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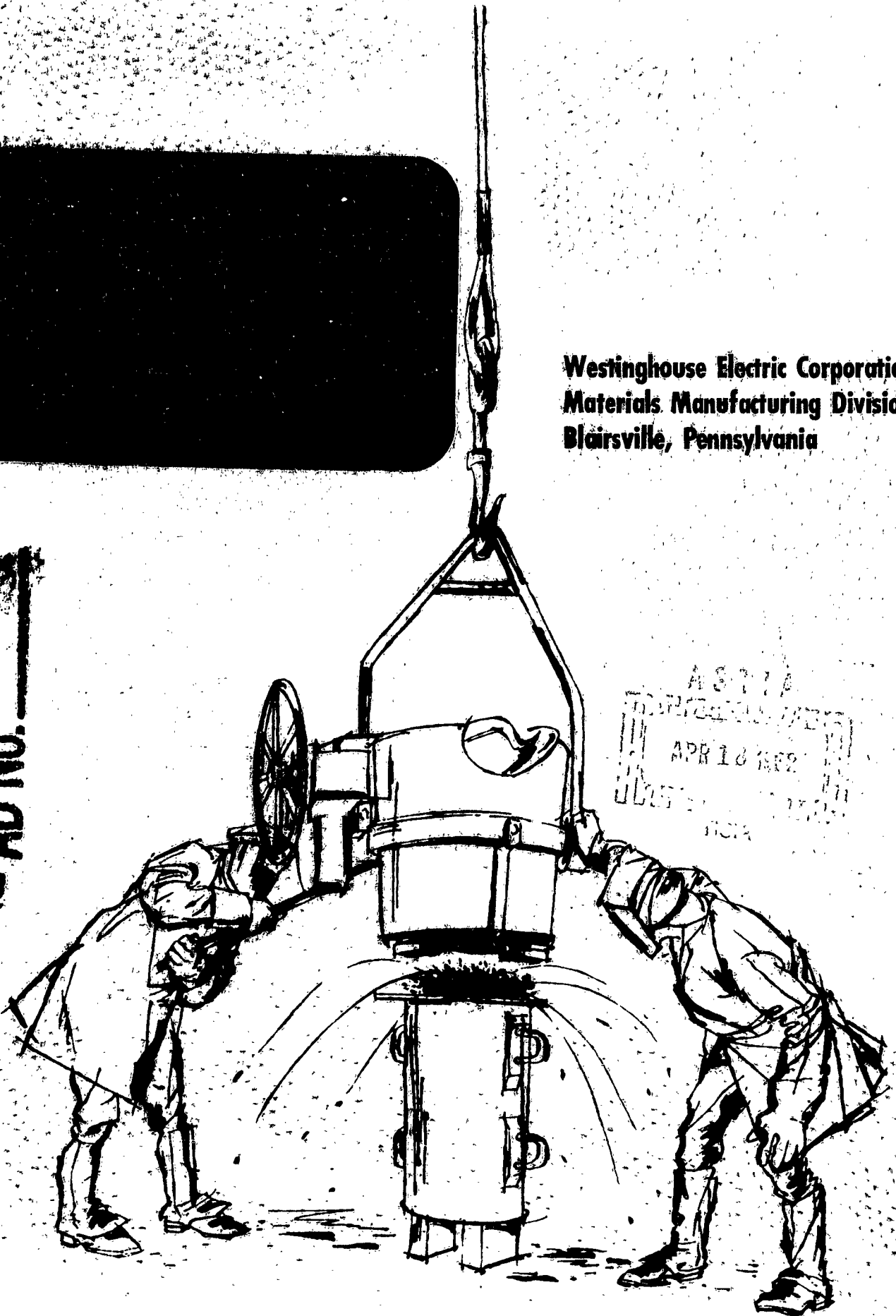
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**Westinghouse Electric Corporation  
Materials Manufacturing Division  
Blairsville, Pennsylvania**

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INTERIM TECHNICAL  
PROGRESS REPORT NO. 6

HIGH ENERGY RATE  
EXTRUSION

Contract No. AF33 (600)-41948

# Westinghouse

ELECTRIC CORPORATION



SUBJECT: High Energy Rate Extrusion  
Contract No. AF 33(600)-41948  
Interim Technical Progress Report No. 6

Gentlemen:

In accordance with the distribution list for the subject contract,  
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Any comments pertinent to this report and the results obtained are  
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contract would be appreciated.

Very truly yours,

F. L. Orrell  
Section Manager  
Development Contracts

FLO:ls

Enclosure

HIGH ENERGY RATE EXTRUSION

by

J. M. Rippel

Westinghouse Metals Plant  
Blairsville, Pa.

The investigation of the high energy rate extrusion process has continued. The effect of ram mass and reduction ratio has been analyzed on pull-off length with results that compare well with experimental data. The Ti-6Al-4V alloy has been extruded in 10-foot lengths. Steel extrusions 10 feet long have been extruded but they separated inertially into smaller lengths. A braking device has been made which gives the desired effect but not to a degree sufficient for making 10-foot extrusions of steel. The extrusion constants for titanium, steel and aluminum under high-velocity extrusion conditions have been determined. The speeds and stresses involved during the extrusion period have been measured and an analysis made of the requirements for a successful braking device.

HIGH ENERGY RATE EXTRUSION

by

J. M. Rippel

WESTINGHOUSE ELECTRIC CORPORATION  
Materials Manufacturing Division  
Blairsville, Pennsylvania

Contract No. AF 33(600)-41948

ASD Project No. 7-882

Interim Technical Progress Report No. 6

Phase II

28 December 1961 to 31 March 1962

Aeronautical Systems Division  
Air Force Systems Command  
United States Air Force  
Wright-Patterson Air Force Base, Ohio

FOREWORD

This Interim Technical Progress Report covers the work performed under contract AF 33(600)-41948 from 28 December 1961 to 31 March 1962. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract was awarded to the Westinghouse Electric Corporation and is being carried out at the Materials Manufacturing Division, Blairsville, Pennsylvania. Mr. J. M. Rippel of the Westinghouse Materials Manufacturing Division, was the Project Engineer. Mr. D. G. Rabenold, Materials Manufacturing Division also contributed. It was administered under the technical direction of Mr. T. S. Felker, ASRCTB, Manufacturing Technology Laboratory, Wright-Patterson Air Force Base, Ohio.

APPROVED:

  
F. L. Orrell  
Section Manager  
Development Contracts

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A. INTRODUCTION

The purpose of this contract is to advance the state-of-the-art of high energy rate extrusion and to determine the capabilities of the Dynapak machine when applied to the extrusion of various metals into structural shapes of the quality required for aircraft, missile and spacecraft construction.

Investigation of the process parameters will comprise the bulk of effort in determining precisely the capabilities and limitations of the machine relative to extruding the desired lengths and cross-sections..

The first phase of the contract required a literature review and state-of-the-art survey. This report was completed 15 February, 1961, and authorization to begin Phase II was received 1 March, 1961.

The objective of Phase II is to develop the basic extrusion operation for steel and titanium and conduct experimentation necessary to evolve an optimum manufacturing process for the production of selected materials into extrusions equivalent to those normally supplied by the industry.

As Phase II progressed, five major problem areas became apparent:

- (1) The available energy of the 1210 Dynapak machine did not appear sufficient to extrude the required volume, 18 cubic inches, of titanium and steel to make the desired 10-foot lengths of a 2" x 1" x .050" T-section.
- (2) The reduction ratio for this thin walled configuration is very high.
- (3) The die erosion, which occurs when extruding titanium, is very high and adversely affects tolerances and extrusion surface quality.
- (4) The high speed of the machine and the severe reduction

ratios caused numerous tooling failures. (5) The phenomena of inertial separation, a condition caused by the rapid deceleration of the extrusion, prevented the extrusion of long lengths. At the start of the extruding operation, the nose of the extrusion emerges from the die at approximately 1000 feet per second and several milliseconds later the tail of the extrusion emerges at less than 50 feet per second. Inertial separation occurs because the force required to slow the front end of the extrusion exceeds the tensile strength of the extrusion and it literally pulls itself apart.

It now appears that the 1210 Dynapak has the energy to extrude 10 foot lengths of aluminum and 10-foot lengths of titanium. This machine, however, cannot extrude the required volume of steel to make 10 feet of the 2-inch by 1-inch T-section. In the past quarter, work on an 1810 Model Dynapak machine, rated at 450,000 ft. lb., demonstrated that 10 foot lengths of both titanium-6AL-4V and 4340 steel can be extruded on this machine. The energy requirement is no longer a limitation for Phase II extrusions.

The reduction ratio problem has been minimized by using the smallest possible billet that will cover the configuration (2-1/16-inch diameter). The 2-inch by 1-inch T-section has been extruded successfully from this size and die fill-out has not been a problem. The reduction ratio is 22:1 rather than 33:1 or 47:1 which it would be if a conventional 2-1/2-inch or 3-inch diameter container were used for this configuration.

Die wear has been considerably reduced by using ceramic coated dies for titanium. Die life varies from 1 to 4 shots; failure results when the oxide coating chips off, actual die wear is small.

Many tooling failures were encountered, most of which were a result of overloading. Stresses up to 250,000 psi are often encountered in this type of operation. Failures have been minimized by improved tooling design, more uniform billet heating, die design (entrance angle), and the use of higher strength materials. The use of strain gauges on the tooling during extrusion has provided much information on the tooling requirements.

The problem of inertial separation has yet to be completely solved. Work in the past quarter has led to the development of a simple friction brake with which a single-piece titanium extrusion 10 foot long was produced. It has not, however, been possible to make 10-foot steel extrusions in one piece and work during the next period will be directed toward this goal.

#### B. CONCLUSIONS

- (1) It has been demonstrated that the Model 1810 Dynapak machine is capable of extruding Ti-6Al-4V alloy and AISI 4340 steel in the volume (18 cubic inches) necessary to obtain 10-foot lengths of the required "T" configuration. Since previous work during this program has demonstrated the equivalence of 4340 steel and type 304 stainless steel for extrudability, it has been demonstrated indirectly, then, that the necessary volume of stainless steel can also be extruded by the Model 1810 Dynapak machine.
- (2) Sufficient experimental data were obtained to permit defining quantitatively the effect of different ram weights (equivalent masses) on the length of product, other extrusion conditions being held constant. The variation of these parameters under a number of extrusion conditions has been developed graphically.

- (3) The diameter of the tooling has a direct effect on the length of extrusions which can be obtained. The smaller the diameter at a fixed reduction ratio, the longer the piece which can be obtained.
- (4) The speed at which the extrusion is produced does not greatly affect the extrusion pressure over the range of speeds from 15 in./sec. (conventional extrusion) to 500 in./sec. (high-velocity extrusion).
- (5) To obtain 10-foot lengths of titanium on the 1210 machine, a brake is required that can exert a uniform retarding force of approximately 3,000 pounds.
- (6) The efficiency of the 1210 Dynapak machine varies from approximately 83% at 900 psi fire pressure to 62% at 2000 psi fire pressure.

### C. DISCUSSION AND RESULTS

#### 1. Catching Devices

The phenomena of inertial separation has led to a series of devices and methods for preventing it. One of the most simple devices which was investigated was a wooden frictional brake.

Two pieces of wood 2" x 4" x 10' were placed below the die and the "T" section extruded into the gap between them. One of the pieces of wood was cut to allow the bottom leg of the "T" to slide through without being restricted (Figure 1). On the first trials a .030-inch to .040-inch gap was maintained between the braking faces. Later, the clearance was reduced to zero and the wooden pieces were held tightly together with clamps. With the proper lead in, the extrusion could be led into this slot. This worked satisfactorily except that the hot extrusion pressing against the wood caused the wood to smoke and burn. This condition was



FIGURE 1

Wooden friction brake used to catch and decelerate extrusions. Wood is faced with 1/4-inch transite. The brake is clamped together and inserted into the bolster just below the die. The extrusion enters after traveling several inches and is then retarded and held rigid as it forces its way between the surfaces.

eliminated by facing the wood with a 1/4-inch transite plate. Transite is a high-temperature, fire-resistant material often used in furnace construction. This was effective in reducing smoke and makes a suitable surface for the extrusion to slide on.

The effect of the brake can be readily seen by comparing extrusion number 358 (Table 1) with 364 and 353. Without the brake, extrusion number 358 pulled off after 36 inches had been extruded. The other two extrusions did not pull off or even neck down (see Figure 2) after 76 inches had been extruded. This does demonstrate the feasibility of this type of brake although it was not entirely successful in later attempts when larger and longer pieces were made on the 1810 Dynapak machine.

The limiting force which can be applied with this type of device is the sum of the force required for the extrusion to open the brake and force itself between the two faces in a wedge-like fashion plus the sliding frictional force. In most cases, because of the high speed and type of materials involved, the frictional force is probably very low until the latter part of the extrusion period when the extrusion has slowed down. The force required for the nose of the extrusion to open up the brake and force its way through can probably be increased by making the brake of harder and heavier material. By making the brake from harder material there will be less tendency for the brake material to be compressed and thus the forces exerted against the extrusion will be maintained at higher levels, similar to differences in forces exerted on a nail as it is driven into soft and hard wood. By making the brake

No.	Material	Red. Ratio	Die Entry Angle	Energy 1000 Ft.Lbs.	Temp. Of	Billet Dia. (In.)	Ext. Lgth. (In.)	Extruded Vol. in <sup>3</sup> /1000 Ft. Lbs.	Remarks
372	Ti6Al4V	22	90°	97.5	1650	1-7/8	34	.048	Partial ext.; no pull off
373	Ti6Al4V	22	90°	105	1650	1-7/8	38	.051	Partial ext.; no pull off
371	Ti6Al4V	22	90°	115	1650	1-7/8	41	.051	Partial ext.; no pull off
4A1	6061Al	22	90°	65	300	1-7/8	17	.038	Partial ext.; no pull off
5A1	6061Al	22	90°	65	300	1-7/8	19	.041	Partial ext.; no pull off
6A1	6061Al	22	90°	65	300	1-7/8	19	.041	Partial ext.; no pull off
376	Ti6Al4V	20.6	90°	125	1650	1-7/8	58	.066	Partial ext.; no pull off
378	Ti6Al4V	20	90°	125	1560	1-7/8	38	.043	Partial ext.; no pull off
374	Ti6Al4V	20	90°	125	1560	1-7/8	39	.044	Partial ext.; no pull off
375	Ti6Al4V	20	90°	125	1560	1-7/8	36	.041	Partial ext.; no pull off
379	6061Al	27:1	120°	97.5	390	1-7/8	--	----	Tooling Fabrics; no extrusion
368	4340	21	90°	74	1875	1-1/4	--	.051	Pull off
370	4340	21	90°	74	1875	1-1/4	41	.038	Partial ext.; no pull off, die broke
369	4340	21	90°	74	1875	1-1/4	50	.046	Partial ext.; no pull off, die broke
365	4340	21	90°	74	1875	1-1/4	33.5	.038	Partial ext.; no pull off, die broke
363	4340	20.6	90°	89	1875	1-1/4	40.8	.041	Partial ext.; no pull off, die broke
352	Ti6Al4V	16.2	120°	90	1700	1-1/4	54.5	.073	Partial ext.; no pull off
174	Ti6Al4V	16.2	120°	90	1700	1-1/4	62.8	.068	Partial ext.; no pull off
390	Ti6Al4V	21.5	90°	90	1700	1-1/4	72	.064	Partial ext.; no pull off, die broke
367	4340	17.5	180°	96	1875	1-1/4	--	.049	Pull off, no brake used this shot
364	4340	17	180°	96	1875	1-1/4	48.8	.040	Partial ext.; no pull off (wooden brake used)
358	4340	13	180°	96	1875	1-1/4	36&1/4	.056	Pull off (no brake used this shot)
356	304S.S.	16.3	180°	112	1875	1-1/4	66.2	.043	Partial ext.; no pull off (wooden brake used)
353	304S.S.	16.3	180°	153	1875	1-1/4	76.5	.042	Partial ext.; no pull off (wooden brake used)
354	304S.S.	16.2	180°	153	1965	1-1/4	---	.044	Partial ext.; no pull off (wooden brake used)
355	304S.S.	15.3	180°	153	2010	1-1/4	76.75	.045	Partial ext.; no pull off (wooden brake used)
359	4340	15	180°	153	2050	1-1/4	75	.050	Partial ext.; no pull off (wooden brake with transite facing used)

TABLE 1 - LIST OF EXTRUSIONS MADE ON 1210 DYNAPAK MACHINE

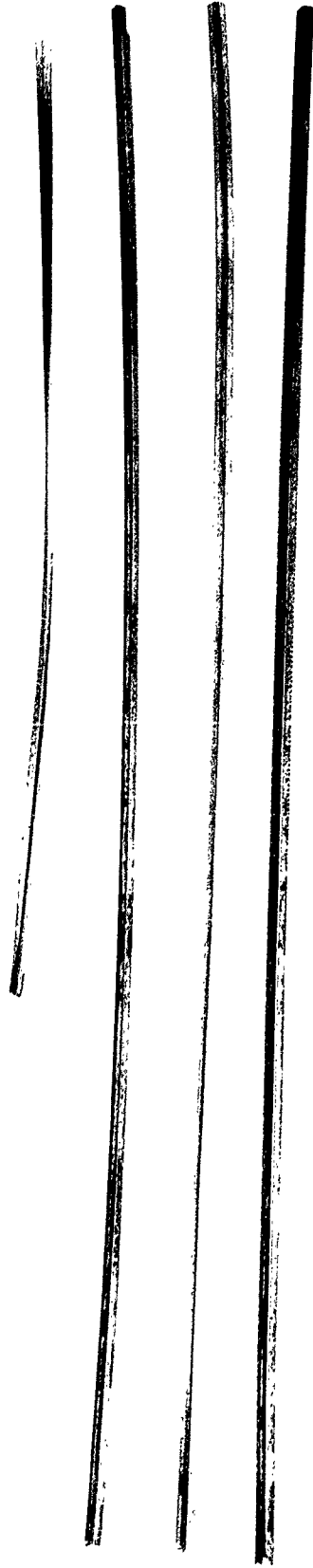


FIGURE 2

Steel extrusions. Top - type 4340 steel necked down and pulled off after 39 inches. Center - two 304 stainless steel extrusions 76 inches long, made by extruding into a wooden frictional brake. Bottom - type 4340 steel extrusion, also 76 inches long made with the aid of the frictional brake.

heavier the force required to push it aside will increase as the larger mass has a higher momentum and thus larger forces will be required to make it move.

## 2. Extrusions on 1810 Dynapak

Six extrusions were made on the 1810 Dynapak machine to verify the fact that the 1810 machine is capable of extruding 10-foot lengths of titanium and steel. From previous data based on the power required to extrude lesser amounts of material, it appeared that this machine could extrude 10-foot lengths of titanium at less than full power and 10 feet of steel near full power. This, as it turned out, was the case. Two extrusions each, of Ti-6Al-4V and 4340 type steel, were made approximately 10 feet long at 1600 psi and 1800 psi fire pressure, respectively. The extrusion conditions are summarized in Table 2.

The extrusions made were of the "T" design 2 inches across the top with a 1-inch leg and thickness from .040 to .055 inches. The variation in thickness occurred mostly in the ceramic coated dies. The ceramic was applied too thick and was not ground down to the proper size. This variation in the thickness of the "T" legs did not have any adverse effect on the extrusions but did increase the reduction ratio on the extrusions with the very thin legs.

The extrusion techniques(parameters) were similar to those previously used on both the 1210 and 1810 Dynapaks. The billets were coated with glass for protection during heating and for lubrication. The container and die were heated to 300°-400°F and liberally coated with a graphite and water lubricant. The billets were heated in an induction furnace

<u>No.</u>	<u>Material</u>	<u>Red. Ratio</u>	<u>Entry Angle</u>	<u>Energy Ft. Lbs. x 1000</u>	<u>Temp. Of</u>	<u>Billet Dia.</u>	<u>Ext. Lenth. (In.)</u>	<u>Vol. Cu. In. Per 1000 Ft. Lbs.</u>	<u>Remarks</u>
391	T16Al4V	22.3	120°	190	1700	1-15/16	77	.062	Partial extrusion; no pull off (no brake).
392	T16Al4V	20.7	120°	210	1700	1-15/16	67	.062	Partial extrusion; no pull off (no brake).
395	T16Al4V	25.1	120°	250	1700	1-15/16	120	.062	Partial extrusion; pull off; Wooden brake used.
396	T16Al4V	25.3	120°	267	1700	1-15/16	116	.054	Partial extrusion; no pull off Wooden brake with transite facing used.
348	4340	23.8	120°	267	2050	1-15/16	121	.042	Partial extrusion; pull off; Wooden brake with transite facing used.
312	4340	23.4	120°	320	2050	1-15/16	113.5	.051	Partial extrusion; pull off; extrusion in pieces due to too high extrusion temp. Wooden brake with transite facing used.

TABLE 2 - LIST OF EXTRUSIONS MADE ON 1810 DYNAPAK MACHINE.

and could be unloaded and extruded with an average transfer time of seven seconds. The tooling was made from H-13 hot work die steel heat treated to 48-50 Rc. The container and punch were 2-1/16-inch diameter. The billets were 1-15/16-inch in diameter and 6 to 6-1/4-inches long.

#### Extrusion Numbers 391 and 392

These two Ti-6Al-4V alloy extrusions were made at 1700°F using 1200 psi and 1350 psi fire pressures, respectively. Ceramic coated dies were used with a 120° entry angle and 21:1 reduction ratio. In both cases, part of the ceramic coating spalled off in a manner similar to that shown in Figure 3. Extrusion number 391 was 77 inches long without any indication of neck down. Extrusion number 392 which was extruded at 1350 psi fire pressure was only 67 inches long because of the enlarged die opening due to the spalled die. The actual reduction ratio in this case was 17:1. The volumes extruded were 11.5 and 13 cubic inches from billets of approximately 18 cubic inches. The extrusions were suspended from the die and were straight although there was some twist in them. These two extrusions point out one significant difference between the conical and the shear die. Previous to this, under identical conditions of temperature, billet size and reduction ratio, the longest length extrusion obtained was only 40 inches with a shear die (see Figure 4A). By using a 120° entry angle on the die, 77 inches was obtained and there was no indication of necking due to inertial forces.

#### Extrusion Numbers 395 and 396

These two extrusions, shown in Figure 4B, were also pushed at 1700°F under conditions similar to extrusions numbered 391 and 392 except that

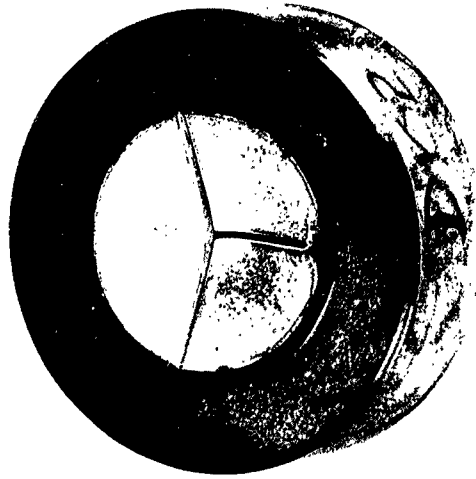


FIGURE 3

Ceramic faced die. Ceramic material did not chip off during extrusion, but chipped while stripping of unexpanded billet. The coating has a tendency to chip on the underside of the Tee intersection.

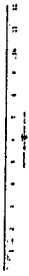


FIGURE 4A

Three titanium-6Al-4V extrusion made at 1700°F. Top extrusion made with shear die, and pulled off after 40 inches. Bottom extrusions made with 120° entry angle, they show no evidence of necked area and are 67 inches and 76 inches respectively.

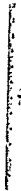


FIGURE 4B

Top type 4340 steel, 121 inches long, extruded at 2050°F. Tee section 2 inches by 1 inch by .050 inch. Center and bottom. Titanium-6Al-4V, 116 inches and 120 inches, extruded at 1700°F.

they were extruded at 1500 psi and 1600 psi, respectively. Extrusion number 395 had a reduction ratio of 25:1 and 120 inches of material was extruded. A wooden friction brake of the type described previously was used. The force exerted by the brake was not sufficient to prevent inertial separation and the extrusion pulled apart in two places. Aside from the front end of the extrusion, which went completely through the brake and bent in the sand, the extrusion was fairly straight. The power was increased for extrusion number 396 in an attempt to make a longer extrusion and the wooden brake was modified by putting transite on the two faces and reducing the gap between the faces from .030 inches to 0. This did prevent the extrusion from parting but there was some necking at the tail end of the extrusion. This extrusion measured 116 inches, including the necked down area. This extrusion turned out to be shorter than anticipated because of die distortion. The die holder was not hardened properly (38 Rc vs 48) and it deformed slightly causing the inserts to distort resulting in a higher reduction ratio than anticipated.

#### Extrusion Numbers 348 and 312

These two extrusions were made from AISI type 4340 steel at 2050°F. The reduction ratio was approximately 23:1 and the fire pressure was 1600 psi and 1800 psi, respectively. At a 13-inch stroke length, 1800 psi fire pressure is approximately 85% of the energy available and is equivalent to an energy of 320,000 ft. lbs. Although the brake was applied to extrusion number 348 in a manner similar to extrusion number 396, it was not sufficient to prevent inertial separation. Two pieces were obtained 86 inches long and 35 inches long for a total of 121 inches.

Extrusion number 312 was heated to 2050°F but either the added energy (267,000 to 320,000 ft. lbs.) or an improper temperature reading caused the material to behave in a hot-short fashion, resulting in many small pieces("pop-corning").

The tooling appeared to hold up well on all extrusions. The punches with which most of the previous tooling failures occurred held up very well. The volume of metal extruded per 1000 ft. lbs. compared favorably with the data previously obtained on the 1210 Dynapak machine although slightly lower.

A significant step forward was made in these 10-foot extrusions of steel and titanium, especially the titanium which was held in one piece with a relatively simple braking device.

### 3. Factors Effecting Inertial Separation

The investigation of the factors which affect inertial separation has continued. Two of the factors, ram mass and billet size, have been investigated on both a 1210 and an 1810 Model Dynapak machine. The effect of these variables are shown graphically in Figures 5 through 8. These curves show the results from more than 100 extrusions. There is a certain amount of variation due to other factors such as billet temperature, die shape, lubrication, stroke length and general die condition which will have an undetermined effect, but the general curves bear out the basic relationships as discussed in the previous reports.

The calculated effect of ram mass predicts that extrusions can be made 70% longer on the 1210 Model Dynapak machine with the heavy ram as compared to the same machine with the light ram. On the curves in

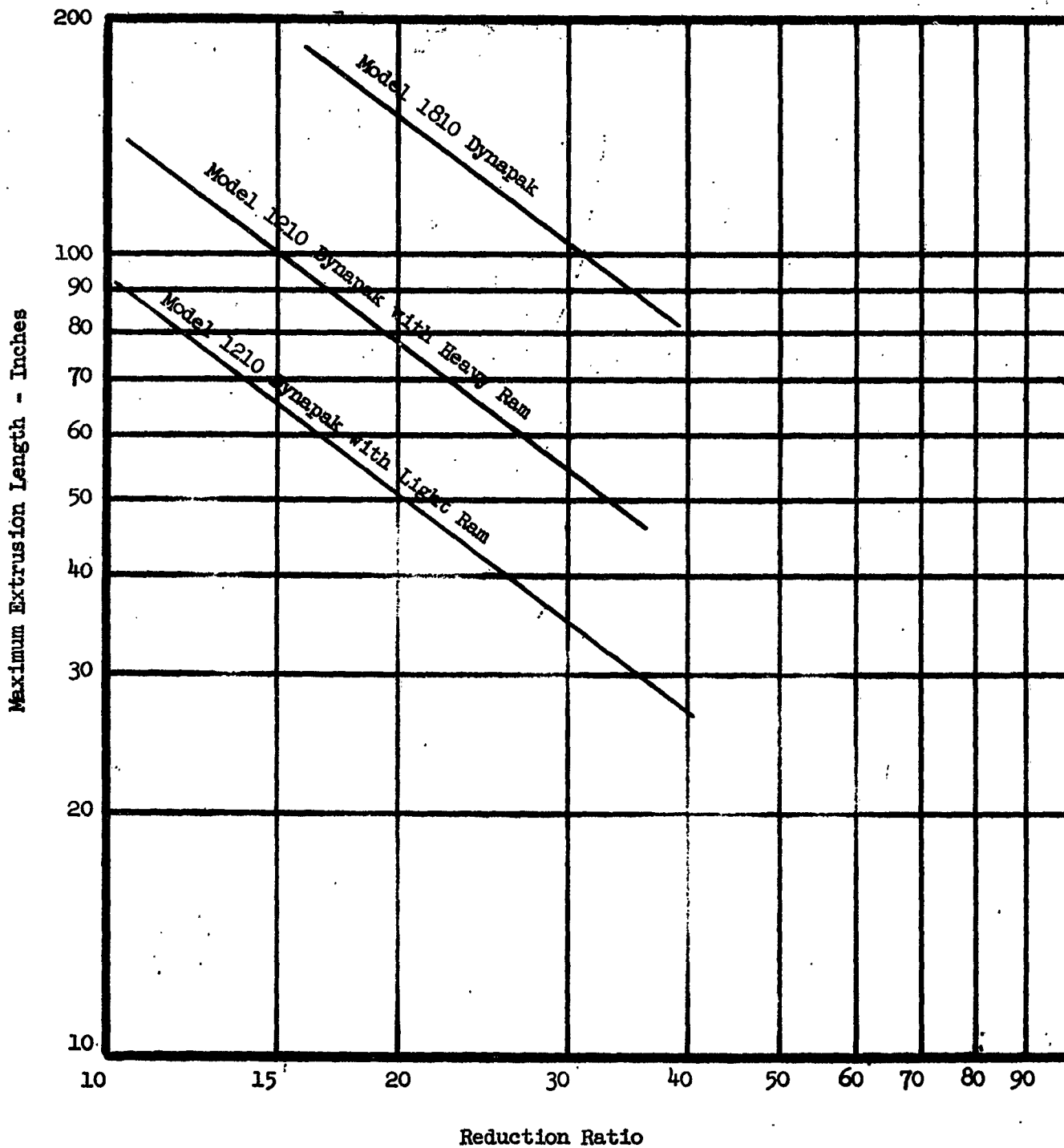
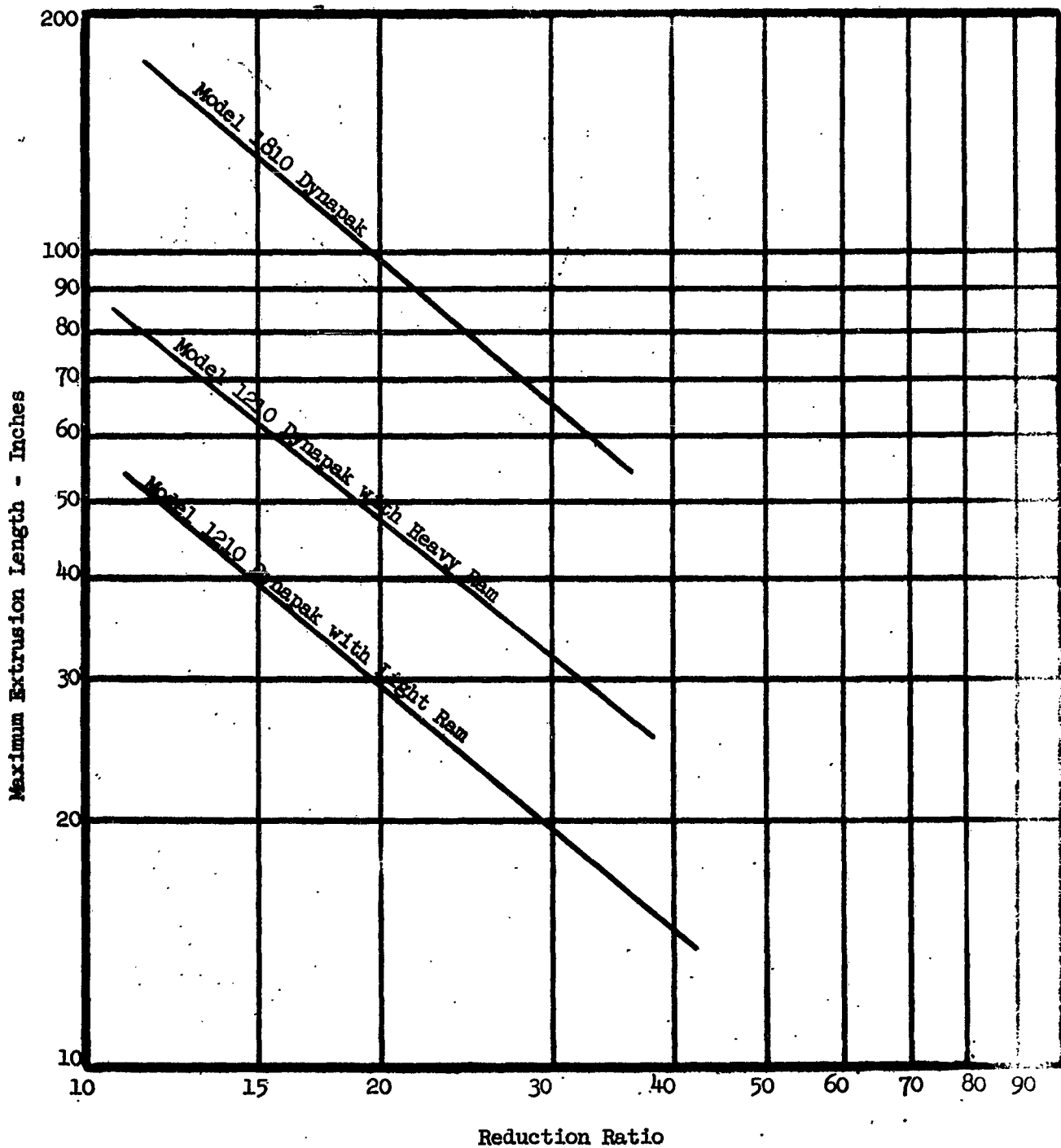
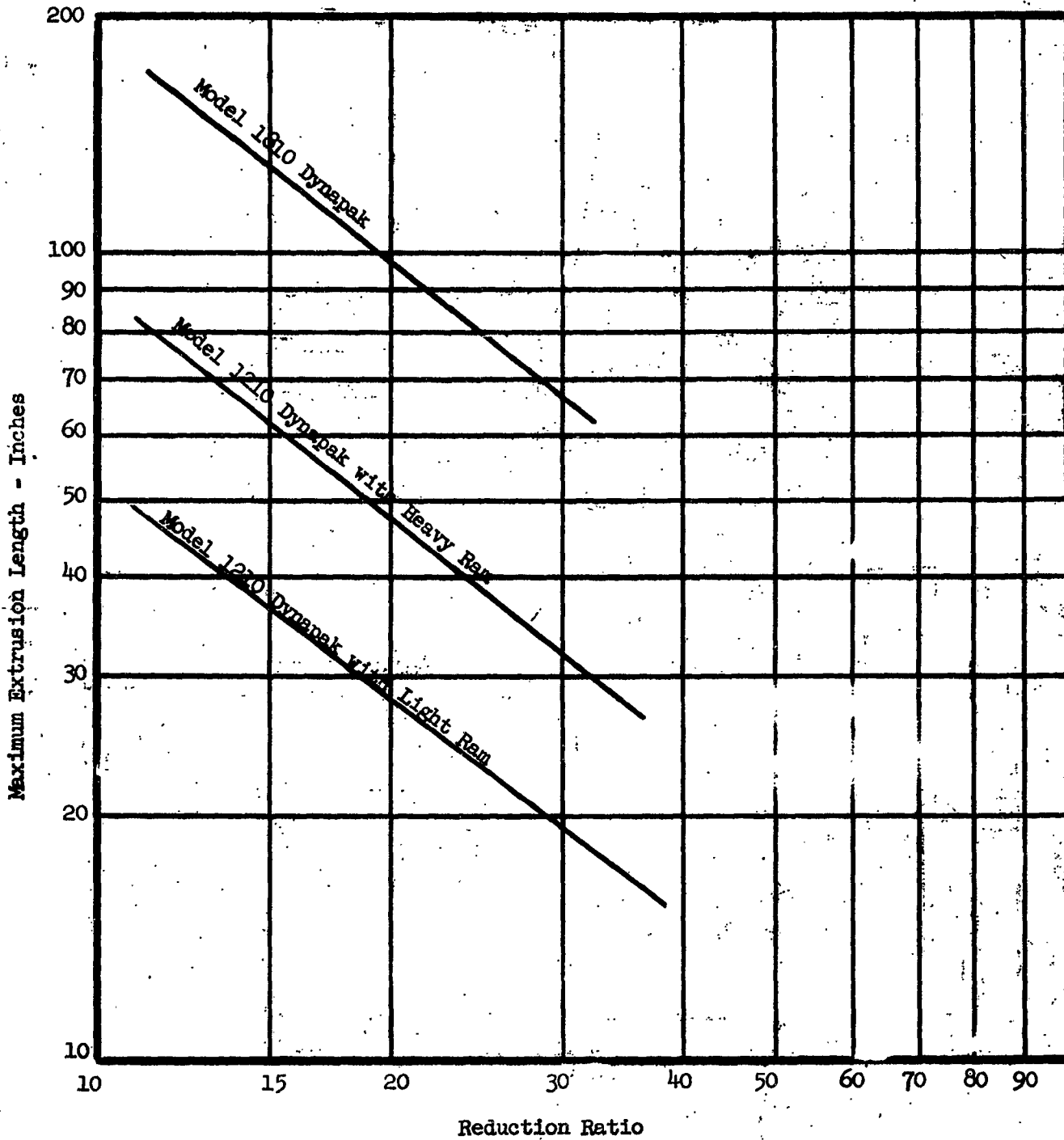


FIGURE 5 - Effect of ram mass and reduction ratio on the maximum length of extrusion which can be obtained in a single piece. These lengths were obtained using Ti-6Al-4V alloy and 1.35 inch diameter tooling.



**FIGURE 6** - Effect of ram mass and reduction ratio on the maximum length of extrusion which can be obtained in a single piece. These lengths were obtained using Ti-6Al-4V alloy and 2 inch diameter tooling.



**FIGURE 7 - Effect of ram mass and reduction ratio on the maximum length of extrusion which can be obtained in a single piece. These lengths were obtained using steel and 1.35 inch diameter tooling.**

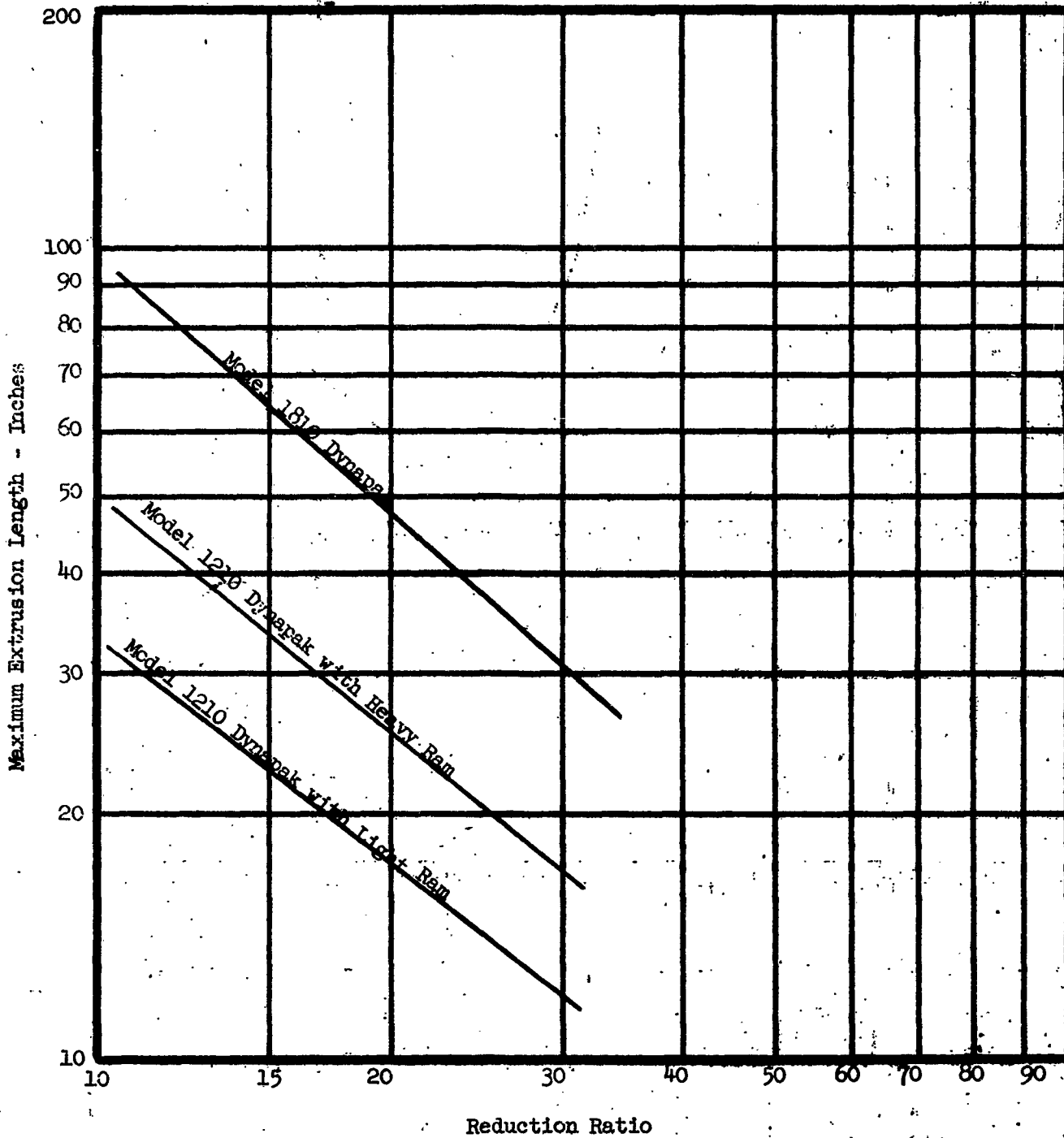


FIGURE 8 - Effect of ram mass and reduction ratio on the maximum length of extrusion which can be obtained in a single piece. These lengths were obtained using steel and 2.0 inch diameter tooling.

Figures 5 through 8 the actual observed increase is 50% to 70% for steel and titanium. The calculated obtainable length on the 1810 machine is twice that which can be obtained on the 1210 machine with the heavy ram and again the figures bear out this relationship with actual increases of 80% to 100%.

The relative mass of the three conditions investigated are 40, 69 and 140 slugs, respectively. Examples of obtainable lengths of steel and titanium (see Figure 9) at a 20:1 reduction ratio under the three conditions are 15 inch, 24 inch, and 48 inches for steel and 30 inches, 45 inches and 90 inches for titanium.

The calculated relationship between container cross sectional area and pull off length compares well with actual values. The cross sectional area of the two containers (1.35" and 2.0" diameter) are 1.46 square inches and 3.14 square inches. The increase from 30 to 52 inches of titanium and 24 to 47 inches of steel under similar conditions represent an increase of 70% to 80%. The actual difference is slightly less than the calculated value (115%) and is probably due to an increase in friction caused by the increase in the surface volume relationship.

The length of the extrusion obtained before tensile failure occurs is a result of the tensile strength of the material and the deceleration of the piece being extruded. Many things affect the deceleration. Factors which increase the deceleration and tend to shorten the extrusion by slowing the ram down at a faster rate are high frictional forces, high extrusion constants, high reduction ratios, long machine strokes, and high back pressure actions on the ram piston. Die design also influences the length, in addition to changing the frictional resistance which is not very significant, it can

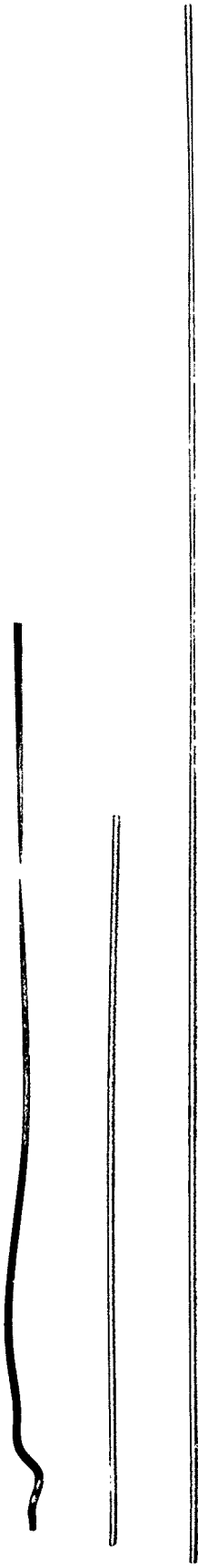


FIGURE 9

FIGURE 9

Titanium-6Al-4V extrusions. Top extrusion (079) made on 1210 machine with light ram. Bottom two extrusions (377 and 376) made using heavy ram. Note the additional length which was obtained using heavy ram.

affect the temperature rise of the extrusion which can have a significant effect on tensile strength. In one case, the length of extrusions increased from 40 to 77 inches when changing from a shear to a conical die.

#### 4. Instrumentation

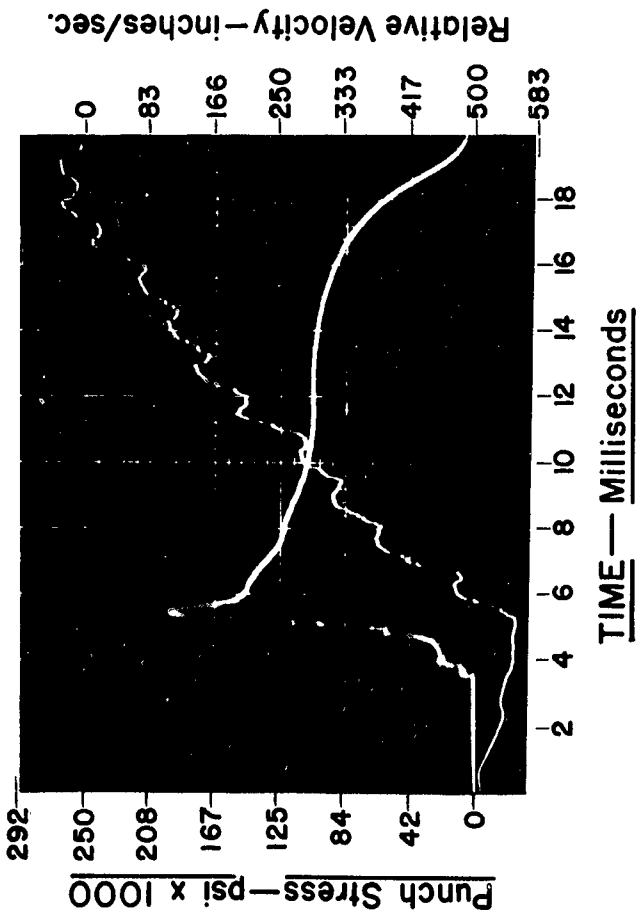
During the past quarter the instrumentation previously described<sup>(1)</sup> has been used on a number of extrusions to obtain ram velocity and extrusion pressure. The extrusion pressures and K factors of steel, Ti-6Al-4V alloy and 6061 aluminum are listed in Table 3. The average K factors obtained for three steel extrusions were 47,000(304 S.S.) 57,000(AISI 4340) and 62,000(AISI 4340). These appear to be typical for these materials at an extrusion temperature of 1875°F. The K factor at break through was approximately 50% higher and resulted in a loading of the punch of 300,000 psi. The punch which was used failed under this load. Type 6061 aluminum at 300°F had a K factor of about the same magnitude as 4340 steel at 1875°F. This appears reasonable when considering their relative strength at their extrusion temperature. As anticipated the K factor for the titanium alloy is somewhat lower with an average value of 48,000 at 1560°F and 34,000 at 1700°F. Even though the speed of this process is many times faster than conventional extrusions, the K factor of material is not appreciably effected. Examples of the photographs of the oscilloscope traces and the conditions under which the material was extruded are shown in Figures 10 and 11.

One extrusion(number 376) was analyzed to determine the stresses imposed on the extrusion at various lengths and to obtain data from which a braking device could be designed. This extrusion is a Ti-6Al-4V alloy

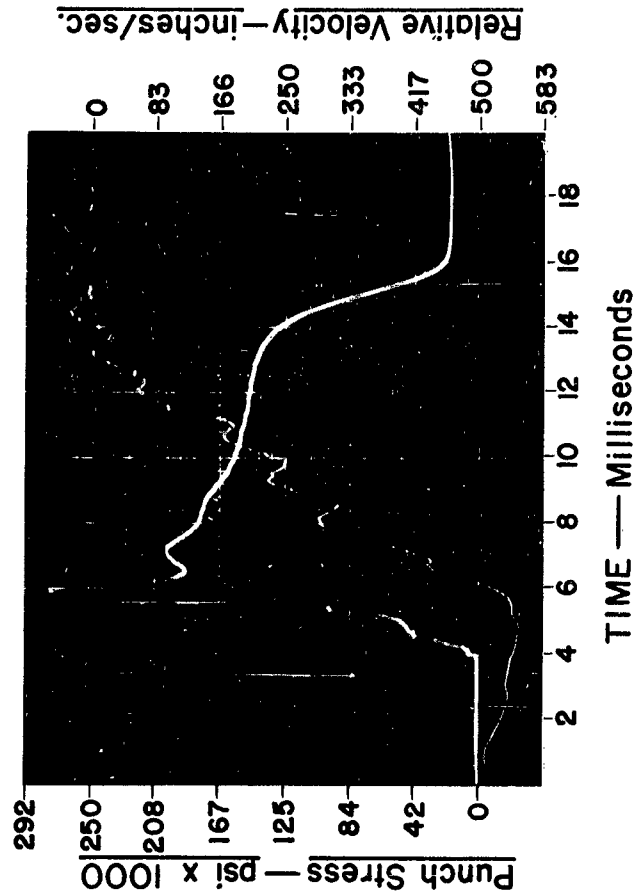
Ext. No.	Material	Temp. °F.	DIE		Punch at break through	STRESS (EXTRUSION PRESSURE) AND K FACTORS x 1000 PSI		
			Red. Ratio	Entry Angle		High	Low	Ave.
250	304 S. S.	1875	22:1	90	Stress 220 K	165	125	145
5A1	6061A1	300	22:1	90	Stress 235 K	51 200	40 170	47 185
6A1	6061A1	300	22:1	90	Stress 235 K	76 190	55 170	60 180
376	T16A14V	1700	22:1	90	Stress 192 K	73 145	55 105	58 120
378	T16A14V	1560	22:1	90	Stress 275 K	62 185	34 145	39 160
374	T16A14V	1560	22:1	90	Stress 89 K	60	47	52
375	T16A14V	1560	21:1	90	Stress 262 K	170	140	160
379	6061A1	300	26:1	120	Stress 84.5 K	55	45	52
368	4340	1875	21:1	90	Stress 206 K	155	115	125
369	4340	1875	21:1	90	Stress 66.5 K	50	37	40
					Stress 300 K	Tooling	Failure	
					Stress 92 K	205	175	190
					Stress 306* K	67.5	57.5	62.5
					Stress 100 K	210	170	175
					Stress 290* K	69	56	57.5

\* These two extrusions bent punch.

TABLE 3 - EXTRUSION CONSTANTS AND PUNCH STRESSES MEASURED WHILE EXTRUDING TITANIUM 6AL-4V, STEEL AND 6061 ALUMINUM. THE HIGH, LOW AND AVERAGE VALUES WERE OBTAINED AFTER BREAK THROUGH AND DO NOT INCLUDE PEAK STRESS.



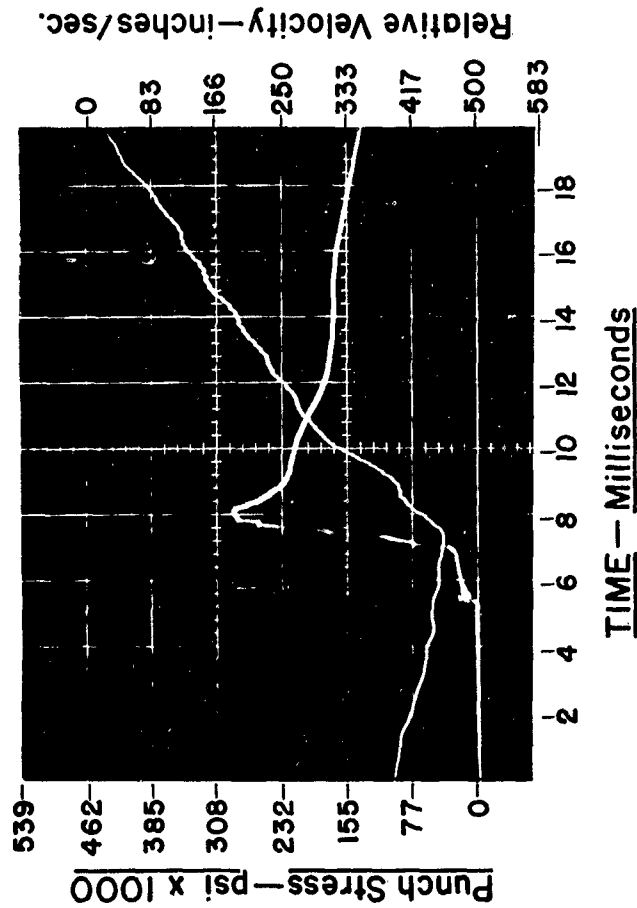
Billet Number	376
Material	Ti-6Al-4V
Temperature	1700°F
Reduction Ratio	22:1
Billet Diameter	2 inches
Fire Pressure	1700 psi
Peak Stress	192,000 psi
Peak Velocity	550 inches/sec.
Length Extruded	58 inches



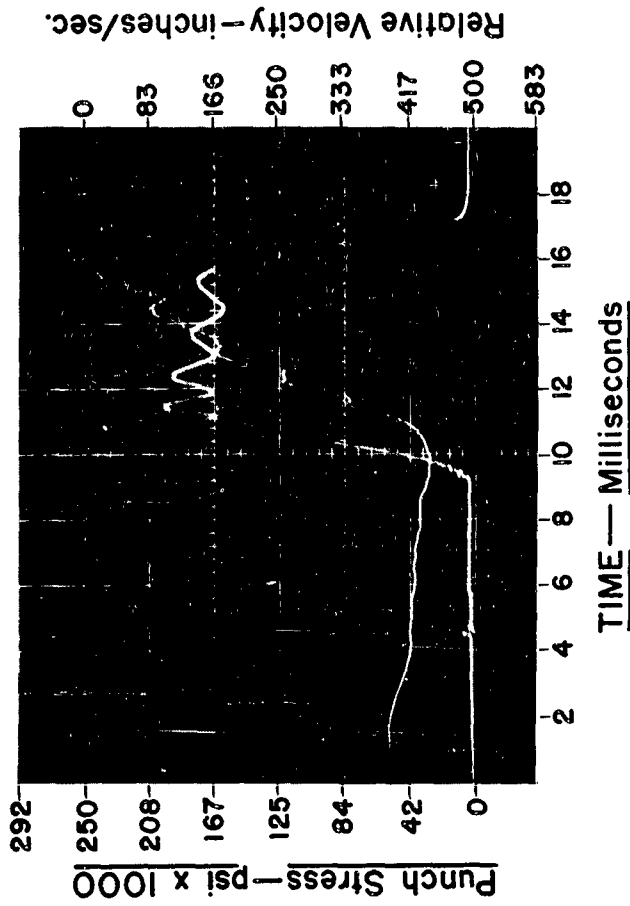
Billet Number	378
Material	Ti-6Al-4V
Temperature	1560°F
Reduction Ratio	22:1
Billet Diameter	2 inches
Fire Pressure	1700 psi
Peak Stress	275,000 psi
Peak Velocity	550 inches/sec.
Length Extruded	38 inches

FIGURE 10

Photograph of oscilloscope trace of strain gauge and velocity transducer output during extrusion. Stress reads from the bottom and velocity from the top of photograph.



Billet Number 369  
 Material 4340 Steel  
 Temperature 1875°F  
 Reduction Ratio 21:1  
 Billet Diameter 1-1/4 inches  
 Fire Pressure 1200 psi  
 Peak Stress 290,000 psi  
 Peak Velocity 458 inches/sec.  
 Length Extruded 43 inches



Billet Number 5 Al  
 Material 6061 Al  
 Temperature 300°F  
 Reduction Ratio 22:1  
 Billet Diameter 2 inches  
 Fire Pressure 1000 psi  
 Peak Stress 235 psi  
 Peak Velocity 442 inches/sec.  
 Length Extruded 20 inches

FIGURE 11

Photograph of oscilloscope trace of strain gauge and velocity transducer output during extrusion. Stress reads from the bottom and velocity from the top of photograph.

and was extruded at 1700°F with a reduction ratio of 22:1. These conditions are similar to those required to extrude the prescribed "T" section. Plots of the speeds, stresses and forces are shown in Figures 12 through 15. Of primary interest are the calculated stresses imposed on the extrusion as shown in Figure 15. A tensile failure began in this extrusion after 36 inches had been extruded and the stress was approximately 13,000 psi. A minimum stress of 20,000 psi would be required to avoid necking of the 120-inch extrusion. This is a force of 3,000 pounds for the cross sectional area being considered (.15 square inches) or a retarding force of 25 pounds per inch of extrusion length.

Similar data were obtained for steel extrusions. When the temperature of the steel is adjusted so that similar deceleration rates are obtained, the force acting on the extrusion is proportional to the density of the material. Thus to make a 120-inch extrusion of steel requires a braking force of approximately 50 lbs. per inch of extrusion and tungsten would require approximately 120 lbs. As the extrusions are made at lower and lower temperatures the deceleration rates increase and the force required by a braking device would also increase. The tensile strength of the extruded material would also increase but this would not significantly reduce the forces required by the braking device.

Essentially a braking device is required that can exert retarding forces of 3,000 pounds to 15,000 pounds over a 120-inch long extrusion as the speed of the extrusion decreases from 1000 ft./sec. to zero ft./sec.

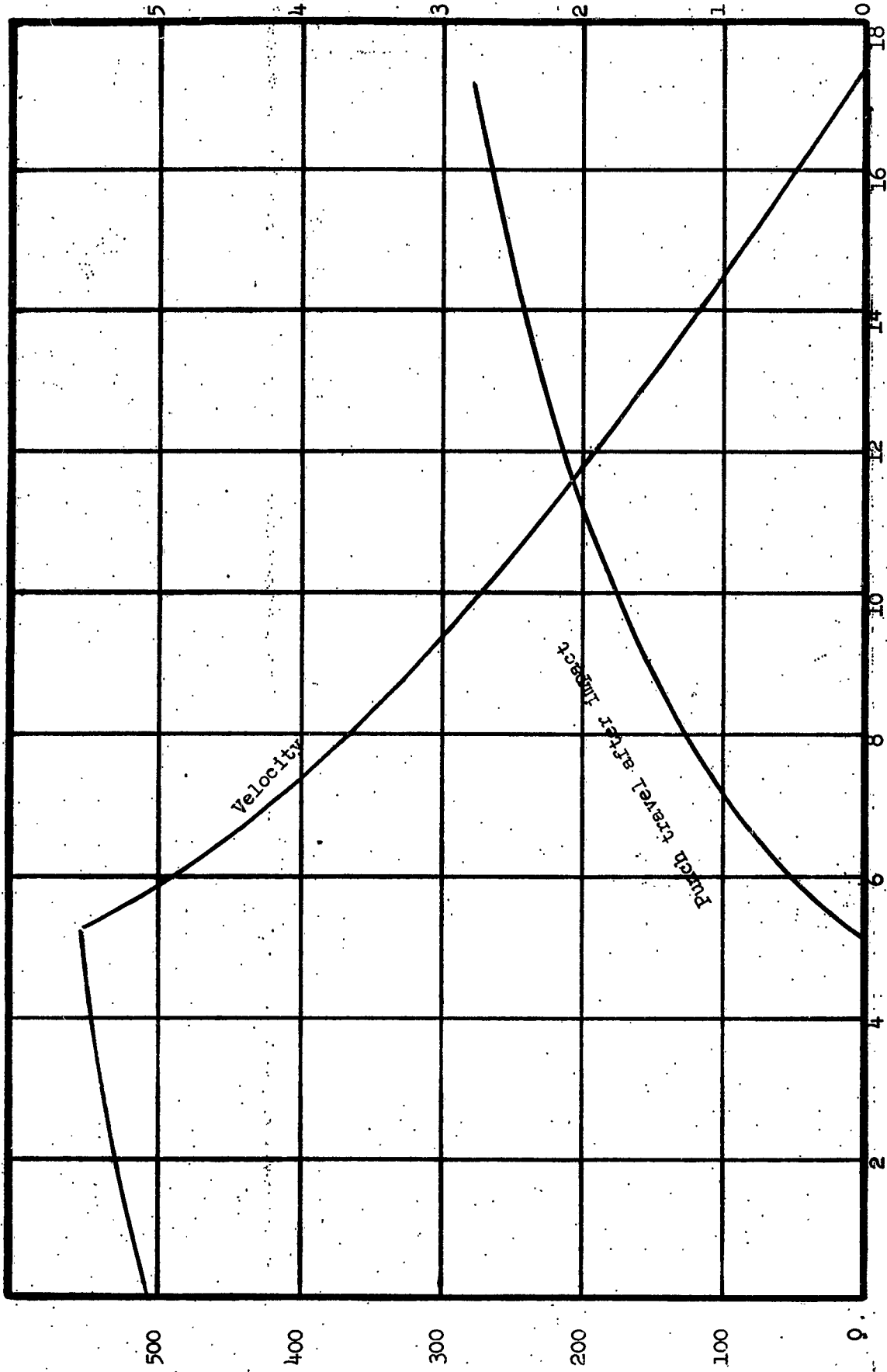


FIGURE 12 - Plot of the relative punch and ram velocity and the relative movement after impact of extrusion 376. The velocity curve is reproduced from Figure 10. Distance traveled after impact is a function of velocity and time.

Relative Velocity - Inches/sec.

Time - Milliseconds

Velocity

Punch travel after Impact

500

400

300

200

100

0

2

4

6

8

10

12

14

16

18

5

4

3

2

1

0

Punch Travel - Inches

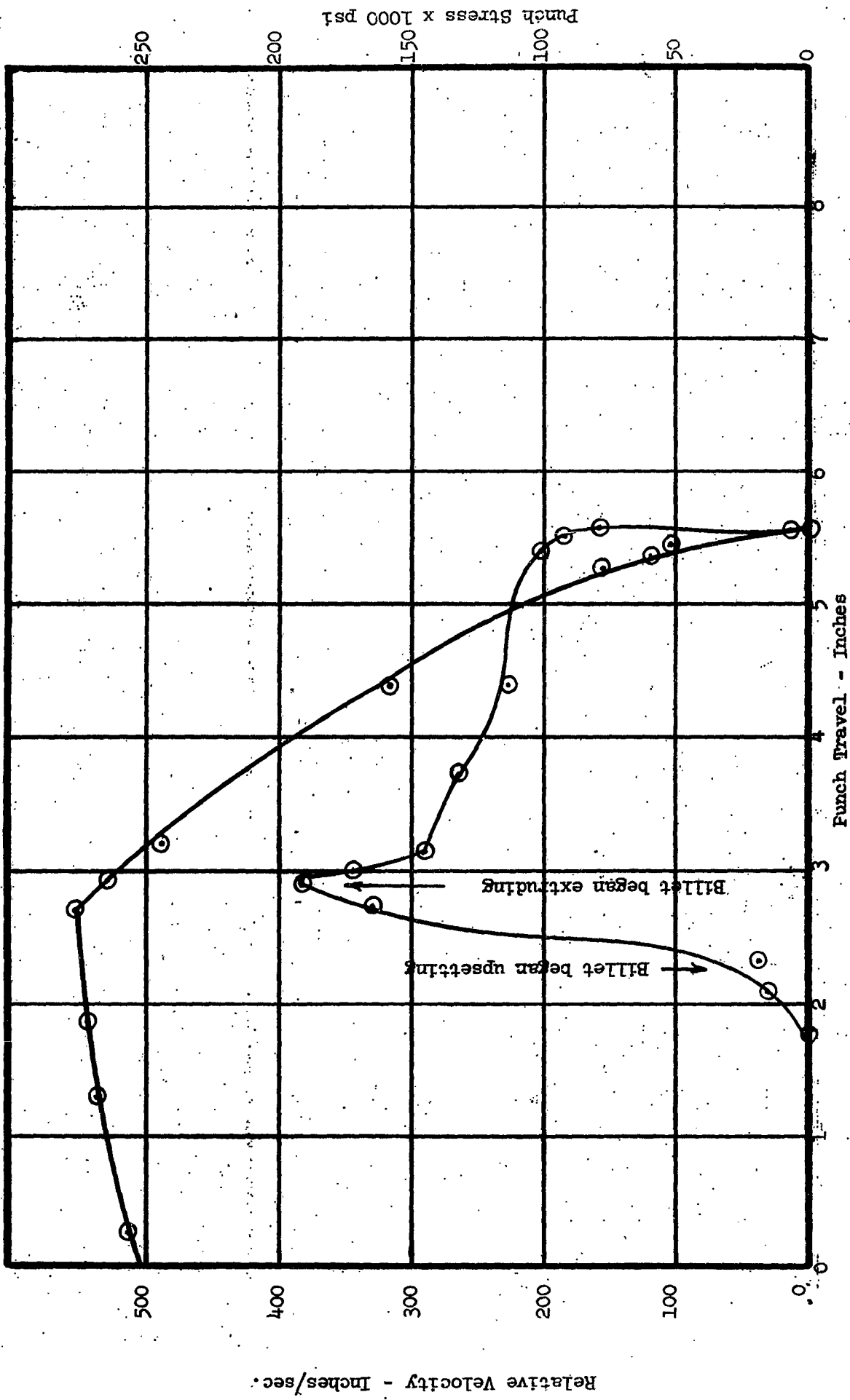


FIGURE 13 - Relative punch and bolster velocity and punch strain as a function of distance. Notice the shape of the curves as compared to Figure 10.

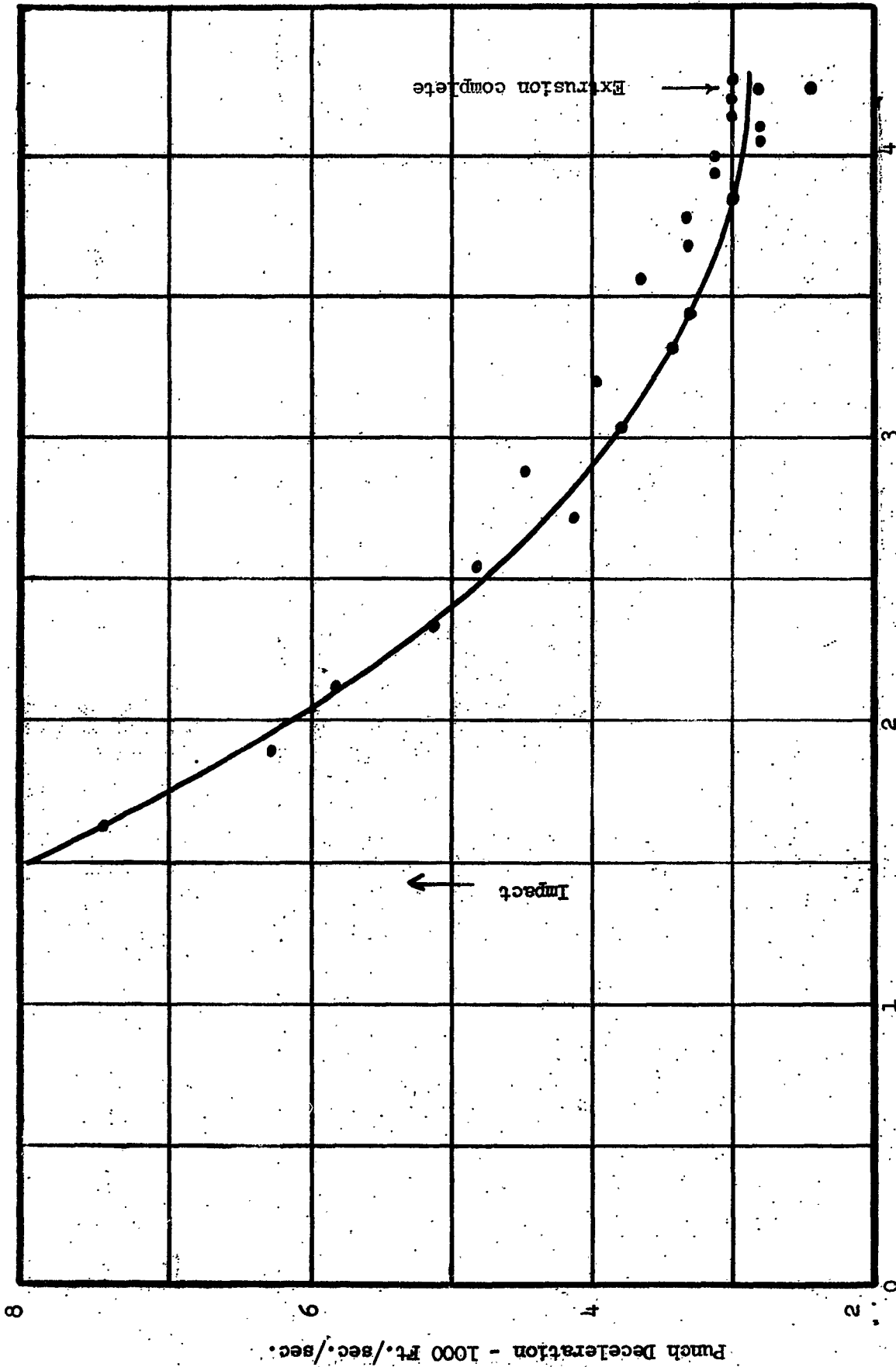


FIGURE 14 - Punch deceleration as a function of travel or length of billet extruded. The deceleration values are derived from velocity in Figure 12.

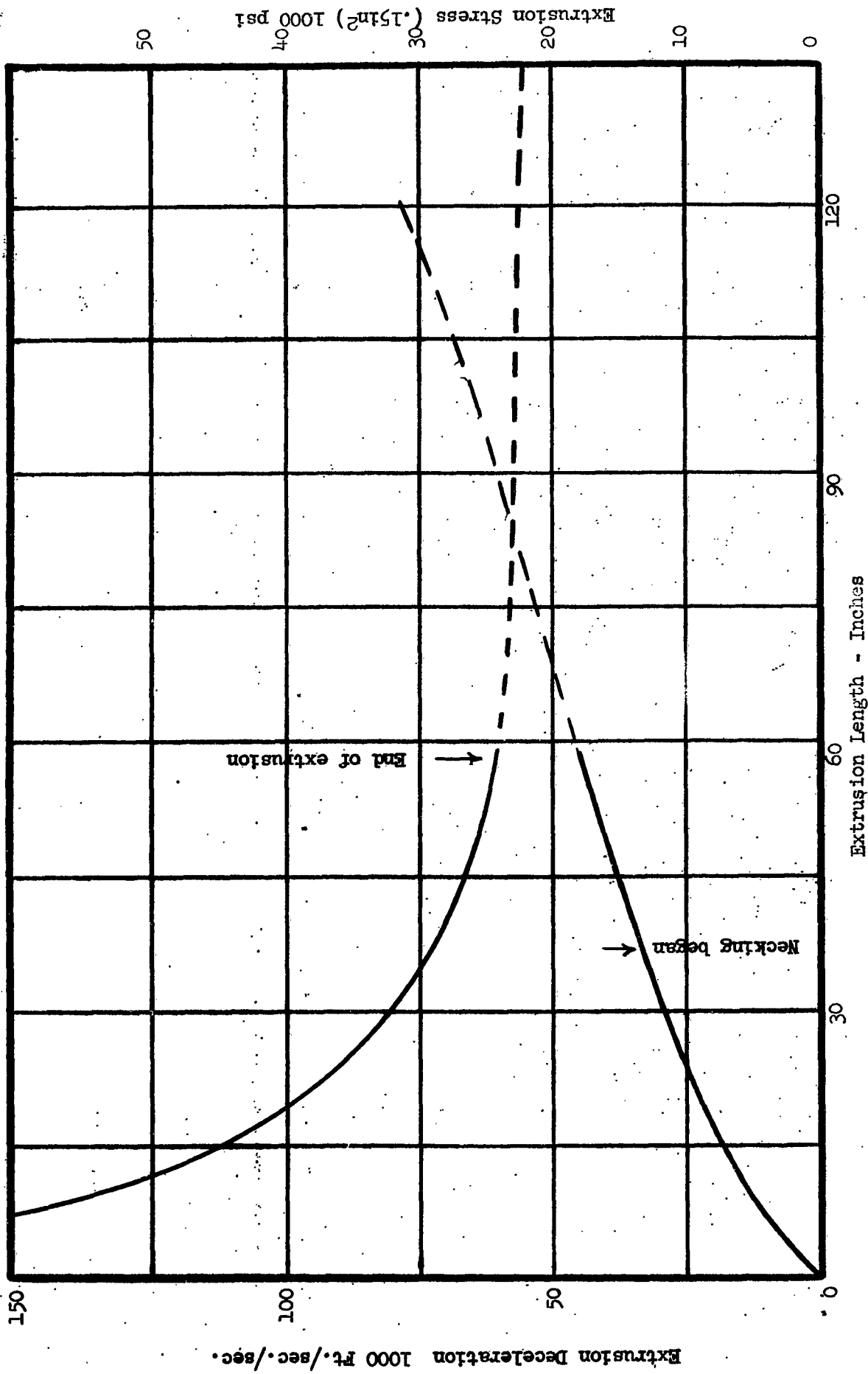


FIGURE 15 - Plot of extrusion deceleration and extrusion stress vs extrusion length. Stress of the extrusion is a function of the mass of the length and the deceleration.

Velocity and energy measurements made on a number of extrusions from 900 psi to 2,000 psi fire pressure are shown in Table 4. The variation in the relative velocity of the ram and bolster is negative at all fire pressures, that is, the measured velocity is lower than the calculated velocity based on energy contained in the fire pressure gas. The difference in velocity varied from 9.1% at 900 psi fire pressure to 21.2% at 2,000 psi fire pressure. The gradual reduction in efficiency is probably a result of the restriction imposed by the orifice through which the gas must flow. The energy efficiency is somewhat lower varying from 83.3% at 900 psi to 62.4% at 2,000 psi. Actual velocities and energies are shown graphically in Figures 16 and 17. The energy of the machine was checked by two different means. One, as a function of the velocities and two, by the actual work done. In Figure 13 the kinetic energy of the system at impact is 72,000 ft. lbs. while the work done in producing the extrusion (calculated from product of punch stress and length of billet extruded) is 82,000 ft. lbs. The calculated energy of the machine is 102,000 ft. lbs. at impact and 122,000 ft. lbs. at the end of the extrusion period. The 72,000 ft. lbs. and 102,000 ft. lbs. do not represent the total potential energy of the system for additional energy, approximately 10,000 ft. lbs., is delivered by the expanding gas in the fire chamber while the ram travels 3 inches during the extrusion period.

##### 5. Dies and Tooling

Less trouble was experienced with tooling than in previous reporting periods. The H-13 type steel is still being used for the majority of the punches, dies and containers with some experimental punches made from M-2 high speed tool steel. The M-2 steel was selected on the

Fire Pressure	Velocity ft./sec.			Energy 1000 ft. lbs.		
	Calculated	Measured	% Variation	Calculated	Measured	% Variation
900	37.5	34.1	9.1	48	40	16.7
1200	44.6	37.8	15.3	68.7	49.2	28.4
1400	48.8	40.6	16.8	82	56.7	31.1
1600	52.7	43	18.4	95.5	64.5	32.4
1800	56	45.5	18.8	108.5	70	35.4
2000	59.5	46.9	21.2	122	76	37.6

TABLE 4 - COMPARISON OF MEASURED RELATIVE VELOCITIES OF RAM AND BOLSTER WITH THOSE CALCULATED FROM GAS EXPANSION FORMULA. MEASUREMENTS WERE MADE ON 1210 DYNAPAK MACHINE. CALCULATION AND MEASUREMENTS WERE BOTH FOR A NINE INCH STROKE.

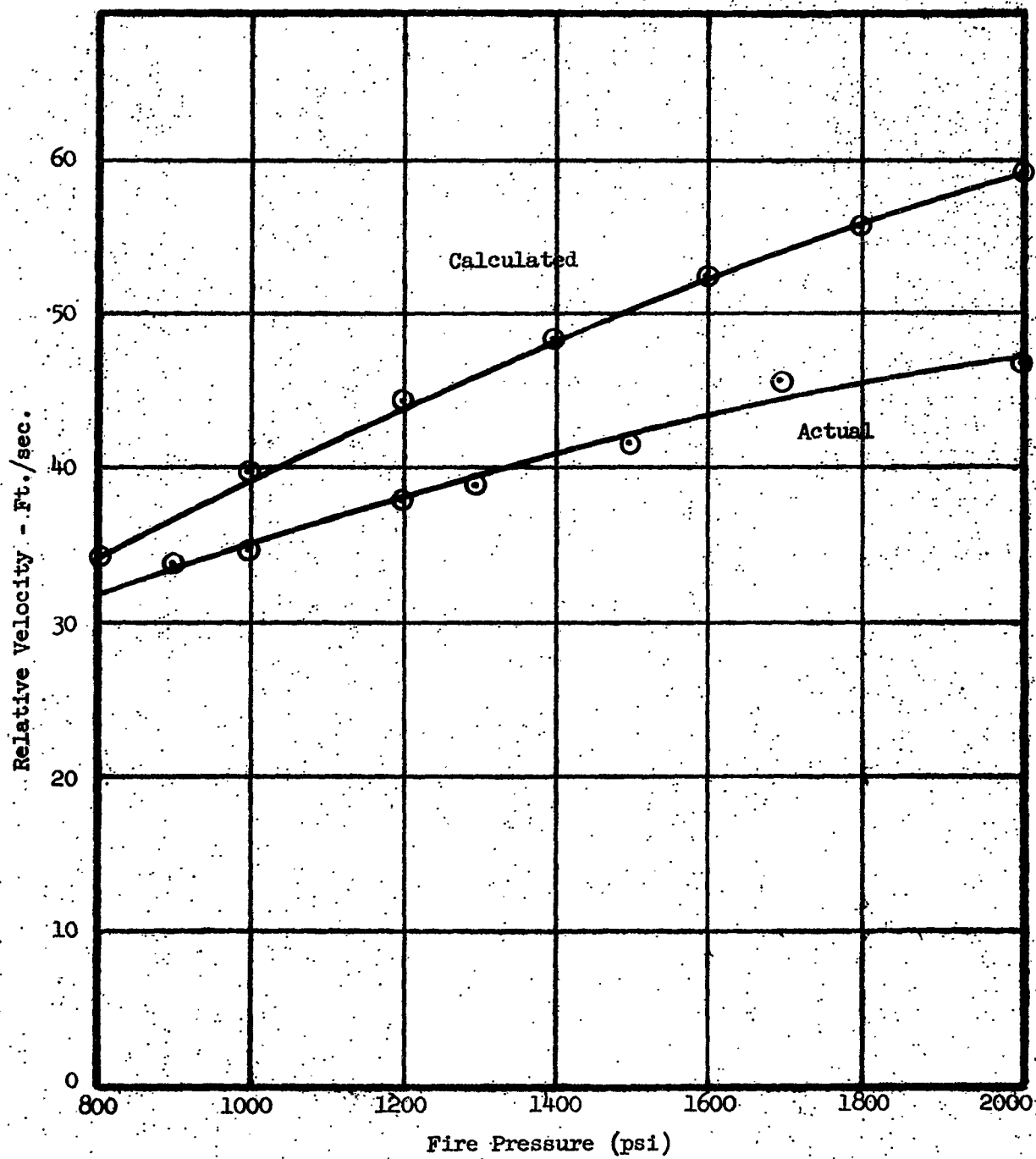


FIGURE 16 - Variation between measured and calculated velocity on 1210 Dynapak machine at 9 inch stroke.

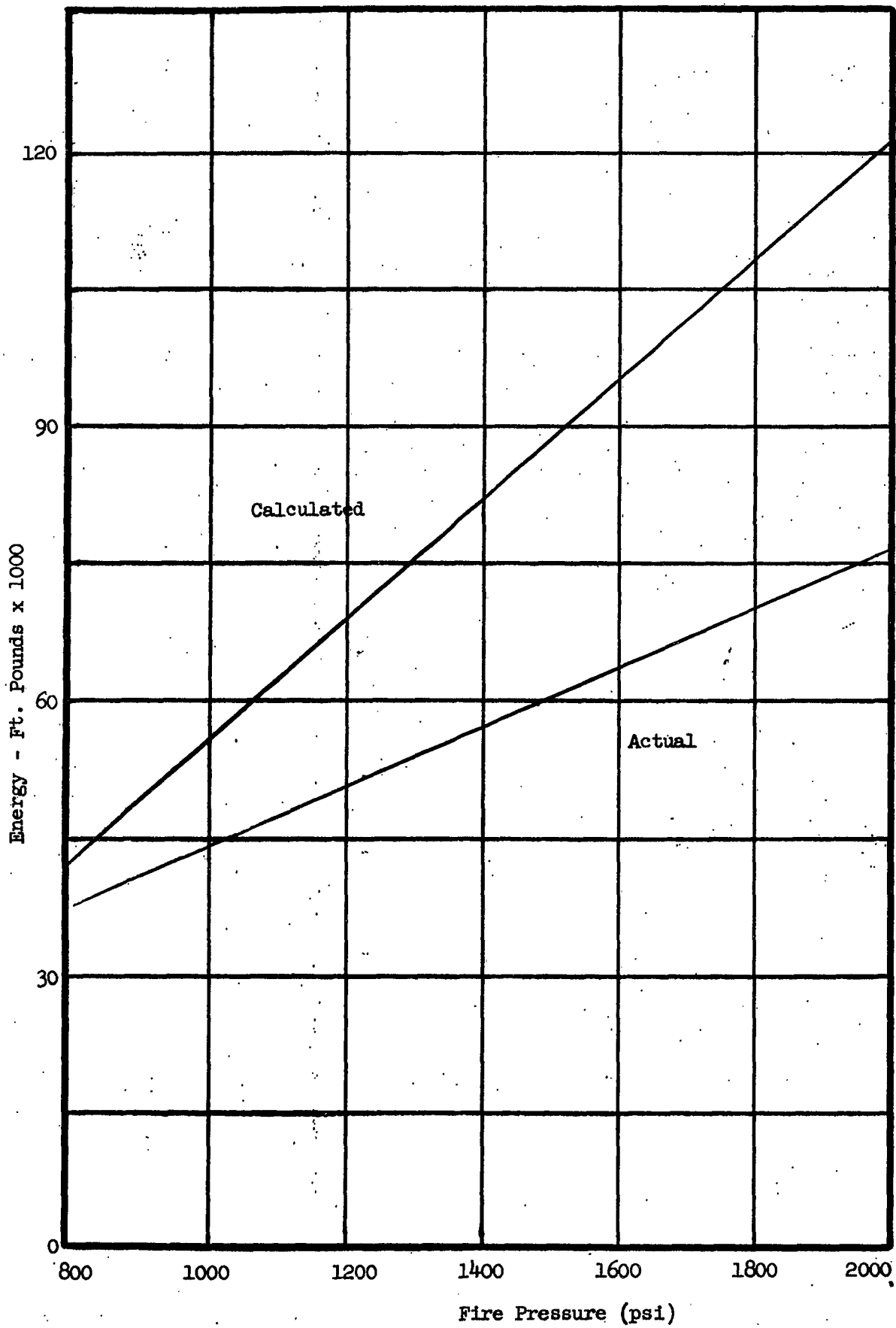


FIGURE 17 - Variation between measured and calculated energy on 1210 Dynapak machine at 9 inch stroke.

basis of having a good combination of strength and toughness at  
54 - 58 Rc.

One failure occurred on the 1210 Dynapak while extruding steel through a shear die at 21:1 reduction ratio. This punch was made from M-2 high speed steel hardened to 54 Rc and failed after being stressed to 300,000 psi on two successive extrusions. Slight bending was observed after the first extrusion and after the second extrusion the punch was bent out of alignment so that it could no longer be used. It is interesting to note that the M-2 punch had a ductile rather than brittle failure at this hardness. One other M-2 experimental punch is being hardened to 58 - 60 Rc in an attempt to raise the yield strength to avert this type of failure. Other materials that are being considered for this application at hardness levels of 54 - 60 Rc are AISI type S-1, low carbon M-2, low carbon T-1 and H-26.

Some other changes have been made to the tooling. Heavy backup plates are being used where possible to give more support to the die. The billet container has been modified to allow for larger heads on the hold down bolts, this reduces some of the flashing. To eliminate die breakage split dies are being used. The single piece die has a high stress concentration in the corners of the "T" configuration and most of the die failures are a result of cracks which originate at the point. The three piece die is split at each corner of the "T" and is held together by a close fitting holder.

D. WORK FOR NEXT REPORTING PERIOD

Work for the next reporting period will be directed at completing Phase II. To meet the objective, 10-foot extrusions, 2 inch by 1 inch

by .050 inch, in the "T" configuration, effort will be directed primarily at improving the existing braking device and working on new concepts for better types of decelerators. In addition, work will be continued on die design and die coatings for improving die life and surface finish. Other parameters of the extrusion process, temperature, K factors and tooling stresses will continue to be investigated.

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The investigation of the high energy rate extrusion process has continued. The effect of ram mass and reduction ratio has been analyzed on pull-off length with results that compare well with experimental data. The Ti-6Al-4V alloy has been extruded in 10-ft. lengths. Steel extrusions 10ft. long have been extruded but they separated inertially into smaller lengths. A braking device has been made which gives the desired effect but not to a degree sufficient for making 10-ft. extrusions of steel. The extrusion constants for titanium, steel and aluminum under high-velocity extrusion conditions have been determined. The speeds and stresses involved during the extrusion period have been measured and an analysis made of the requirements for a successful braking device.

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