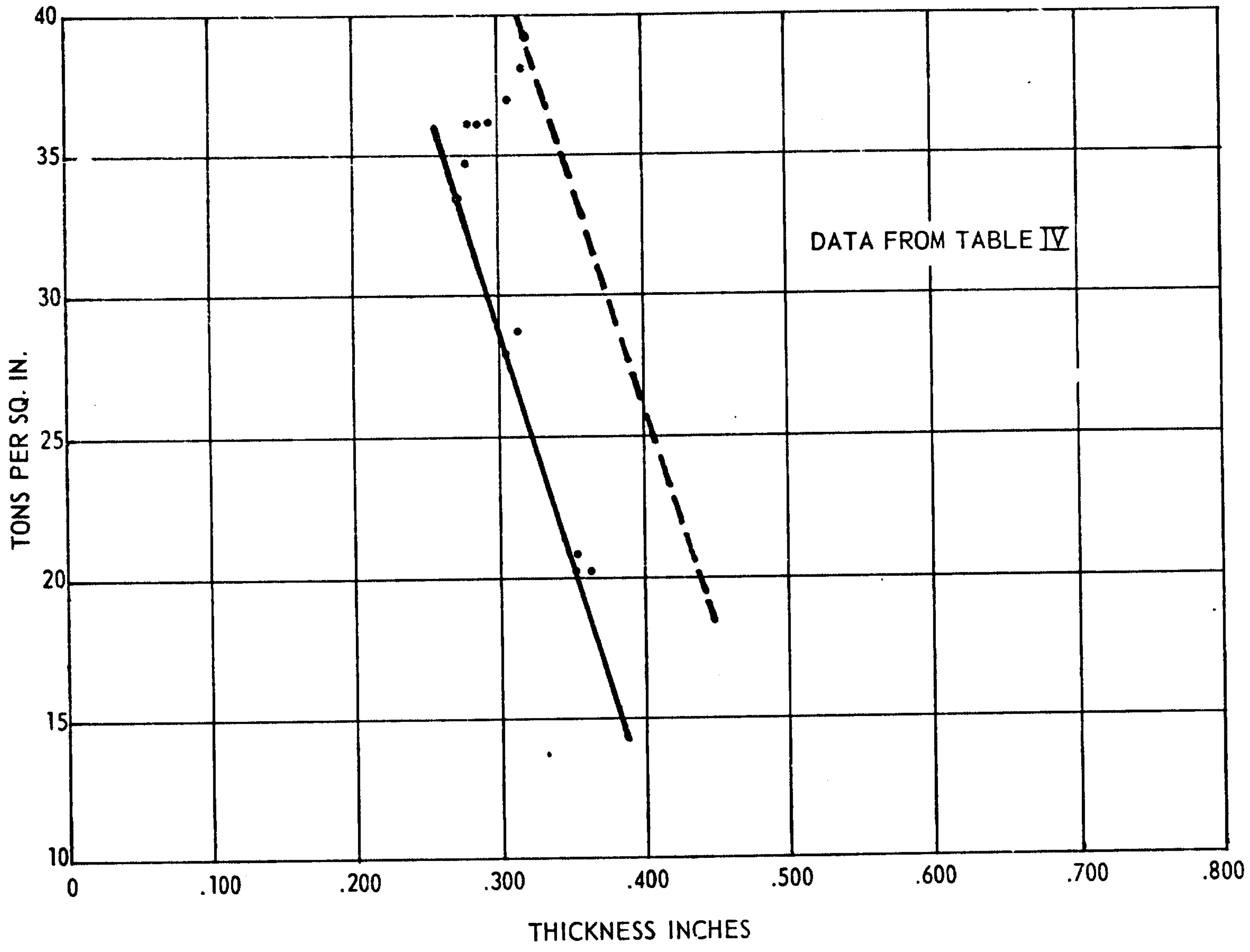

Figure 4. Unit Forging Load for 811 TitaniumAlloy Upset Forged on 400 F. Dies

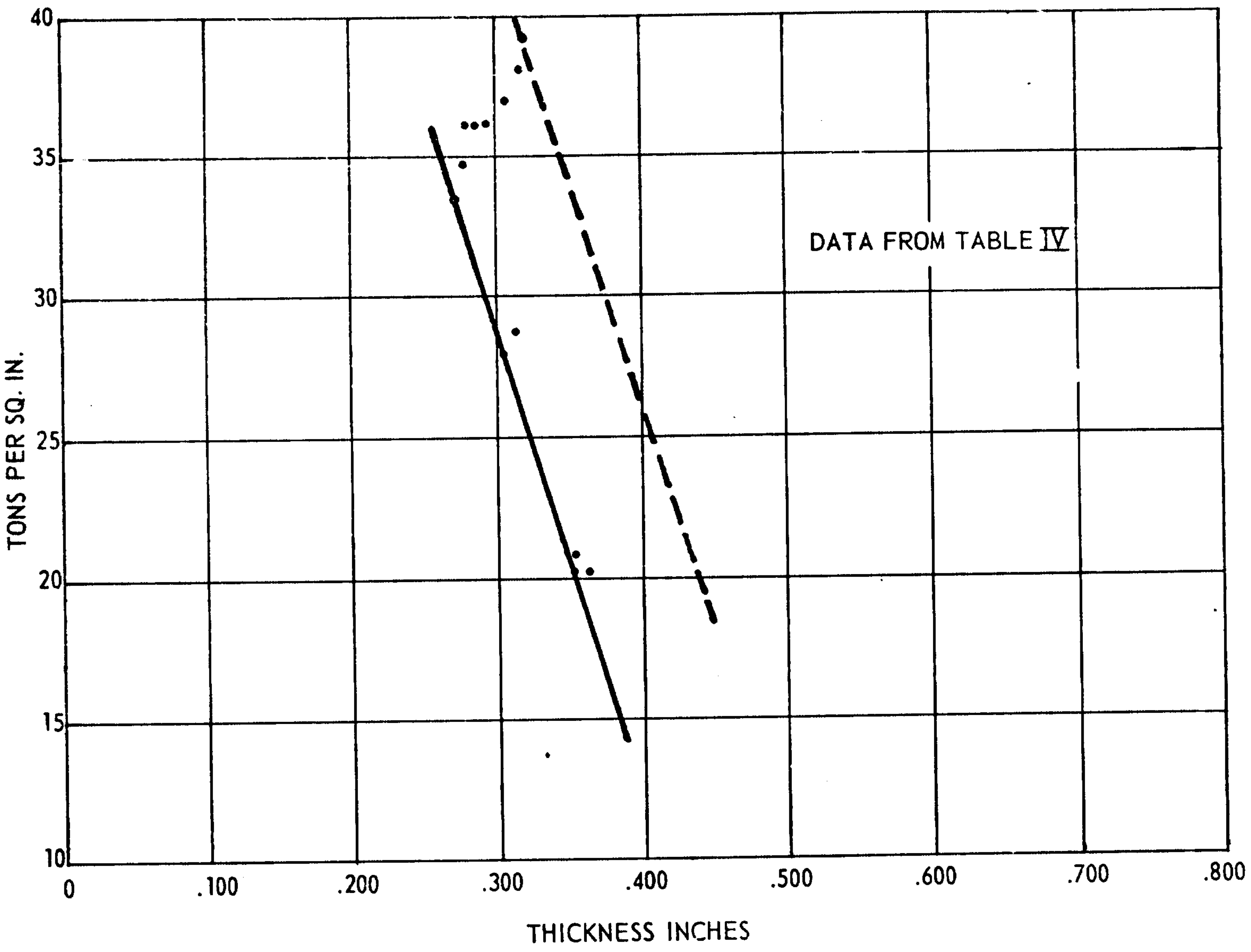

Figure 4. Unit Forging Load for 811 TitaniumAlloy Upset Forged on 400 F. Dies

800°F Die Tests

The results of these tests are presented in Table V, plotted in Figure 6, and the general appearance of the forged pieces shown in Figure 7.

Comparison of the data with that of the 400°F die tests shows that thinner biscuits were produced at each ram load and unit forging force on the biscuits was correspondingly reduced. The line in Figure 6 is again drawn through the minimum points of the data with the spread indicated by the parallel dotted line passing through the point showing the greatest spread. The minimum line has been shifted significantly to the left compared to that for the 400°F dies; however, its slope has changed only slightly. This line shows that with 800°F dies a forging force of 25 tons per square inch would produce a bisciut 0.170" thick while 15 tons per square inch would produce a biscuit 0.290" thick. This is a large change from the capabilities with 400°F dies for which 32 tons per square inch would be required to produce a thickness of 0.290" and the 0.170" thick biscuit could not be produced under approximately 45 tons per square inch. The spread of the data is somewhat greater than that for the 400°F dies and is fairly large at all ram loads, probably reflecting the cooling of the dies which is more rapid due to the higher temperature level.

The comparative size and shape of the biscuits produced are illustrated in Figure 7. These biscuits are arranged in the same order as listed in Table V. They show the progression of size resulting from increase in ram load but cannot be directly compared in size with those of Figure 5 because of a decrease made necessary to get them all in the photograph and show as much surface detail as possible. The surfaces are smooth and regular, indicating good metal flow and, although they are not truly circular, the irregularities are minor indicating reasonably uniform lubrication.

TABLE V

Upset Forging - 811 Titanium Alloy
Die Temperature 800°F

Run	Sample	Ram Load (Tons)	Die Temperature (°F.)	Thickness	Area	Tons/sq.in.
27	31	251	800	.307	14.5	17.3
	32	252	"	.326	13.6	18.5
	33	254	"	.272	16.4	16.6
27	4	425	800	.268	16.6	25.6
	5	520	"	.277	16.2	25.8
	6	423	"	.300	14.8	28.5
26	9	543	800	.190	23.4	23.2
	10	"	"	.210	21.2	21.6
	11	"	"	.244	18.2	29.8
	12	"	"	.241	18.5	29.3

Notes: (1) Forging Stock: 2" diameter, 1.5" high, 1/4" radius.
(2) Slugs dipped in glass slurry prior to heating.
(3) Forging Temperature: 1950°F
(4) "Phosphotherm" on dies prior to heating.
(5) Glass wool between dies and slug on forging.

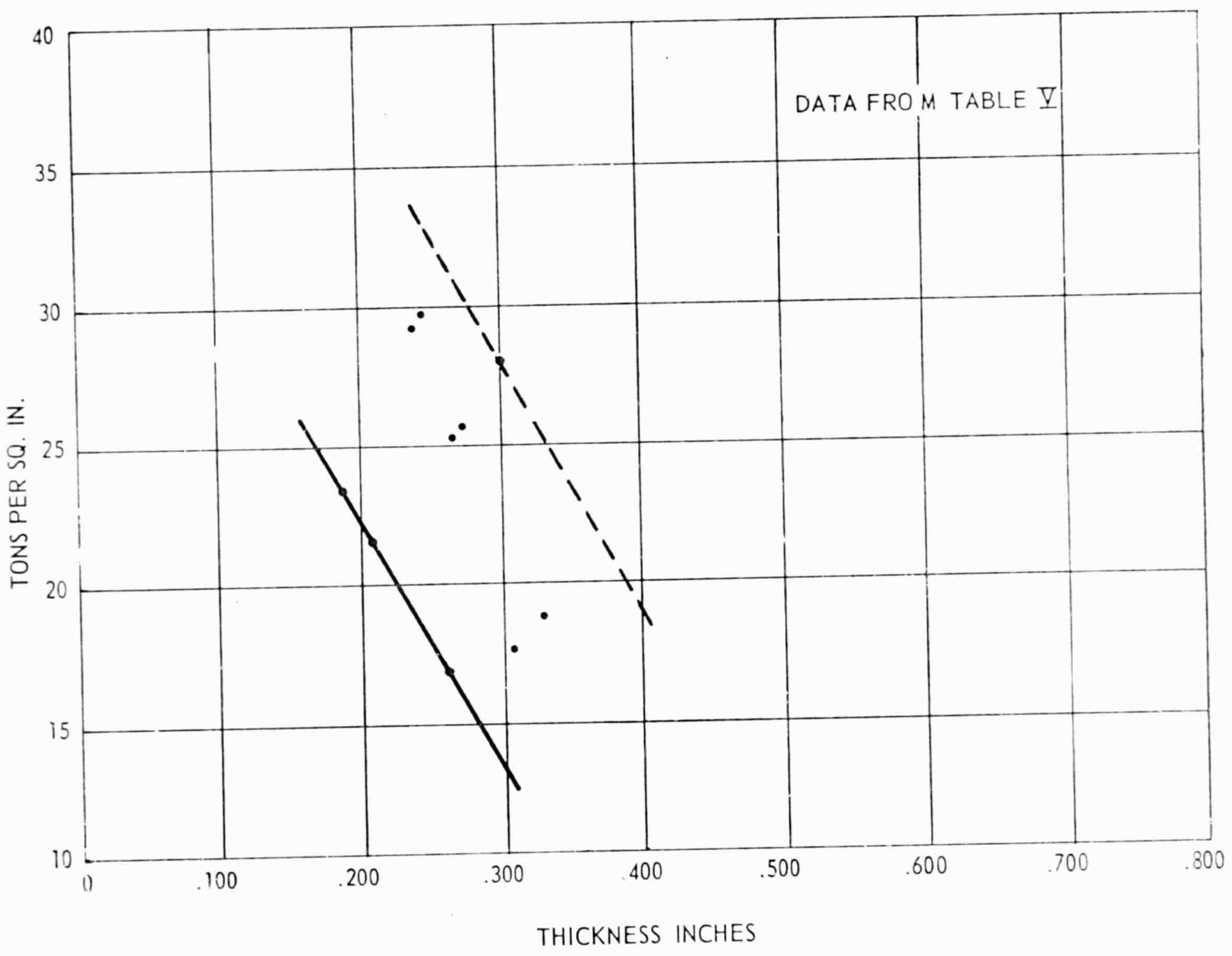

Figure 6. Unit Forging Force For 811 Titanium Alloy Upset on 800°F. Dies

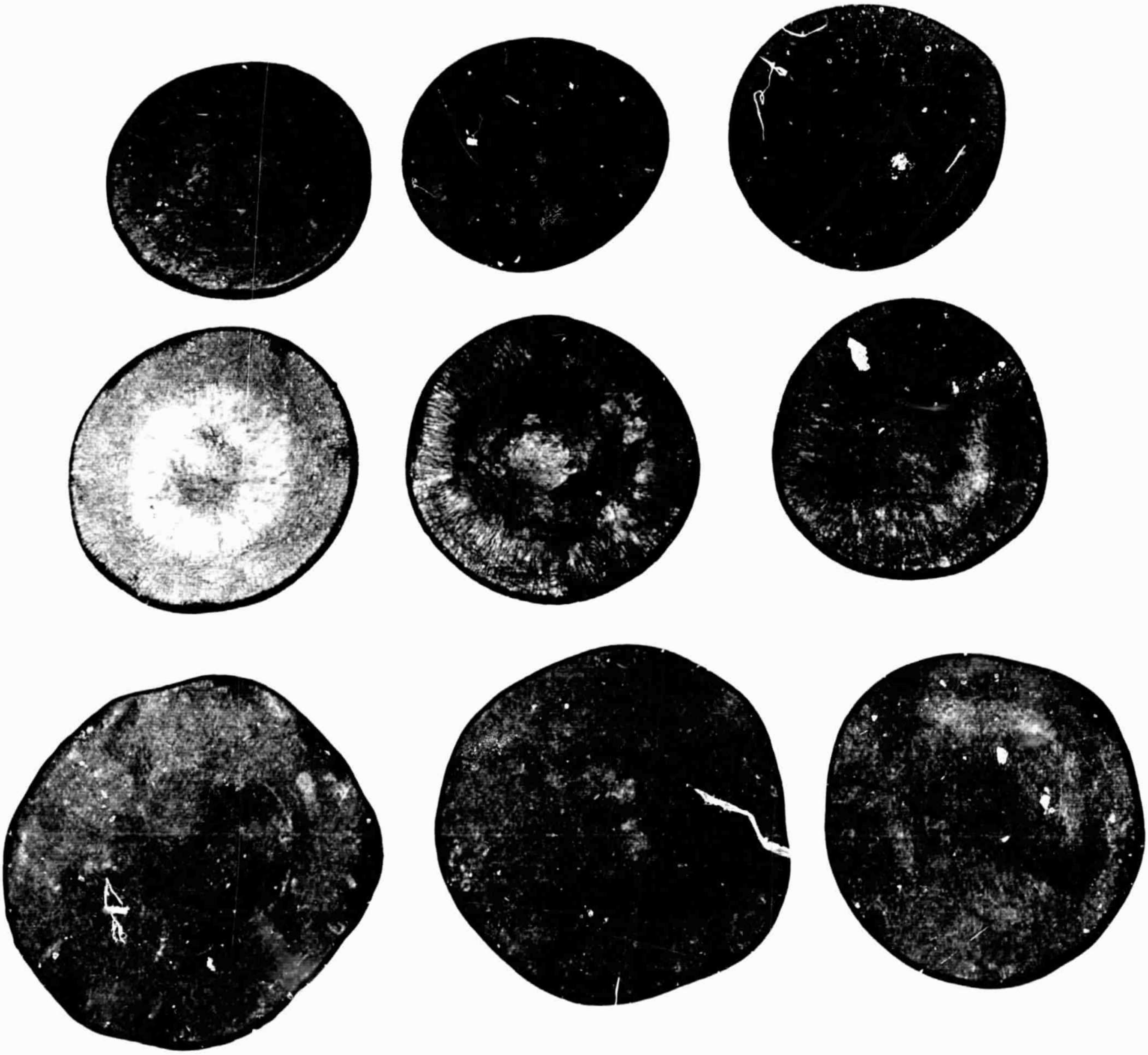

Figure 7. General appearance of 811 titanium alloy biscuits upset forged on 800°F dies. The biscuits are arranged in the same order listed in Table V, with those forged at the lowest ram load at the top and those at full press capacity in the bottom row. Approximately 1/4 full size.

1200°F Die Temperature

The data for 1200°F die temperature tests are presented in Table VI, plotted in Figure 8 and the general appearance of the forgings produced is shown in Figure 9.

The data of Table VI are plotted in Figure 8, again with a line drawn through the points of minimum thickness and unit forging force to show the greatest benefits to be obtained with this die temperature and the forging conditions involved. A parallel dotted line through the maximum point is again used to indicate the spread of the data points.

Comparison of the data and chart with those of the 800°F dies again shows thinner biscuits and lower forging loads made possible by the 400°F increase in die temperature. For example; on the 1200°F dies, 20 tons per square inch forging force produced 0.170" thick biscuit compared to 0.215" thick biscuit with 800°F dies. This is a significant improvement and suggests additional benefits are possible with still higher die temperatures.

Figure 9 shows the relative size and general appearance of the biscuits in this data set. They are arranged in the same order as listed in Table VI with samples 1, 4, and 6 shown as representative of the last set which was forged at full ram load. As in the previous set, the shape is quite regular, although not perfectly circular, indicating uniform lubrication and metal flow. The surfaces are also smooth, but compared to the previous photographs, show somewhat more indication of slug scaling as shown by the radial markings. These are believed to indicate the mode of break-up of the surface scale in forging.

TABLE VI

Upset Forging - 811 Titanium Alloy
Die Temperature 1200°F

Run	Sample	Ram Load (Tons)	Die Temperature (°F.)	Thickness	Area	Tons/sq.in.
27	34	247	1200	.270	16.5	15.0
	35	242	"	.248	17.9	13.5
	36	242	"	.252	17.7	13.7
27	7	415	1200	.207	21.5	19.3
	8	415	"	.223	19.9	20.8
	9	415	"	.208	21.4	19.4
22*	1	543	1200	.169	26.3	20.6
	2	"	"	.195	22.8	23.8
	3	"	"	.194	23.0	23.6
	4	"	"	.182	24.5	22.1
	5	"	"	.187	23.8	22.8
	6	"	"	.202	22.1	24.5

Notes: (1) Forging Stock: 2" diameter, 1.5" high, 1/4" radius.
(2) Slugs dipped in glass slurry prior to heating.
(3) Forging emperature: 1950°F.
(4) Glass slurry on dies prior to heating.
(5) Glass wool between dies and slug on forging.
(6) *Data recalculated for short ton basis.

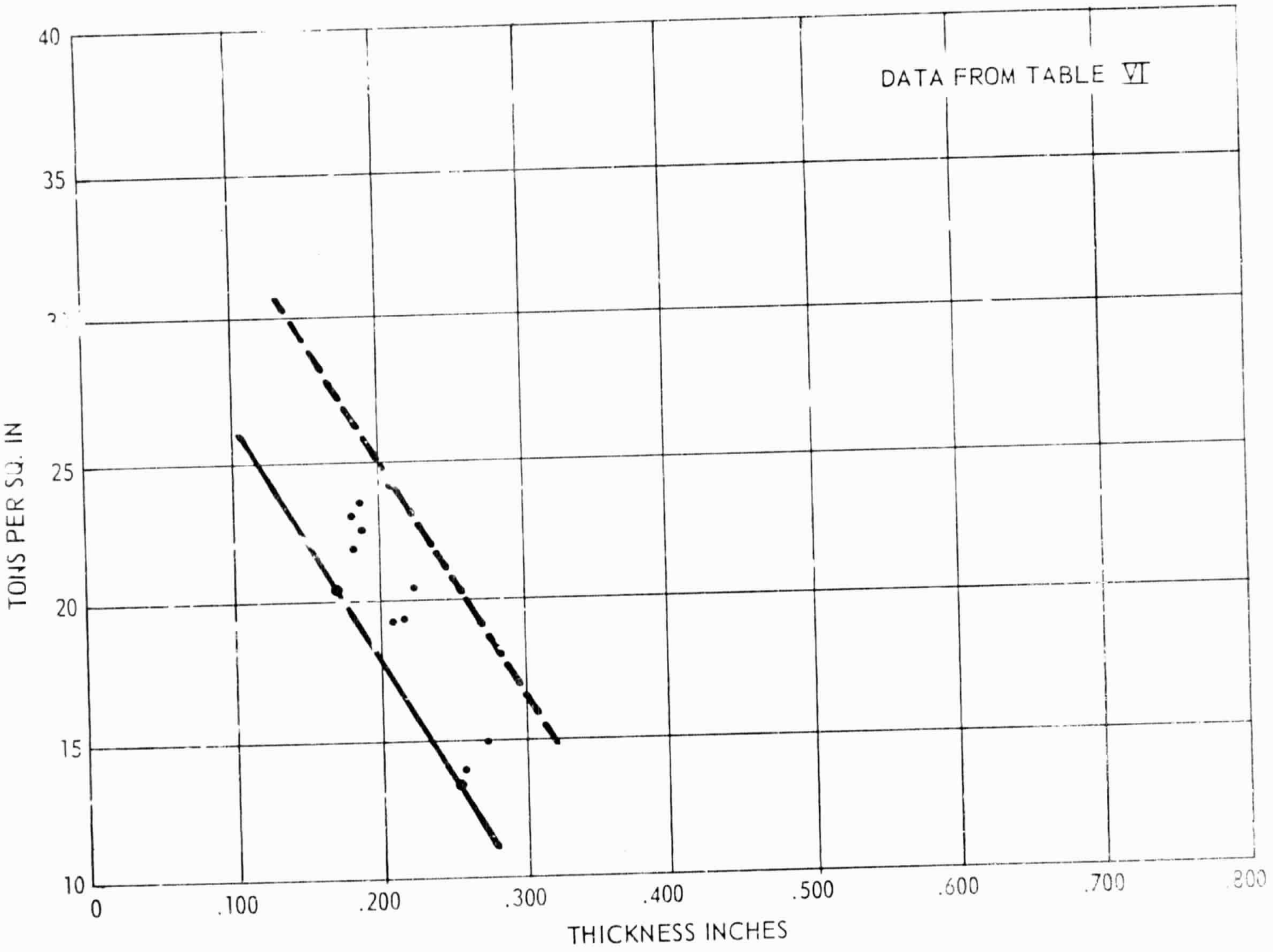

Figure 8. Unit Forging Force For 811 Titanium Alloy Upset on 1200°F. Dies

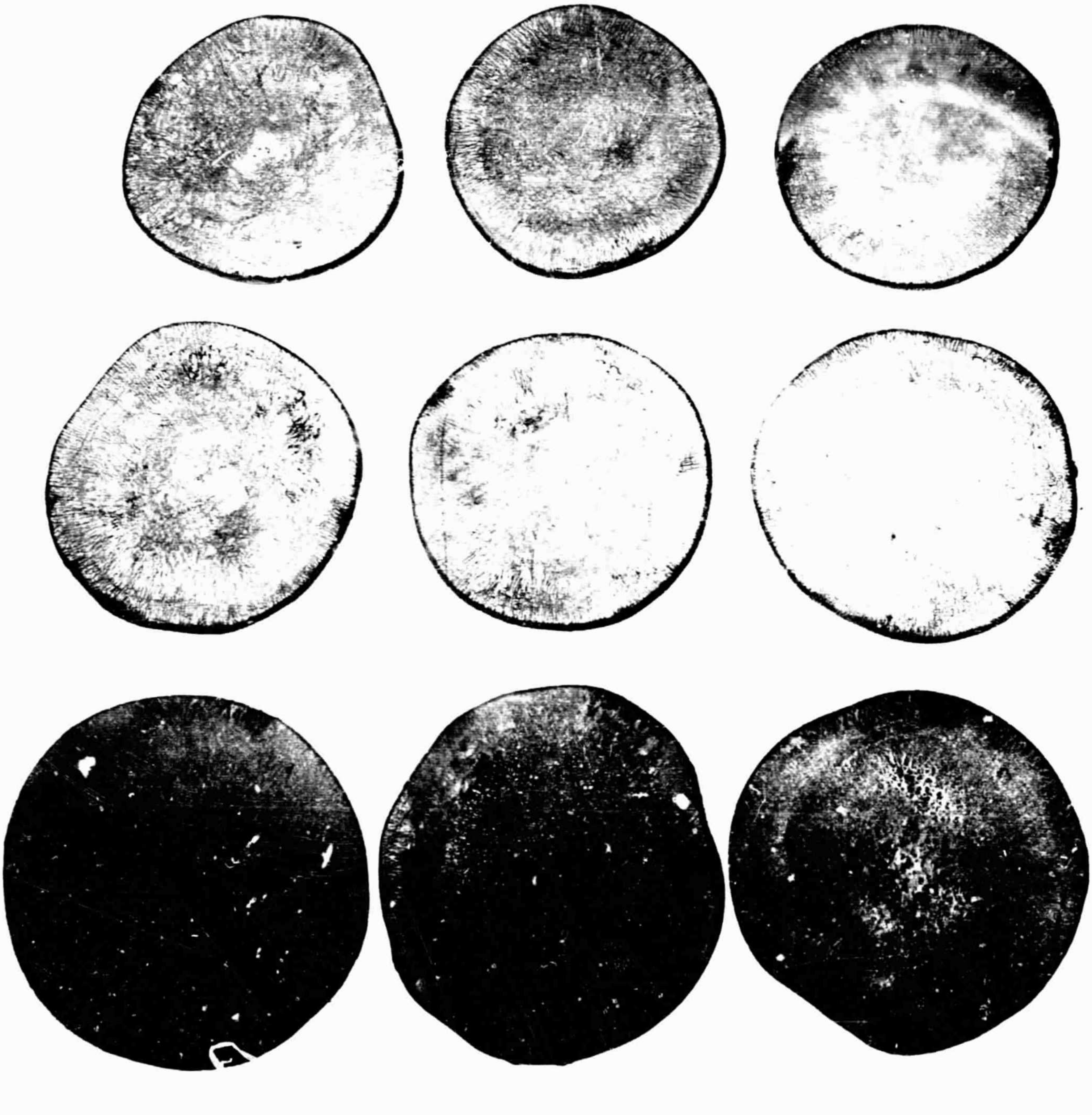

Figure 9. General appearance of 811 titanium alloy upset forged on 1200°F dies. These biscuits are arranged in the same order as in Table VI with those forged at the lowest ram load in the top row and representative pieces of those forged at full press capacity in the last row. Approximately 1/4 full size.

1400°F Die Temperature

The data for upset forging on 1400°F dies are presented in Table VII, plotted in Figure 10 and the general appearance of the biscuits is shown in Figure 11.

As can be seen from the figures and graph these data are in sharp disagreement with the 400, 800 and 1200°F data. The disagreement is so great that it must be concluded that there was some drastic change in conditions. Since lubrication and temperature control of both the dies and slugs were essentially unchanged, it is believed that excessive oxidation of the slugs is the probable cause. As indicated in the table, two sets of data were obtained, Run 28 being the first set, and Run 34 being the second. These two sets agree with each other so it is apparent that both have been affected by the same cause. In both cases, heating the dies to 1400°F took a much longer time and problems of press operation also caused interruptions and delays. As a consequence, the slugs were in the heating furnace about three hours which is much longer than normal and had accumulated an abnormal oxide coating. This would act to restrict metal flow in forging and reduce the effectiveness of the glass wool lubrication. Evidence of this can be seen in the rough veined surface of the biscuits in Figure 11. This photograph includes only the biscuits from Run 28, but those from Run 34 were quite similar.

This series of forging tests should be repeated with particular attention to prevention of oxidation and excessive heating time. It is quite unlikely that the 1400°F die temperature would result in higher forging force and thicker forged biscuits than obtained with lower temperature dies. There are no metallurgical effects in the alloy to account for such a possibility.

TABLE VII

Upset Forging - 811 Titanium Alloy
Die Temperature 1400°F

Run	Sample	Ram Load (Tons)	Die Temperature (°F.)	Thickness	Area (sq.in.)	Tons/sq.in.
28	1	*	1325	.574	7.7	11.9
	2	94	"	.503	8.8	10.7
	3	90	"	.516	8.6	10.5
34	12	120	1400	.437	10.2	11.8
	13	120	"	.449	9.7	12.1
34	10	255	1400	.300	13.4	19.1
	11	240	"	.320	12.5	19.2
28	4	*	1445	.368	12.1	20.3
	5	253	1325	.323	13.8	18.8
	6	238	1325	.344	12.9	18.4
34	5	427	1400	.220	20.2	21.1
	8	450	"	.233	19.1	23.5
	14	427	"	.240	18.6	23.0
28	7	*	1350	.228	19.5	28.0
	8	545	1350	.209	21.3	25.8
	9	547	1350	.221	20.2	27.0
34	6	543	1400	.198	22.5	24.1
	7	*	"	.220	20.2	26.6
	15	525	"	.205	21.7	24.2
	16	543	"	.205	21.7	25.0

Notes:
(1) Forging Stock: 2" diameter, 1-1/2" high, 1/4" radius.
(2) Slugs dipped in glass slurry prior to heating.
(3) Forging Temperature: 1950°F.
(4) Glass slurry on dies prior to heating.
(5) Glass wool between dies and stock.
(6) (*)Pressure record missed, calculations based on average pressure.

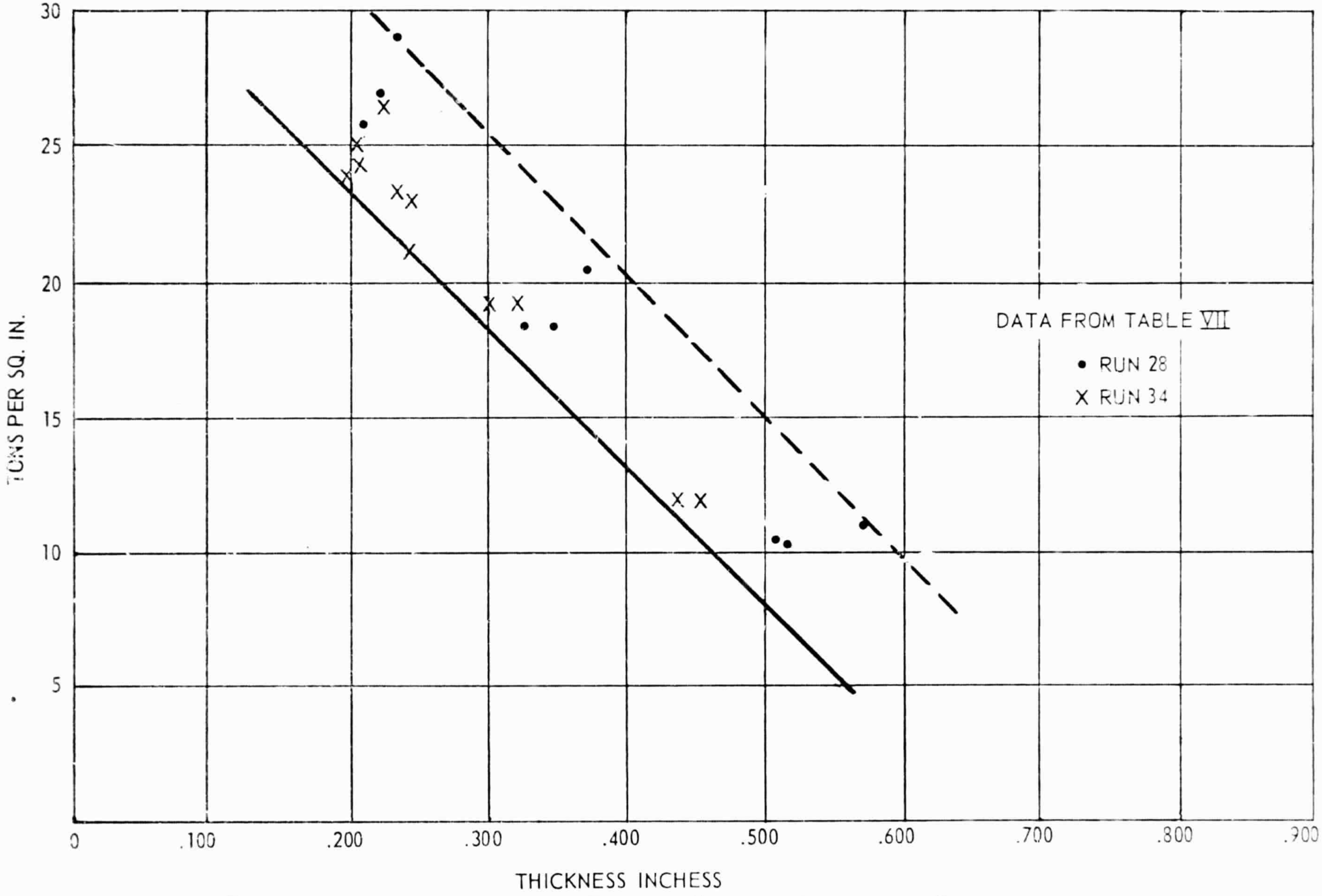

Figure 10. Unit Forging Load For 811 Titanium Alloy Upset Forged on 1400°F. Dies

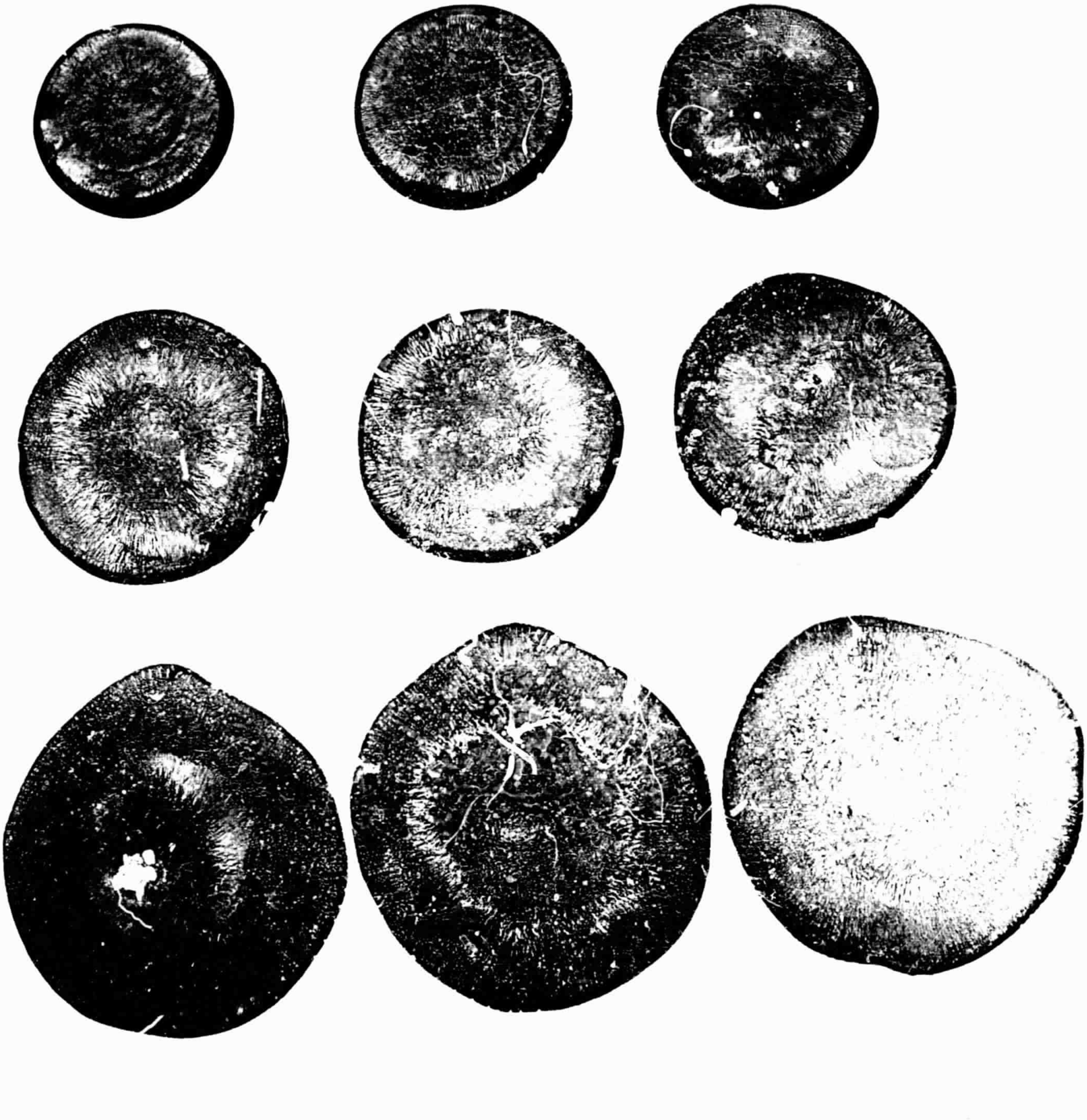

Figure 11. General appearance of 811 titanium alloy biscuits upset forged on 1400°F dies. These biscuits are arranged in the same order as listed in Table VII with those forged at the lowest ram load in the top row and those forged at full press capacity in the bottom row. Approximately 1/4 full size.

SECTION VIII

FLAT DIE WORK ON MARAGING STEEL

The work on the flat die forging of maraging steel is incomplete and the conclusions based on it should be considered tentative. Additional confirmatory data will be required to verify the trends which the present data indicate.

The available data are summarized in Figure 12 which shows the minimum forging load lines for die temperatures ranging from 400 to 1400°F. For this chart the lines are shown dotted to emphasize their tentative character and are drawn parallel to each other with the slope based on the data for the 800°F tests which were considered most complete.

Despite their tentative nature, the lines show a definite and significant trend of decreasing forging load required for a given biscuit thickness as the die temperature increases from 400 to 1400°F. A biscuit thickness of 0.200-inch, which the data suggests would require a unit forging force of almost 35 tons per sq.in. with the die temperature at 400°F, required only about 26 tons per sq.in. at 800°F die temperature, 22-1/2 tons per sq.in. at 1200°F and about 18 tons per sq.in at 1400°F die temperature. This is a significant reduction and gives a general idea of the benefit elevated temperature dies can provide.

Comparing this chart with the similar chart for the 811 titanium alloy (figure 3), it is apparent that the maraging steel required the greater forging force for die temperatures of 800°F and above. The slope of the 811 titanium alloy line is much steeper than those for the maraging steel; again emphasizing the increasing forging loads required to form thin sections in the titanium alloy.

Experimental Procedure

These tests were conducted according to the same procedure used for the 811 titanium alloy as described in the previous section. That is, 2" diameter slugs, 1.5" high were upset between flat dies in a single stroke using a 500-ton hydraulic press. The forging load was determined by monitoring the pressure in the hydraulic system of the press. The forging

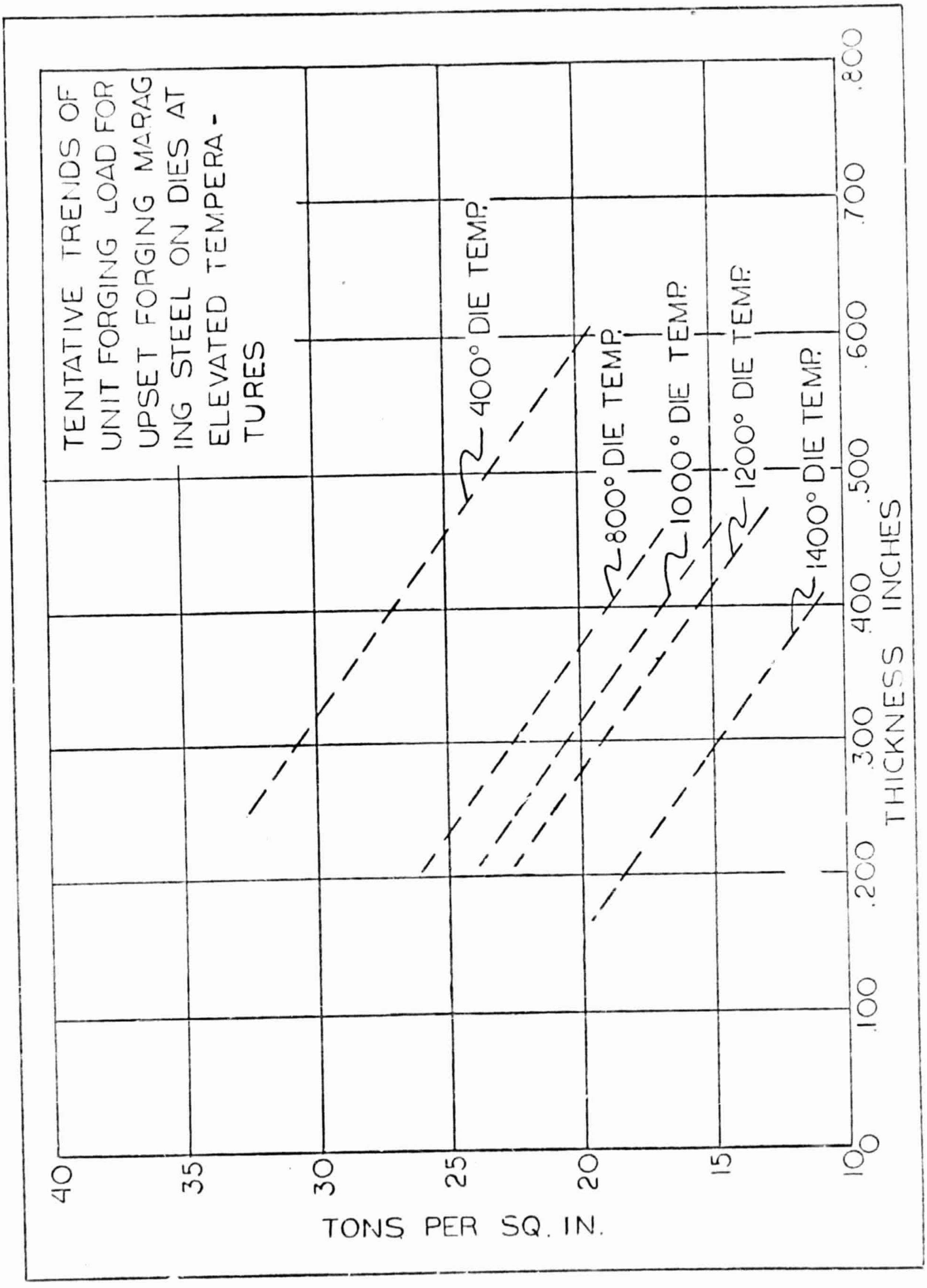
TENTATIVE TRENDS OF UNIT FORGING LOAD FOR UPSET FORGING MARAGING STEEL ON DIES AT ELEVATED TEMPERATURES
400° DIE TEMP.
800° DIE TEMP.
1000° DIE TEMP.
1200° DIE TEMP.
1400° DIE TEMP.
TONS PER SQ. IN.
40
35
30
25
20
15
10
THICKNESS INCHES
0
.100
.200
.300
.400
.500
.600
.700
.800

FIGURE 12

temperature was 1950°F with the slugs protected by a glass slurry coating and a flow of argon gas during heating. The dies were coated with the same glass slurry prior to heating. They were heated with oxy-acetylene torches played over the working face and with the help of a refractory brick enclosure. Glass wool pads were placed under and over the slugs as they were placed on the die for forging. As with the titanium alloy, this was quite satisfactory to 1000°F but produced sticking of the piece to the dies at higher temperatures. This sticking slowed down the forging operation considerably and made frequent re-heating of the die necessary. From three to four pieces were forged under each set of conditions. Variation in thickness of the forged pieces was obtained by regulating the hydraulic pressure in the system.

400°F Die Temperature

The data for the 400°F die temperature tests are shown in Table VIII arranged in order of increasing forging force rather than in chronological order. These data are plotted in Figure 13 to show the relation between unit forging force and biscuit thickness. In this figure, parallel dotted lines are drawn through the minimum and maximum points observed. They are dotted in this and succeeding plots because the data was incomplete as yet and the slopes are tentatively chosen. The distance between these lines effectively illustrates the spread of the data which, while considerable, is not excessive for the conditions involved. The line representative of the minimum forging force and thickness is considered the more significant of the two, since it shows the lowest forging forces obtained, and is probably indicative of the minimum which can be obtained. Accordingly, this is the line that is plotted in Figure 12 for summary of these data and for comparison with the tests at higher die temperatures. The upper line shows the maximum forces encountered. It shows the influence of all of the factors which can be expected to raise the force required for forging; that is, inadequate lubrication, uneven distribution of temperature, press malfunction, slow operation, etc., and hence indicates spread to be expected but does not establish the limit which may be encountered.

The appearance of the forged pieces is shown in Figure 14. They are arranged in the same order of increasing forging force and hence thickness as in Table VIII. It will be noted that

TABLE VIII

Upset Forging - Maraging Steel
Die Temperature 400°F

Run	Sample Number	Pressure (tons)	Die Temperature (°F.)	Thickness (inches)	Area (Sq.In.)	Tons/sq.in.
27	13	180	400	.627	7.1	25.4
	14	181	400	.604	7.4	24.5
	15	190	400	.577	7.7	23.5
27	10	381	400	.412	10.7	35.6
	11	378	400	.374	11.6	32.5
	12	386	400	.389	11.4	33.8
25	1	543	400	.277	16.4	33.0
	2	543	400	.296	15.1	34.9
	3	543	400	.270	16.5	32.8
	4	543	400	.263	16.8	32.2

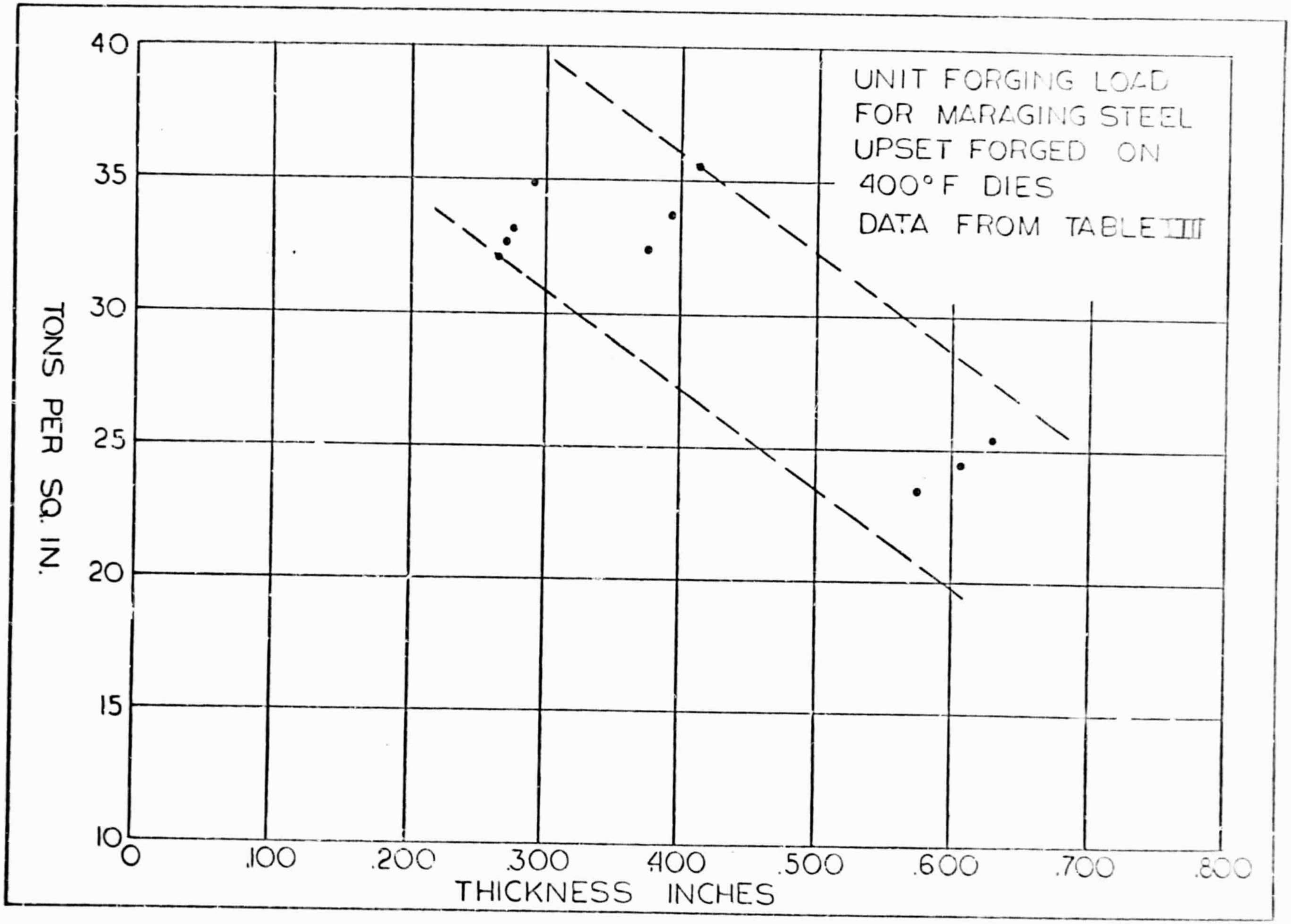
UNIT FORGING LOAD
FOR MARAGING STEEL
UPSET FORGED ON
400° F DIES
DATA FROM TABLE III
TONS PER SQ. IN.
40
35
30
25
20
15
10
0
.100
.200
.300
.400
.500
.600
.700
.800
THICKNESS INCHES

FIGURE 13