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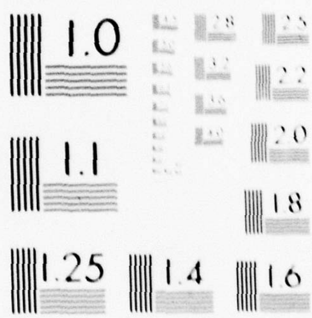

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EVALUATION OF LUBRICATION SYSTEMS FOR ISOTHERMAL FORGING OF ALPHA-BETA AND BETA TITANIUM ALLOYS

WYMAN-GORDON COMPANY
RESEARCH AND DEVELOPMENT
~~NORTH GRAFTON, MASSACHUSETTS~~ 01536
Worcester, MA 01613

NOVEMBER 1977

FINAL TECHNICAL REPORT - AFML-TR-77-181
1 APRIL 1976 TO 15 JULY 1977

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Project Engineer
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FOR THE COMMANDER

Henry C. Graham

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Acting Chief, Processing and
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This technical report presents the results of the lubrication evaluations on the newly-developed lubricants for isothermal forging of both alpha-beta and beta titanium alloys. It was demonstrated that, for alpha-beta titanium alloy lubricants, each lubricant still has its relative virtues and limitations in manufacturing performance. None of the present lubricants could provide satisfactory lubrication-functions for use in the gas-fired environment. However, several lubricants for beta-titanium alloys displayed excellent combinations of lubricity and adhesion properties in both electric and gas-fired environments and may represent the state of the art for isothermal forging lubricants.

FOREWORD

This Technical Report covers the work performed by Wyman-Gordon Company under Air Force Contract F33615-76C-5083 during the period 1 April 1976 through 15 July 1977. The primary objective of this program is to evaluate and to scale-up the newly-developed lubrication systems for isothermal forging of titanium alloys.

This contract with Wyman-Gordon Company is monitored technically by Mr. A. M. Adair, Processing and High Temperature Materials Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The program work was conducted by the Research and Development Department of Wyman-Gordon Company with C. C. Chen as program manager. Mr. J. E. Coyne is Vice President and Technical Director of the company, and Mr. W. H. Couts is Manager of the Research and Development Department.

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SECTION I

SUMMARY AND RECOMMENDATION

A. Main Objective of the Program

The main objective of the subject program is to evaluate and to scale-up the newly-developed lubrication systems for isothermal forging of both alpha-beta and beta titanium alloys. It is to further continue investigations in improved lubricant compositions from the standpoint of lubrication effectiveness, practical requirements, and environmental acceptability, for manufacturing aircraft quality components through isothermal forgings.

B. Lubricants for Alpha-Beta Titanium Alloys

1. There is a detrimental influence of gas-fired environment on both anti-friction and adhesion characteristics of the lubricants. None of the present lubricants could provide satisfactory lubrication-functions for use in the gas-fired environment.
2. In a gas-fired furnace, the performance of TRW's GFBN-8 and GFTC-8 was extremely poor. Acheson's Deltaglaze-69 gave the most acceptable performance.

3. By heating in an electric furnace, the best combination of lubricity, adhesion, and surface finish was achieved by TRW's GFBN-8. Acheson's Deltaglaze-69 provided excellent anti-friction characteristics, but displayed unfavorable adhesion properties. TRW's GFTC-8 gave excellent adhesion, but had lower lubricity.

C. <u>Lubricants for Beta-Titanium Alloys</u>

1. The TRW's LFC-11 gave the best combination of lubricity and adhesion characteristics in both electric and gas-fired furnaces for use in the 1300 to 1550F temperature range, and may represent the state of the art for isothermal forging lubricant of beta-titanium alloys.
2. TRW's LFC-8 provided excellent adhesion properties, but it displayed comparably poor lubricity and stability. The Acheson's Deltaglaze-149 had excellent anti-friction characteristics; however, it gave unfavorable adhesion strength.
3. The gas-fired environment appeared to have an effect on both metal flow and adhesion strength of the coating, but the degree of influence was considerably smaller, as compared with the lubricants (i.e., TRW's GFBN-8 and GFTC-8) for alpha-beta titanium alloys.

D. General Summary

1. Several excellent lubricants have been recently developed for isothermal forging of alpha-beta titanium alloys. However, each lubricant still has its relative virtues and limitations in manufacturing performance.
2. The reliability of the lubricant effectiveness and performance could not be satisfactorily demonstrated before one tests such lubrications directly in actual performance conditions and requirements in the forge shop.
3. The glass coatings for alpha-beta titanium alloys are excellent in lubricity and have good protective nature. However, the inability to good atmosphere stability, good release agent, low accumulation tendency, and low corrosive activity limits the precision achievable with the glass coatings.
4. At the present state of technology, the isothermal forging lubricants for beta titanium alloys may be regarded as much more readily acceptable lubricants for manufacturing applications. Lubricants with excellent combinations of lubricity, adhesion characteristics, and environmental inertness are available.

SECTION II

INTRODUCTION AND BACKGROUND REVIEW

A. State-of-Technology in Isothermal Forging Lubrication

Since the introduction of isothermal forging techniques for producing close-tolerance forgings, considerable effort has been concerned with the development of improved lubrication systems for isothermal forging of titanium alloys ([1]-[5]). This is basically because the ability to produce cost-effective net or near-net structural components through isothermal processing depends strongly upon the effectiveness of the lubrication system used.

In very recent development programs of isothermal forging lubrication systems ([1], [5]), several lubricants have been developed for the isothermal forging of titanium alloys. Among them, the TRW's GFBN-8 and GFTC-8 under AFML Contract F33615-74C-5059, and Acheson's Deltaglaze-69 and TRW's OPT-112 under AFML Contract F33615-74C-5011 should be particularly mentioned. These lubricants were reported to possess superior qualities to those of the previously available hot-die lubricants. In addition to high lubricity, long-term thermal stability, good chemical compatibility with die materials, they were experimentally shown to have the ability to withstand gas-fired furnace atmosphere. However, these lubricants have still some limiting features for a successful production lubricant. It can be generally stated that the Acheson Deltaglaze-69 possesses major advantages over the TRW formulations in the environmental acceptability, ease and safety of application, but the TRW lubricants appear to give better removability, less die build-up in the cavity, and fewer glass stringers.

A successful lubrication system for the manufacturing net or near-net forgings through isothermal processing depends not only on the basic lubrication characteristics, but also upon its actual performance conditions and environmental requirements in the forge shop. From manufacturing viewpoints, there are two fundamental bases for an acceptable and successful lubricant. The primary consideration must be that the lubricant will display excellent lubrication performance for producing structural shape forgings in the forge shop. Secondly, if one considers the extreme thermal environment conditions encountered by isothermal forging systems, the ability of a lubricant to combine the environmental, safety, and health requirements, as well as the ease of handling at high temperature environments is of equal importance.

B. Basic Formulations on the Basis of the Carrier Used

Although the developed lubricants are similar in many respects in optimizing the lubrication characteristics for the use in hot-die systems, the basic concepts of lubricant development can be generally grouped into two different categories depending on the nature of the carrier used, i.e., the water-base ([1], [2]) or the xylene-base ([1], [5]). Others are alcohol-base (e.g. Acheson's Deltaglaze D-347M) and Isopropanol-base (e.g. Acheson's Deltaglaze D-347). The development approach for the water-based lubricants, such as Acheson Deltaglaze formulations, concerns with both basic lubrication characteristics, and environmental and safety requirements from a production basis.

In the case of xylene-based lubricants, such as TRW-OPT formulations and Markal-CRT coatings, the fundamental concept concentrated primarily on maximizing the lubrication effectiveness; the environmental consequences to the use of the lubricant in manufacturing applications are not of particular concern. Xylene ($C_6H_4 \cdot (CH_3)_2$) is a flammable liquid, and also a human-toxic chemical. Its explosive limits in air are 1 to 5% by volume. Examples of available xylene-based lubricants are TRW's OPT-112, GFBN-8, GFTC-8, Markal's CRT, CRT-HA.

C. Experimental Nature of Lubricant Performance

The reproducibility and reliability of the lubricant performance could not be satisfactorily demonstrated before one tests such lubrication systems directly in a die set which is sufficiently large and complex to accommodate the size and geometry required for the actual structural shape forgings. However, the previous development work on evaluating the lubricant effectiveness for isothermal forging of titanium alloys has been limited only to produce laboratory-scale forgings ([1], [5]). In some cases, the evaluation has extended to simulated airframe structural components, but the size and rib-and-web geometry for the components used were generally oversimplified. In view of the advanced progress in the technology of isothermal forgings for titanium alloys, there appears to be a need for accelerating and for demonstrating the validity of the lubricant effectiveness by forging in a more realistic and complex shape component.

D. Status of Isothermal Forging Technology on an Economic Basis

In titanium alloy forgings, the techniques of making isothermally forged components have been available ([1-4]). However, the cost effectiveness of the isothermal processing over a wide range of structural components has been a question of uncertainty. One of the major factors in limiting the economical justification of hot-die processes has been the high cost of the die materials required for the process.

An alternate approach to reduce the cost of isothermal forging systems for titanium alloys is to use the lower die temperature. This suggests that the beta type of alloy such as Ti-10V-2Fe-3Al will be ideal candidate materials because this type of alloys has relatively low beta transus temperature and possesses much lower flow stress than that of alpha-beta alloys at higher temperature (Figure 1)([6]). The possibility of using a die temperature at the 1300 to 1550F range for isothermal forging has excellent advantages from the cost and the stability of available die alloys ([1]).

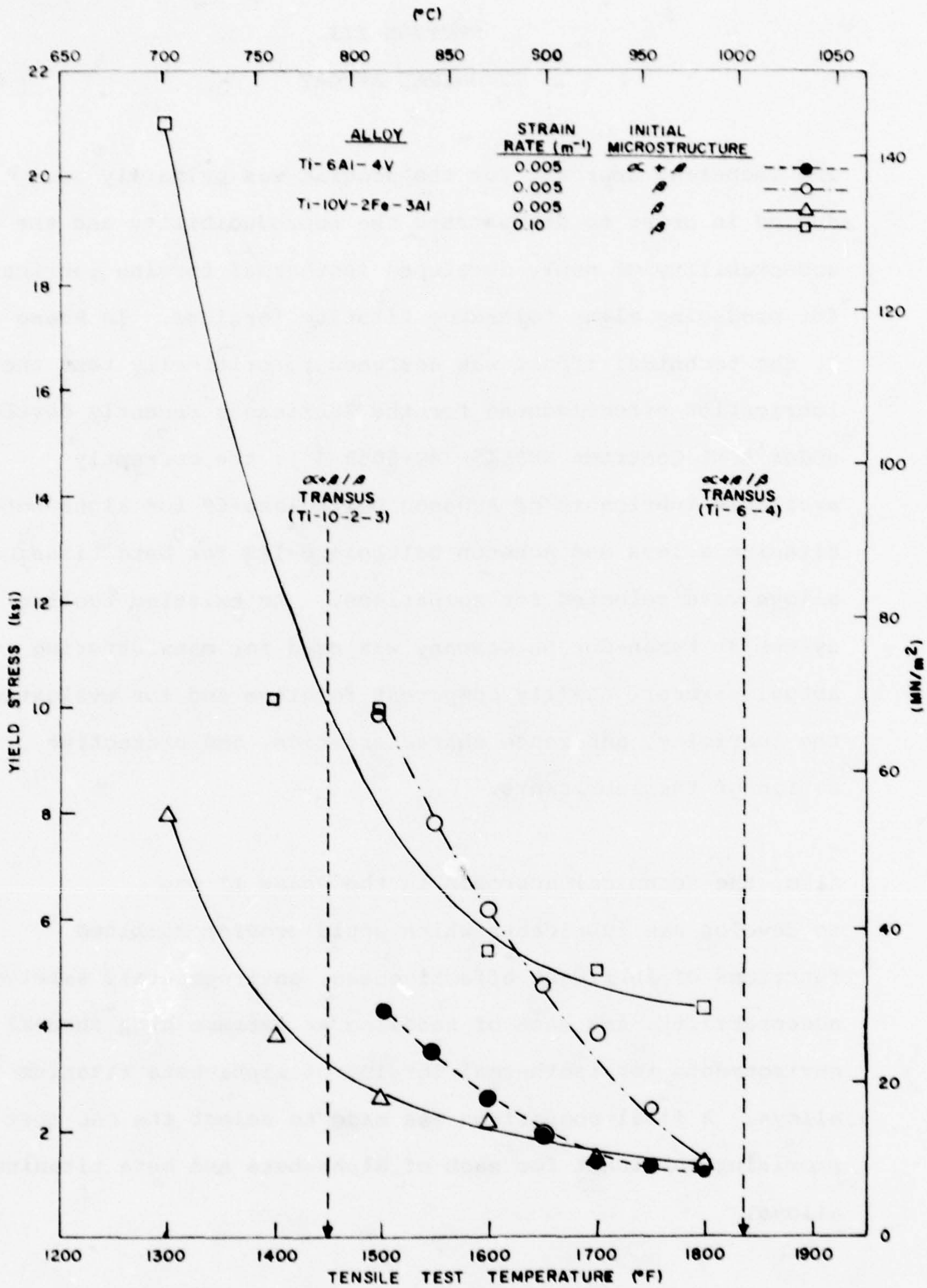


Figure 1 Temperature Dependence of Yield Strength for Ti-6Al-4V and Ti-10V-2Fe-3Al Alloys

SECTION III

TECHNICAL EFFORT

The technical approach for the program was primarily conducted in order to demonstrate the reproducibility and the acceptability of newly developed isothermal forging lubricants for producing close tolerance titanium forgings. In Phase I, the technical effort was designed to critically test the lubrication effectiveness for the lubricants recently developed under AFML Contract F33615-74C-5059 ([5]); the currently available lubricants of Acheson Deltaglaze-69 for alpha-beta titanium alloys and Acheson Deltaglaze-149 for beta titanium alloys were selected for comparison. An existing tooling system at Wyman-Gordon Company was used for manufacturing actual aircraft quality component forgings and for evaluating the lubricity, adherence characteristics, and protective action of the lubricants.

Also, the technical approach in the Phase II was to develop new lubricants which would provide combined functions of lubricant effectiveness, environmental, safety acceptability, and ease of handling at extreme high thermal environments for isothermal forging of alpha-beta titanium alloys. A final comparison was made to select the one most promising lubricant for each of alpha-beta and beta titanium alloys.

The part selected for this program is one of the F-15 bulkhead centerbody components with a projected plan view area of 80 square inches. This die-set (Figure 2) is made of Astroloy and has a die impression volume of 34.2 $in.^3$, web thickness of 0.18 inch, and rib thicknesses ranging from 0.08 to 0.14 inch. The draft angle for the die cavity is 0° 30' draft on two long outside vertical surfaces, and 1° 30' draft on most inside vertical surfaces. This part is very attractive for assessing lubricant efficiency because it represents a typical production part for moderate aircraft components and also characterizes structural rib-and-web shape geometries for large aircraft components. The results obtained from producing this part forging should have direct applicability to produce the still larger forgings most commonly used. In addition, they should serve to validly produce Bearing Support Components for the recently completed AFML Manufacturing Technology isothermal forging tooling program at Wyman-Gordon Company because of similar shape and geometry characteristics ([1]).

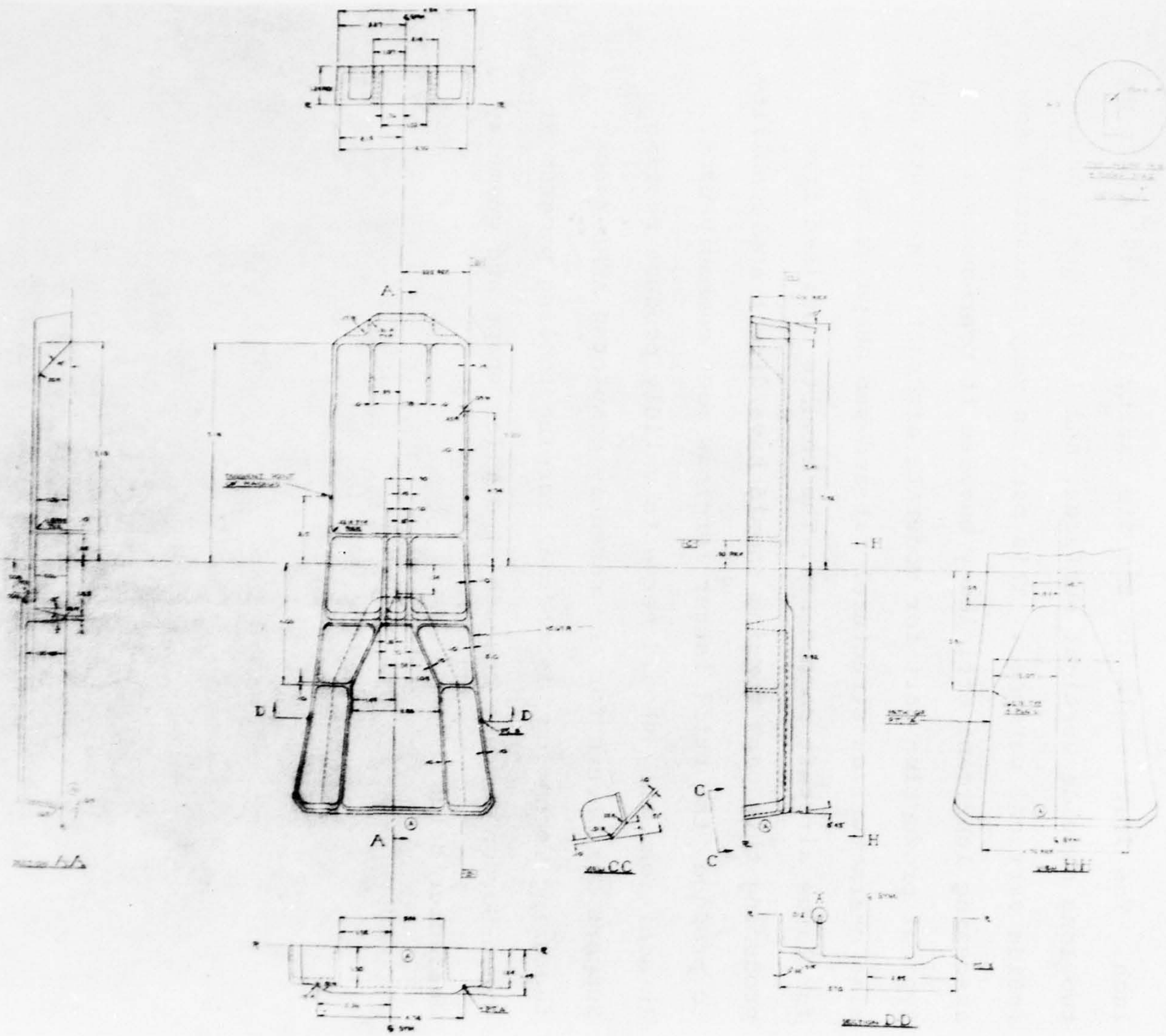


Figure 2 The Airframe Structural Component used for the present evaluations

A. Phase I - Lubricant Evaluation

1. Task I - Alpha-Beta Titanium Alloy (1500-1800F Range)

The Ti-6Al-4V alloy was employed for this portion of the evaluation. Two of the most promising candidate isothermal forging lubricants developed under AFML contract F33615-74C-5059 ([5]) were initially evauated at two isothermal part/die temperatures of 1600F and 1750F. For comparison, the Acheson Deltaglaze-69 was also used for this portion of the program.

(a) Experimental Lubricants Developed Under Contract F33615-74-C-5059

The two AFML-recommended lubricants (TRW GFBN-8 and GFTC-8) were used for forging evaluations in the 1500 to 1800F temperature range ([5, 7]). Ten different lots of lubricants were received; five, one-half gallon quantities representing five different batches per each lubricant. Both experimental lubricants were sampled from batches number A and number E of each lubricant for analyzing undesirable elements at Wyman-Gordon. As given in Table 1, the results of spectrochemical analysis indicated that both lubricants contained only very small amounts of undesirable elements; amounts of As, Bi, Cl, F, Hg, P, Pb, S, Sb, and Na were within the acceptable limit.

TABLE 1

SPECTROCHEMICAL ANALYSIS RESULTS OF VARIOUS CANDIDATE LUBRICANTS

Element*	Lubricant Compositions (PPM)						
	Phase I (Task I)				Phase I (Task II)		Phase II
	GFBN-8		GFTC-8		LFC-8	LFC-II	Water Glass (CP-C9)
	A	E	A	E			
As	<10	<10	<10	<10	<100	<100	<100
Bi	30	50	20	<10	< 10	10	< 10
Cl	<100	<100	<100	<100	< 50	< 50	< 70
F	<50	<50	<50	<50	< 50	< 50	< 50
Hg	<100	<100	<100	<100	< 10	< 10	< 10
P	<30	<30	<30	<30	38	58	< 50
Pb	<10	<10	<10	<10	maj **	10	< 10
S	<20	<20	30	70	<100	<100	40
Sb	<10	<10	<10	<10	< 10	< 10	< 10
Al	maj	maj	maj	maj	1000	1000	500
B	maj	maj	maj	maj	< 10	maj	10
Co	<10	<10	100	100	< 10	maj	< 10
Cr	<10	<10	<10	<10	< 10	>1000 (min.)**	< 10
Fe	maj	maj	maj	maj	maj	10	maj
K	<10	<10	<10	<10	<100	< 100	<100
Mg	maj	maj	maj	maj	100	100	<100
Mn	100	100	100	100	100	100	< 10
Na	<10	<10	<10	<10	1000	10	maj
Si	maj	maj	maj	maj	maj	maj	maj
Ti	<10	<10	maj	maj	< 10	< 10	10

* Ca, Cu, Zn, Zr, and Sn ≤ 10 ppm for all of the lubricants

Ba, Li, Ni, and Sr are ≤100 ppm for all of the lubricants

** maj. = major
min. = minor

(b) Preliminary Rib-and-Web Forging Trials

(1) First Preliminary Evaluation

In order to give a more careful selection of the control lubricants for the program, various Acheson lubricants (samples) were obtained from Acheson for preliminary lubricant evaluation; these lubricants were modified from Deltaglaze-69 and Deltaglaze-149 with either silicate-removal or BN-addition([8]). A series of rib-fill forging tryouts were made to compare the lubrication efficiency of these Acheson lubricants, using Wyman-Gordon Astroloy-U700 rib-and-web dies. As shown in Figure 3, this forging is about 5 inches in length, 3 inches in width, and 0.9 inch in thin vertical ribs. The die cavity has a die impression volume of 5.85 in^3, plane view area of 15 in^2, web thickness of 0.20 inch, rib thickness of 0.12 inch, and 0° 30' draft on all outside vertical surfaces.

Fifteen Ti-6Al-4V flat blanks (0.5 inch x 2.65 inch x 4.64 inch) were machined as preforms for this experiment. The plate stock for these blanks was produced by hot-rolling at 1750F; the preform microstructure for this plate stock is given in Figure 4.

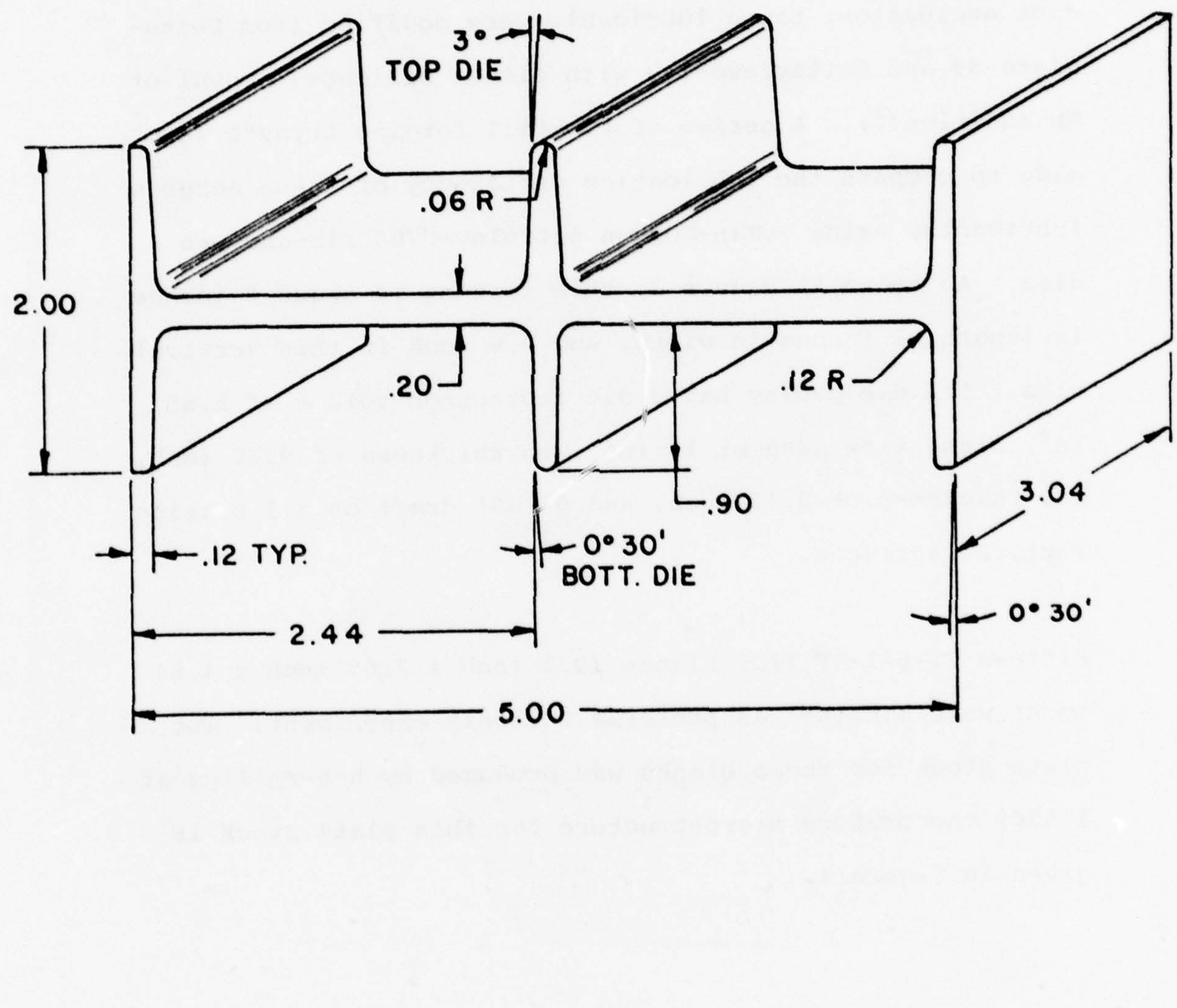


Figure 3 A sketch showing the dimensions of sample shape for rib-and-web forging tryout of lubricants at Wyman-Gordon

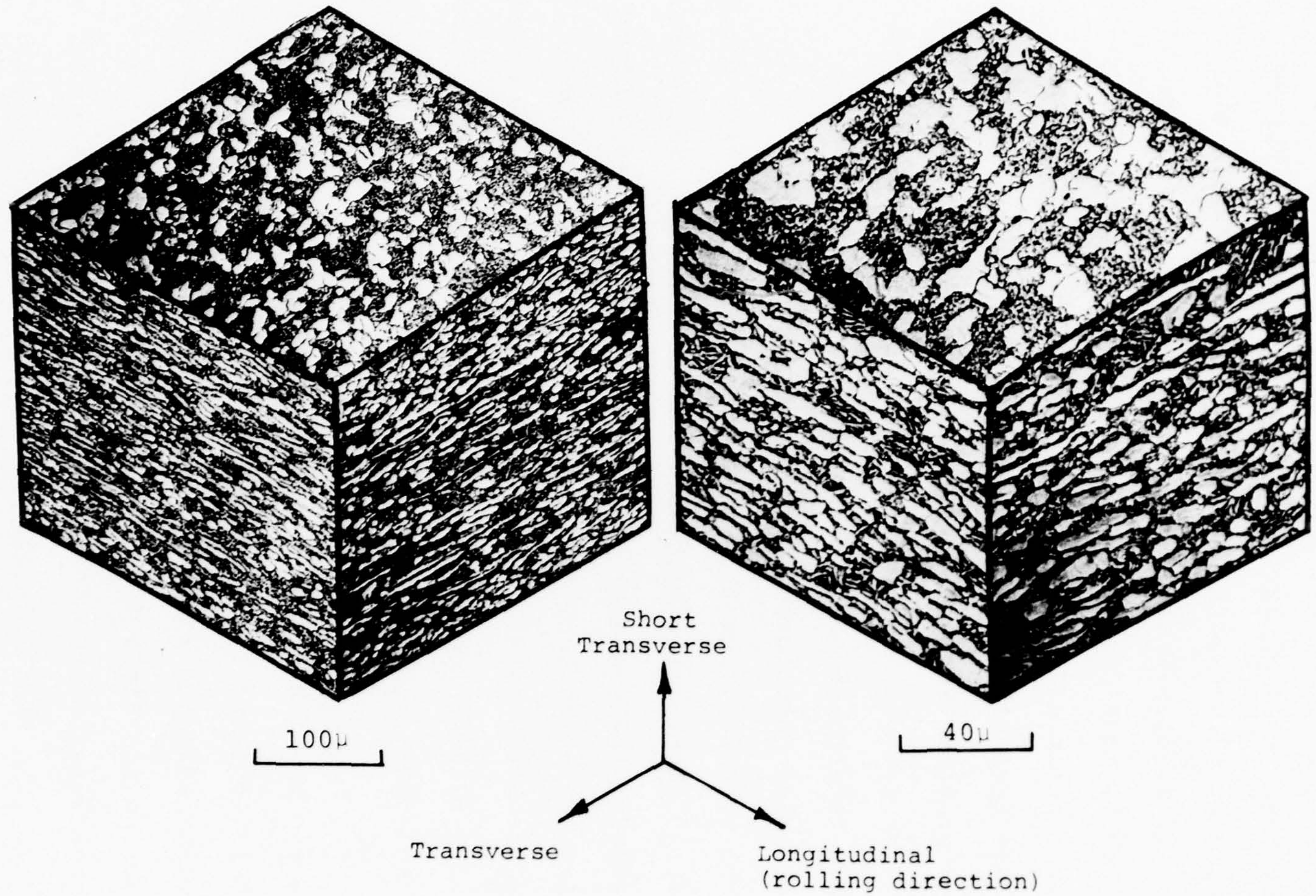
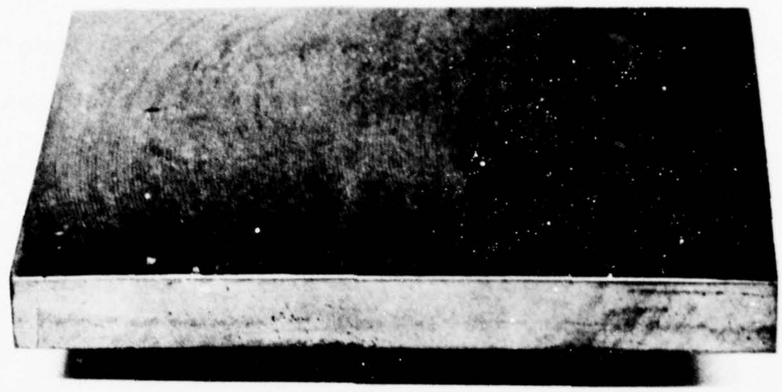


Figure 4 Microstructure of Ti-6Al-4V plate stock used in preliminary rib-and-web lubrication evaluations

The lubricants used for this evaluation included Deltaglaze-69, Deltaglaze-347M, Deltaglaze-349M, TR-939, TR-939+BN, Deltaglaze-149, WO-322A, and TR-750. The 1/2 inch flat blanks of Ti-6Al-4V alloy were one-stage forged to the "H" shape configuration (Figure 3) with closely controlled forging variables. They were forged at three different part/die temperatures (1750F, 1600F, and 1500F). Other forge variables were held constant; average ram rate ≃ 0.2 in/m, average forging time ≃50 seconds, transfer time from furnace to dies ≃5 seconds, furnace time = 45 minutes, preform microstructure = $\alpha+\beta$, excess preform volume = 5%, preform preparation method = machined, lubricant film thickness ≃ 6 mils, lubricant application method = spray. The maximum forging deformation was 50% reduction in thickness. After the forging operation, the forgings were air-cooled and sandblast-cleaned, and the final web thicknesses were measured. Figure 5 illustrates an example of the initial preforms used and the actual forgings produced.

Acheson's WO-315A lubricant is chemically the same as Deltaglaze-69 (originally designated as WO-315) except that the 3% sodium silicate was removed from WO-315 with the intention to improve the die life. Similarly, the WO-322A is a no-silicate version of Deltaglaze-149 (originally designated as WO-322). The TR-939 lubricant was a modification of WO-315A in order to improve the long-term shelf life; shelf life of



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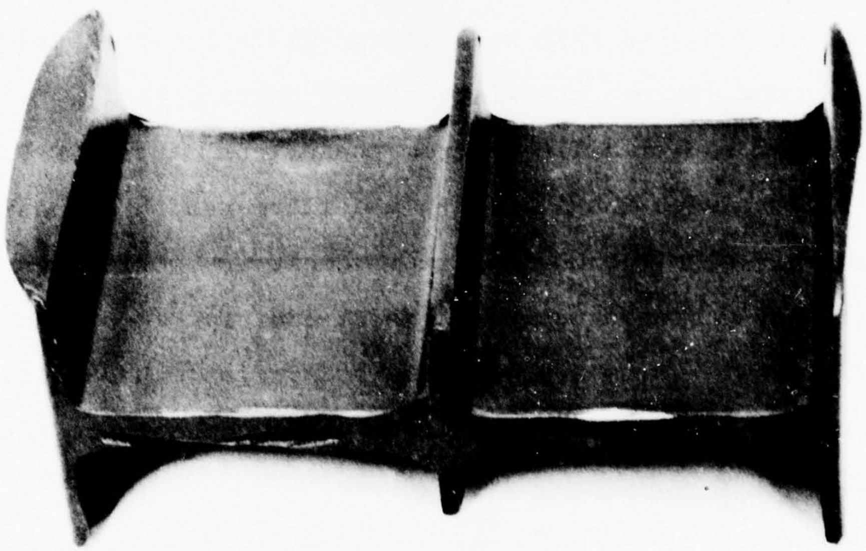


(b)

Figure 5 Example of machined preform used (a) and rib-and-web forging produced (b) for this evaluation.

WO-315A was reduced considerably when the silicate was removed. Deltaglaze-347M and Deltaglaze-349M are chemically similar to Deltaglaze-69 and Deltaglaze-149, respectively, but the alcohol was used as carrier for both Deltaglaze-347M and Deltaglaze-349M. The carrier for TR-750 lubricant is trichlorethane.

It is seen from Table 2 and Figures 6 and 7 that among the Acheson formulations, the Deltaglaze-69 and its alcohol-base version Deltaglaze-347M had favorable anti-friction characteristics, and surface finish at 1600F and 1750F. The Deltaglaze-149 displayed comparably satisfactory results at 1500F, as compared with WO-322A and TR-750; our experience showed poor thermal stability of the coating at 1750F. The removal of sodium silicate from these lubricants (TR-939 and WO-322A) reduced the lubricity and increased the adhesion strength. Also, no obvious improvement in lubrication efficiency was observable by the BN-addition (designated as TR-939 [BN]). From a production standpoint, the adhesion properties for these Acheson lubricants can only be rated as good.

(2) Second Preliminary Evaluation

Very recent results from ring compression and adhesion testings as performed by Westinghouse ([7], [9]) showed that, in

TABLE 2

LUBRICANT CHARACTERISTICS AND RESULTS OF FIRST PRELIMINARY RIB-AND-WEB FORGING EVALUATION FOR VARIOUS ACHESON'S LUBRICANTS

Serial Number	Lubricant*	Stock/die Temp. (F)	Load Applied (tons)	Finish Web Thickness (in)	Degree of Rib Fill (poor, fair, good)	Adhesion Characteristics (poor, good)	Surface Finish (fair, good)	Glass Stringers (no, some)	Ease to Spray (poor, easy)	Settling Tendency (little, some, heavy)	Lube Smell (no, odor)	Lube Buildup (no, some, heavy)	Ease to Remove from Piece (easily, good, hard)
1	D-69** (WO-315)	1750	215	0.236	good	poor	good	no	easy	little	no	no	easily
2	D-347M	1750	215	0.246	good	good	good	no	poor	heavy	odor	no	good
3	D-349M	1750	215	0.216	poor	poor	fair	no	very poor	heavy	odor	no	good
4	TR-939	1750	215	0.253	poor	good	good	no	easy	little	no	no	good
5	D-69+ BN(15%)	1750	215	0.257	poor	good	very good	no	easy	some	no	some	good
6	TR-939 (BN)***	1750	215	0.252	fair	good	very good	no	easy	heavy	no	some	easily
7	D-69	1600	340	0.261	good	poor	very good	no	easy	little	no	no	easily
8	D-347M	1600	340	0.297	fair	poor	very good	no	slightly poor	heavy	odor	no	good
9	D-347M	1600	340	0.302	fair	poor	good	no	poor	heavy	odor	no	good
10	D-349M	1600	340	0.302	relatively fair	good	good	no	poor	heavy	odor	no	good
11	TR-939	1600	340	0.267	good	good	very good	no	easy	little	no	no	good
12	TR-939 (BN)***	1600	340	0.292	fair	good	good	no	easy	heavy	no	some	easily
13	D-149**	1500	400	0.345	very poor	good	fair	no	easy	little	no	some	good
14	WO-322A	1500	400	0.338	very poor	poor	fair	no	very poor	little	no	some	good
15	TR-750	1500	400	0.353	very poor	poor	good	some	poor	heavy	odor	heavy	hard

* D = Deltaglaze
water-based lubricants with two exception: D-347M and D-349 are alcohol-based, and TR-750 is trichloethane-based

** Contains 3% sodium silicate

*** Contains BN

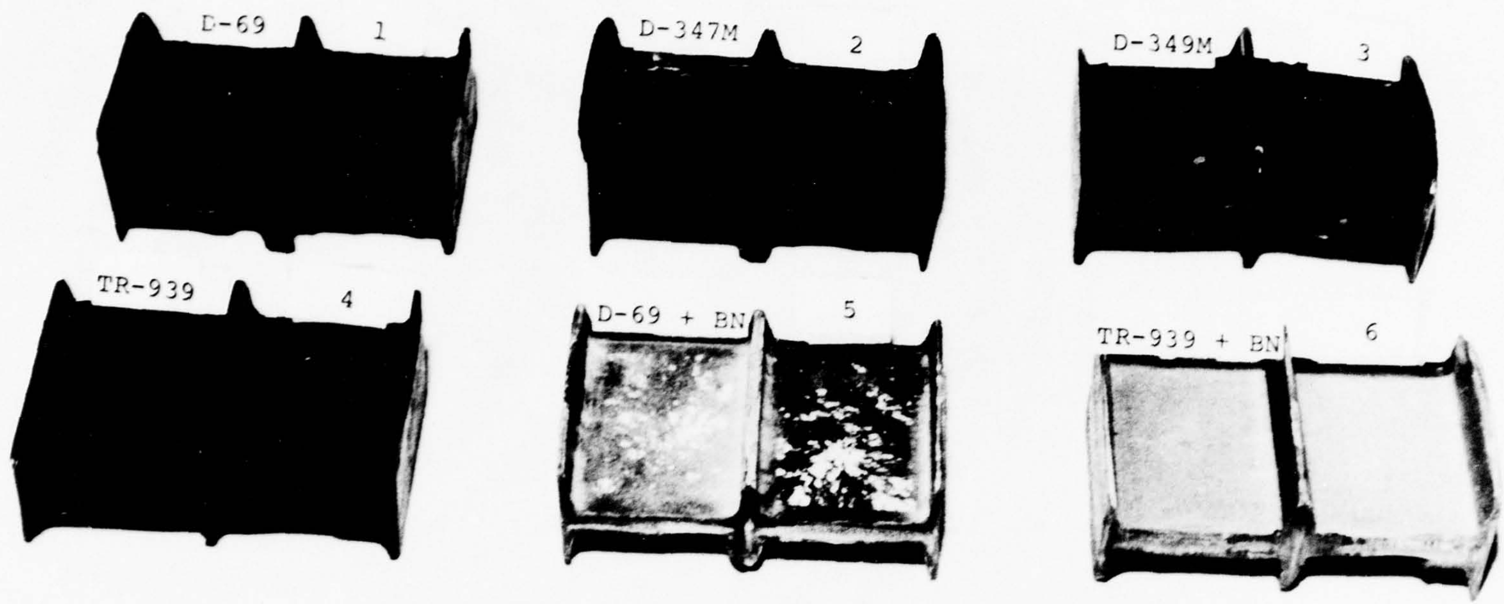


Figure 6 Top view of rib-and-web forgings produced from Phase I first preliminary rib-and-web lubrication evaluation.

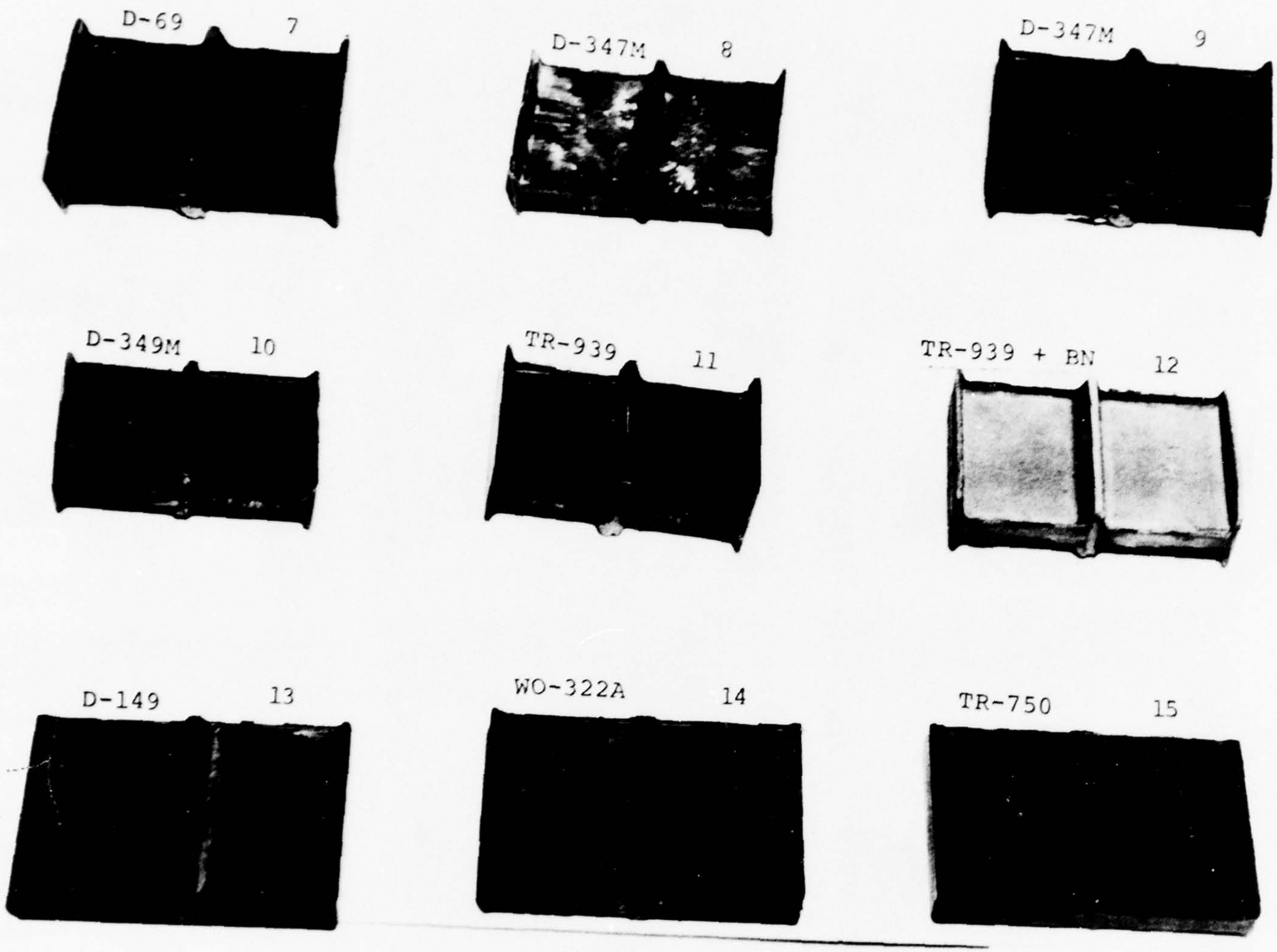


Figure 6 (Continued) Top view of rib-and-web forgings produced from Phase I first preliminary rib-and-web lubrication evaluation.

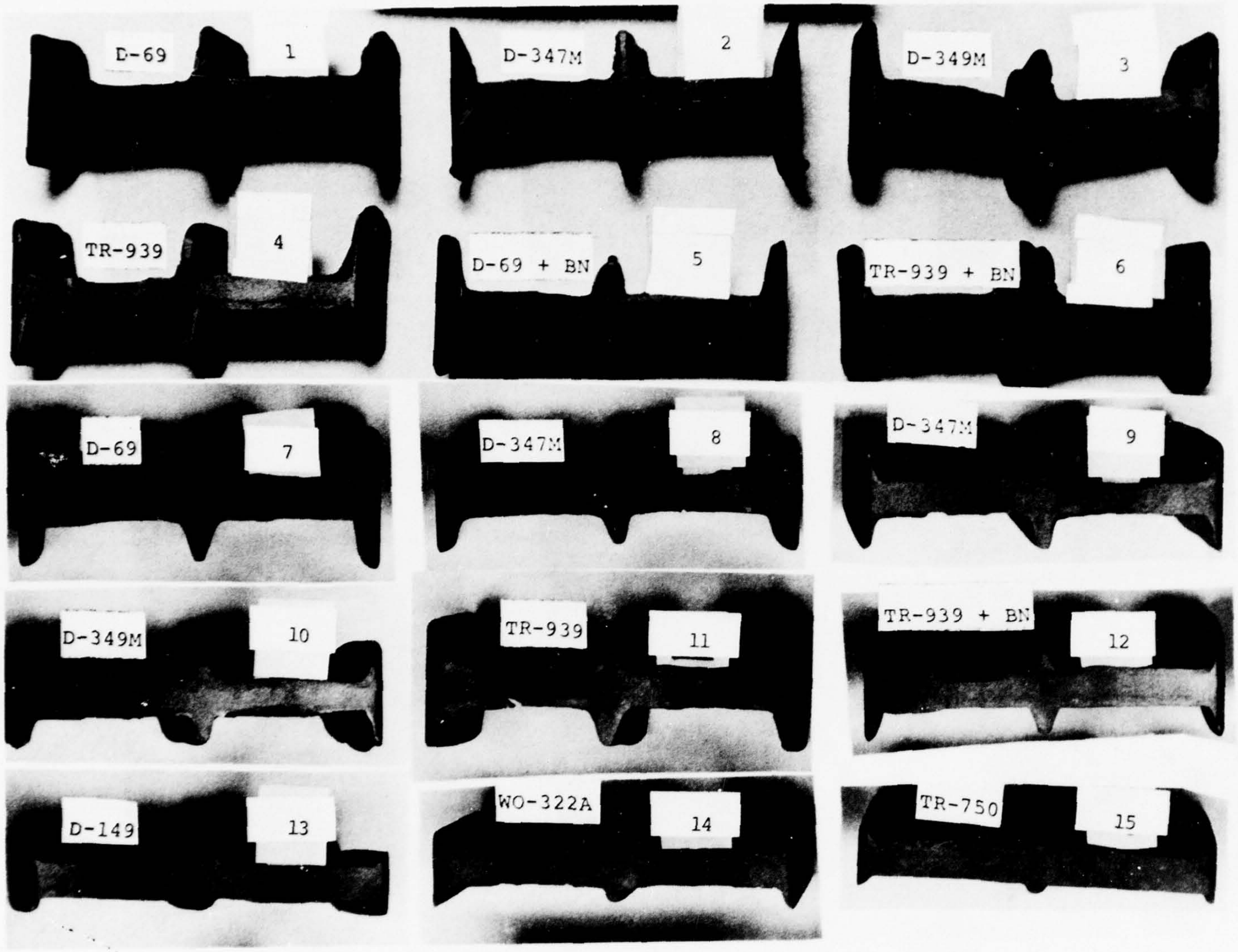


Figure 7 Side view of rib-and-web forgings produced from Phase I first preliminary rib-and-web lubrication evaluation.

spite of excellent anti-friction which could be achieved by the Deltaglaze-69, unfavorable adhesion characteristics were observed. From a production basis, any failure in removing the forgings under the extremely thermal environment conditions encountered by isothermal forging systems in the forge shop will cost many times the amount that can be achieved by improving the anti-friction features. Note that the friction factor for currently promising and available isothermal forging lubricants is of similar magnitude, e.g., the value of m is in the range of 0.05 to 0.15 at 1650F for these lubricants.

One of the important factors for demonstrating the lubrication effectiveness for the newly developed experimental lubricants is the use of a proper "control" lubricant. Hence, an additional effort was made specifically to compare the adhesion and anti-friction characteristics for several most promising lubricants using rib-and-web forging tests. The lubricants included TRW's GFBN-8, GFTC-8, OPT-112, Acheson's Deltaglaze-69, Deltaglaze-149, Deltaglaze-347M, Deltaglaze-349M, and Markal's CRT and CRT-HA coatings. An additional reason for making this lubricant optimization trial is to examine the possible detrimental effect arising from the use of the experimental lubricants, i.e., TRW's GFBN-8 and GFTC-8. It should be noted that recent results obtained at Westinghouse ([9]) indicated that Markal's CRT and CRT-HA coatings are more favorable in adhesion characteristics than Acheson's Deltaglaze-69.

Forty-two flat blanks of Ti-6Al-4V alloy plates were machined from hot rolled plate stock to 0.5 inch x 2.65 inch x 4.64 inch preforms. They were coated with various lubricants (see Table 3) for 6 mils. Again, these preforms were directly finish forged in one operation with closely controlled forging variables. They were forged at four different part/die temperatures of 1750F/1750F; 1600F/1600F; 1750F/1325F; and 1750F/1200F. Furnace time was two (2) hours and transfer time from furnace to die was about five (5) seconds. A dummy sample was used to remove the residual lubes between the different coatings. The forgings were blast-cleaned and the web-thicknesses were measured.

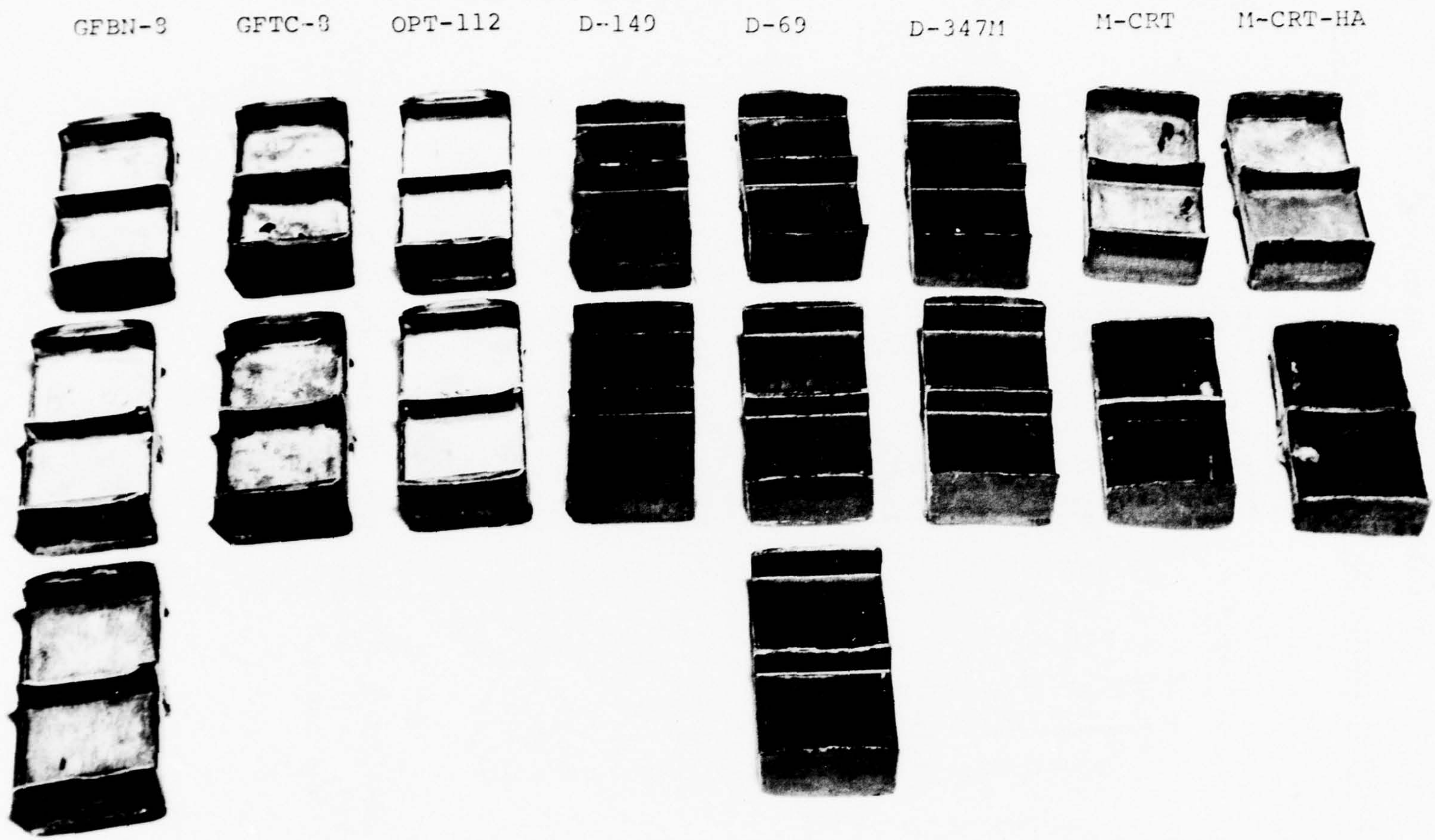
As a result, the best combination of lubricity, adhesion characteristics, and surface finish was achieved by TRW's GFBN-8. TRW's GFTC-8 also gave good performance at 1750F to 1600F temperature range. Acheson's Deltaglaze-69 and Deltaglaze-347M provided excellent rib-fill, but it has a tendency to stick to the dies. TRW's OPT-112 gave excellent adhesion property, however, significantly reduced the degree of part-fill. The performance of Markal's formulations was relatively poor, i.e., heavy die-buildup, poor anti-friction and adhesion characteristics, and poor surface finish. The Deltaglaze-149 displayed satisfactory results at 1750F/1325F and 1750F/1200F conditions. Figures 8 and 9 illustrate the rib-and-web forgings produced from this preliminary evaluation.

TABLE 3

FORGING VARIABLES USED FOR PHASE I SECOND PRELIMINARY RIB-AND-WEB FORGING EVALUATION

Serial Number	Lubricant*	Stock Temp. (F)	Die Temp. (F)	Ram Rate (in/min)	Load Applied (tons)
1,6,10	GFBN-8	1750	1750	0.2	225
2, 11	GFTC-8	1750	1750	0.2	225
3, 12	OPT-112	1750	1750	0.2	225
4, 13	D-149	1750	1750	0.2	225
5,14,15	D-69	1750	1750	0.2	225
7, 16	D-347M	1750	1750	0.2	225
8, 17	M-CRT	1750	1750	0.2	225
9, 18	M-CRT-HA	1750	1750	0.2	225
19, 26	GFBN-8	1600	1600	0.2	375
20, 27	GFTC-8	1600	1600	0.2	375
21, 28	OPT-112	1600	1600	0.2	375
22, 29	D-149	1600	1600	0.2	375
23,30,33	D-69	1600	1600	0.2	375
24, 31	M-CRT	1600	1600	0.2	375
25, 32	M-CRT-HA	1600	1600	0.2	375
34	GFBN-8	1750	1325	5	600
35	GFTC-8	1750	1325	5	600
36	OPT-112	1750	1325	5	600
37	D-149	1750	1325	5	600
38	D-69	1750	1325	5	600
39	M-CRT	1750	1325	5	600
40	M-CRT-HA	1750	1325	5	600
41	GFBN-8	1750	1200	5	800
42	D-149	1750	1200	5	800

* GFBN-8, GFTC-8, and OPT-112 are TRW's formulations; D-149, D-69, D-349M, and D-347M are Acheson's Deltaglaze formulations; M-CRT and M-CRT-HA are Markal-CRT formulations



Stock/die temperatures = 1750/1750F

Figure 8a Top view of rib-and-web forgings produced from Phase I second preliminary rib-and-web lubrication evaluation

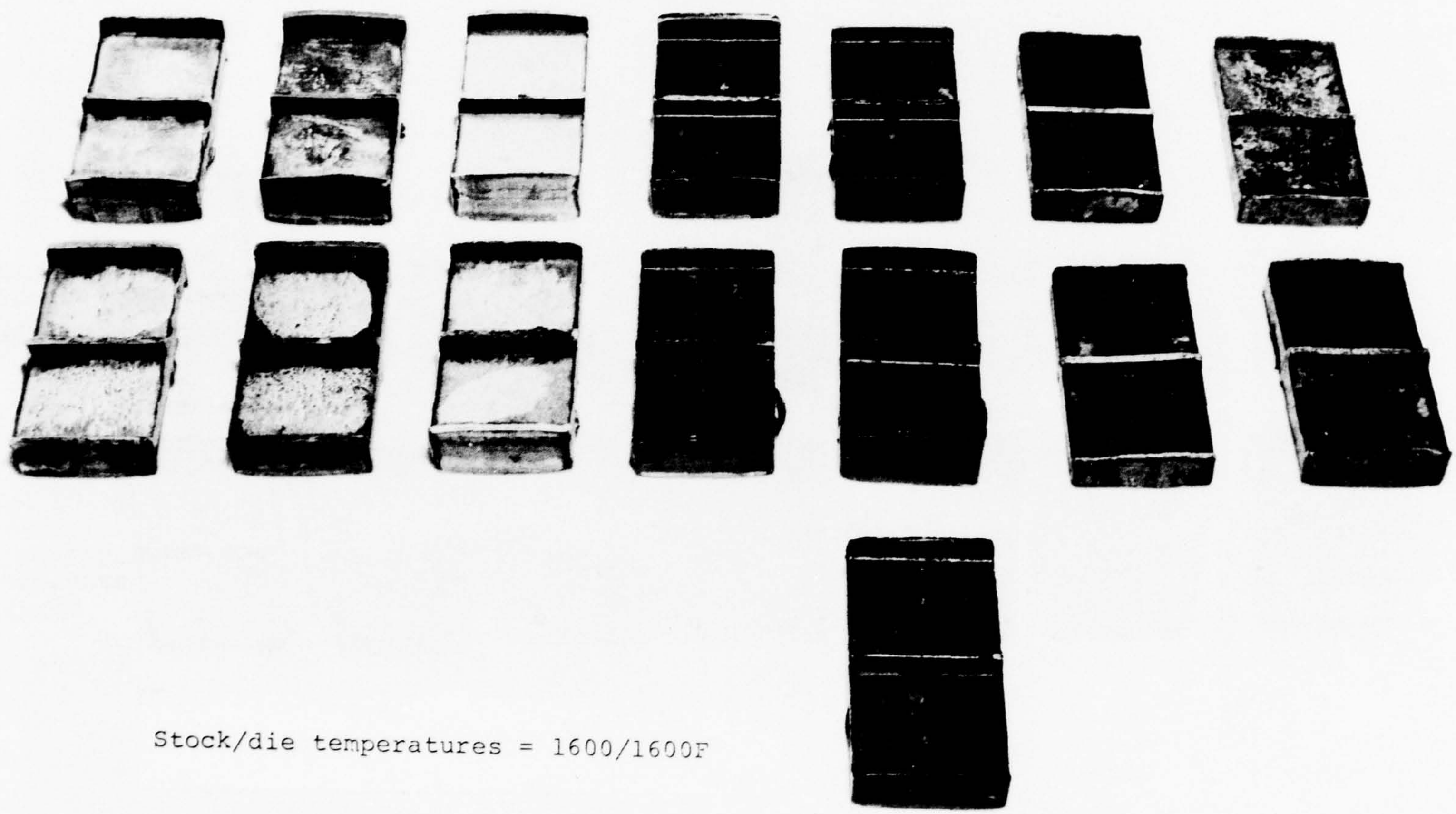


Figure 8b Top view of rib-and-web forgings produced from Phase I second preliminary rib-and-web lubrication evaluation

Figure 8c Top view of rib-and-web forgings produced from Phase I second preliminary rib-and-web lubrication evaluation

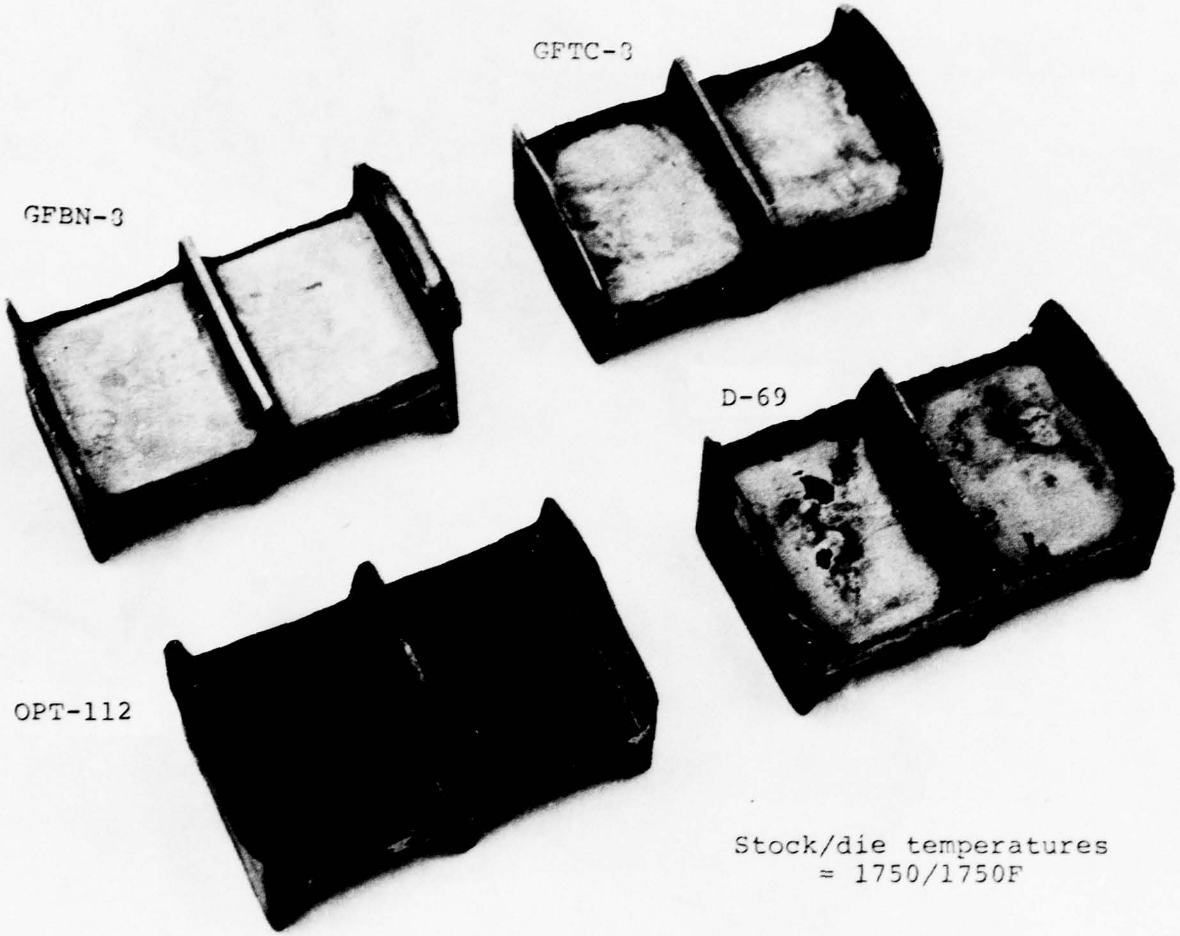


Figure 9a Closeup top view of rib-and-web forgings produced from Phase I second preliminary rib-and-web lubrication evaluation

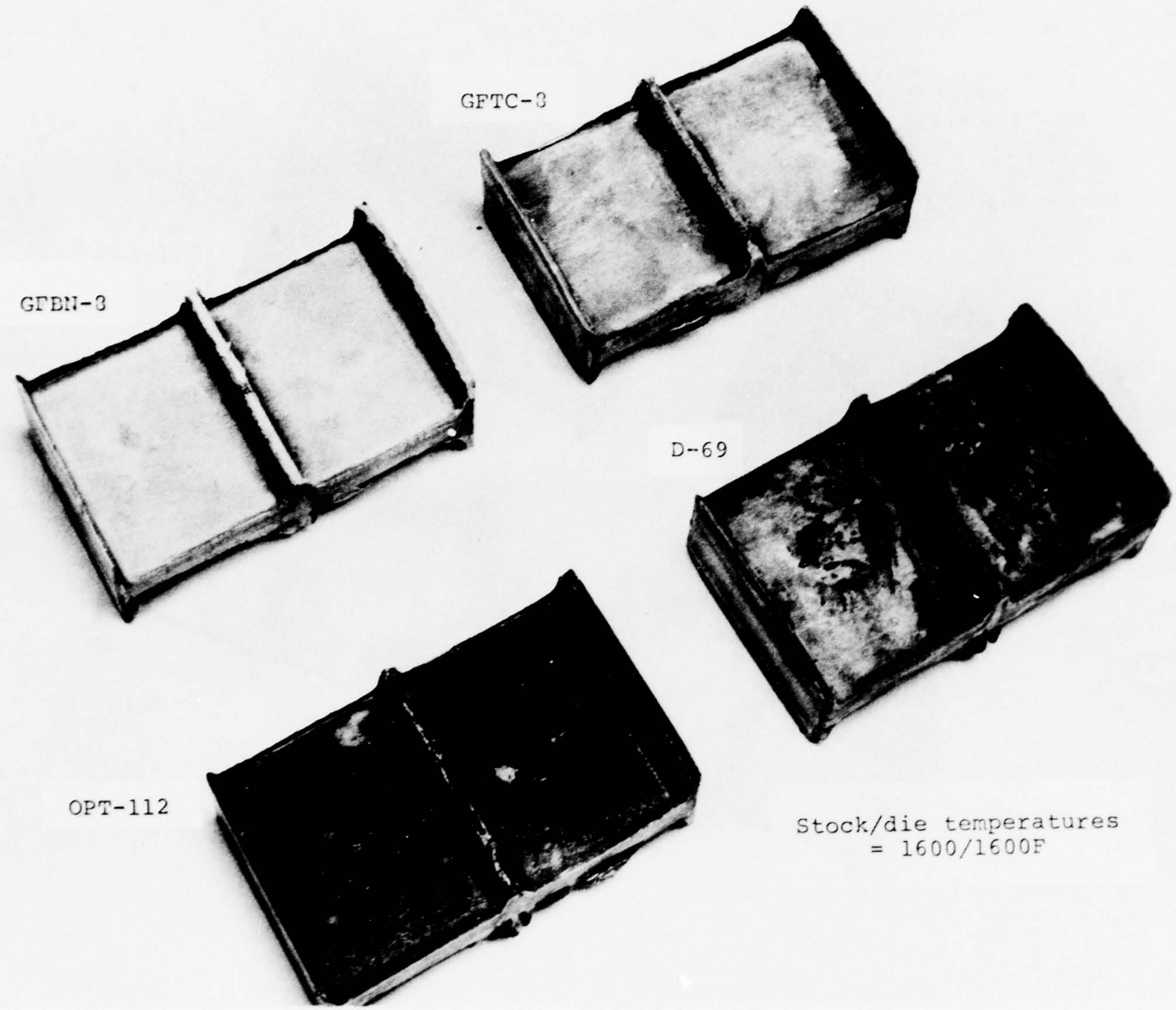


Figure 9b Closeup top view of rib-and-web forgings produced from Phase I second preliminary rib-and-web lubrication evaluation

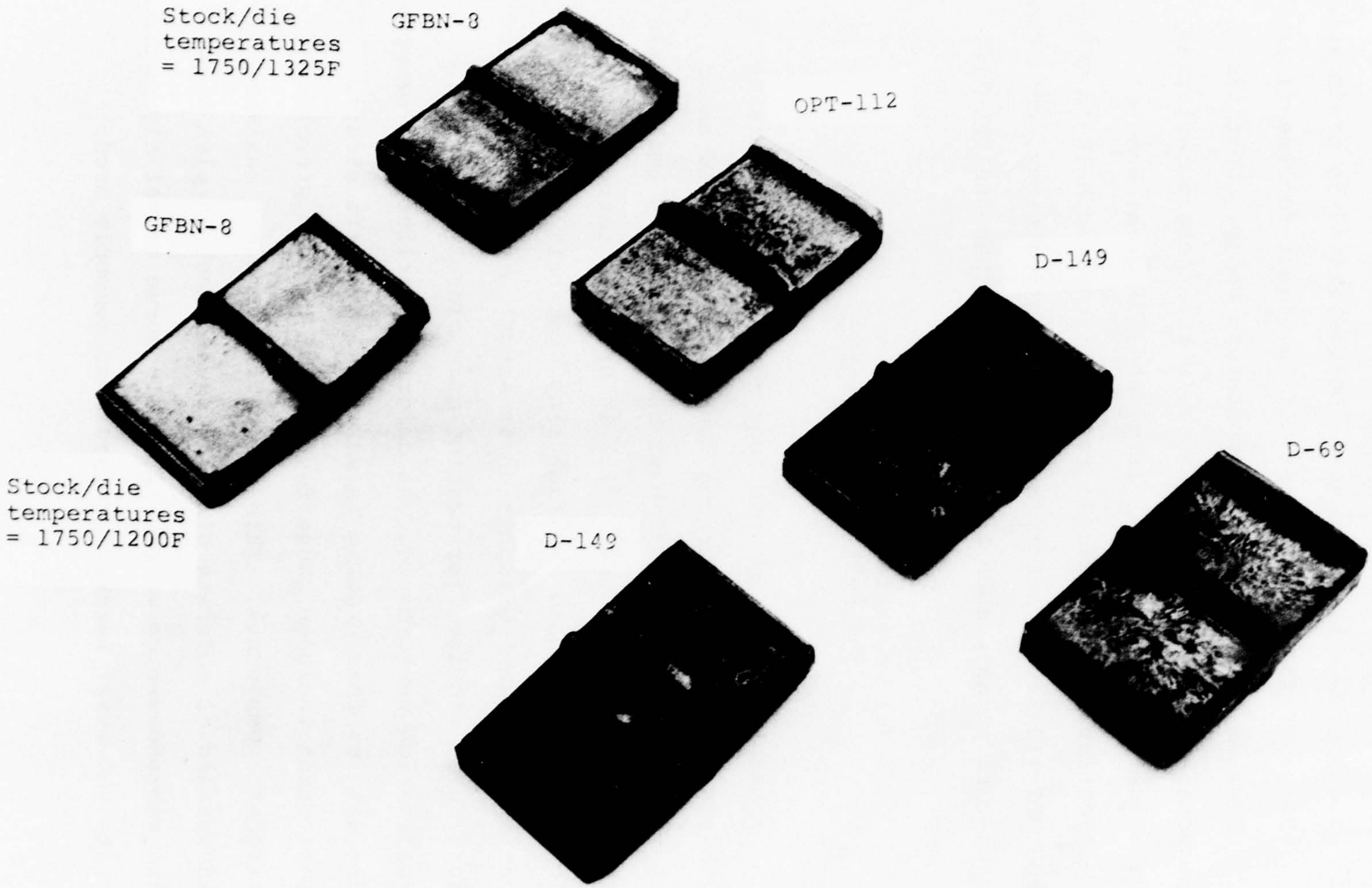


Figure 9c Closeup top view of rib-and-web forgings produced from Phase I second preliminary rib-and-web lubrication evaluation

Based on the results of the two preliminary lubricant evaluations, it was concluded that Acheson's Deltaglaze-69 is preferable to TRW's OPT-112 as the "control" lubricant for the finish forgings in the 1600-1750F temperature range. Specific reasons are: (1) favorable anti-friction characteristics, (2) excellent thermal stability, and (3) great ease of application. An additional reason is that both TRW's GFBN-8 and OPT-112 have similar formulation compositions, and GFBN-8 appears to have much better lubricity than the OPT-112.

(c) A Scaled-up Approach of the Lubrication Systems

The present lubrication testings for the most promising candidate isothermal forging lubricants developed under contract F33615-74-C-5059 have been limited to small-scale laboratory forgings only ([5]). In order to carry on the logical steps toward manufacturing applications, the evaluation of these lubricants on an actual aircraft component forging is required for testing more closely related to application performance. As described earlier, the proposed die set for this program is an actual aircraft structural part which includes those features of typical structural aircraft components. This die cavity combines maximum advantages of moderate size, 80 square inch in plan view, and rib-and-web geometry. It would serve to validly scale-up to the still larger forgings most commonly used.

As previously stated, the theme for this portion of the evaluations is the comparison of the lubrication effectiveness for two experimental lubricants (GFBN-8 and GFTC-8) with the Acheson's Deltaglaze-69. The major variables designed to examine the lubricant performance are as follows: degree of part fill, ease of part release from the die cavity, severity of lubricant buildup, and condition of surface integrity.

(1) Titanium Alloy Forging Stocks

The starting material was 4-9/16 inch diameter Ti-6Al-4V bar, purchased from Titanium Metal Company of America. The chemistry, $\alpha+\beta/\beta$ transus, and microstructure of the as-received stock (TMCA heat N-8554) were checked at Wyman-Gordon. The chemical composition was determined to be closely agreed with the certified chemistry by the ingot producer and the $\alpha+\beta/\beta$ transus was determined to be 1835F. The starting billet had a structure characterized by the $\alpha+\beta$ finish. This material was sonic inspected and met MIL-T-9047 requirement per approved procedure. Table 4 presents chemistry for the program materials.

TABLE 4

CHEMISTRY OF PROGRAM MATERIALS

Alloy (Heat Number)	Analysis Source	Chemical Composition (Weight %)									Technical Efforts
		Al	V	Fe	Cu	C	N	O_2	H_2	Ti	
Ti-6Al-4V (TMCA N-8554)	TMCA	6.6	4.3	0.18	0.005	0.018	0.013	0.18	0.008		Phase I (Task I) and Phase II
	WG	6.36	4.00	0.15	0.01	0.014	0.018	0.179	0.0075	Bal.	
Ti-10V-2Fe-3Al (TMCA V-5145)	TMCA	3.0	9.8	1.9	-	-	0.015	0.10	-	Bal.	Phase I (Task II)
	WG	3.05	9.40	2.30	-	0.011	0.018	0.121	0.0039	Bal.	
Ti-6Al-4V (TMCA N-7628)	TMCA	5.9	3.8	0.15	-	0.022	0.020	0.19	0.009	Bal.	Rib-and-web lubrications

(2) Preliminary Processings for Forging Stocks

The initial Ti-6Al-4V alloy stock was cogged and drawn from 4-9/16 inches round to 2-1/4 inches round at 1750F using hydraulic press. They were then sectioned into 9 inch long multiples, blasted, ground to remove minor wrinkles, and chem-milled to remove surface layers. The flattening, rolling, fuller, preblocker and blocker operations were subsequently carried out for these multiples.

These operations were performed by hammer forging at 1750F in the Worcester plant of Wyman-Gordon Company. Forty-four Ti-6Al-4V alloy blockers were produced for finish forging operations. An example of top and bottom views of the blockers produced is given in Figure 10.

(3) Finish Forging Evaluation for Ti-6Al-4V Alloy (1500-1800F Range)

As stated earlier, in order to insure the constancy of forge operations for the investigation, the forge variables such as forge/die temperature, ram rate, preform volume, furnace time, and forge pressure were closely controlled and applied in a consistent manner. The two experimental isothermal forging lubricants, i.e., TRW's GFBN-8 and GFTC-8, were used for this evaluation (Table 5). For comparison, the Acheson Deltaglaze-69 was used as the "control" lubricant for this portion of the program.

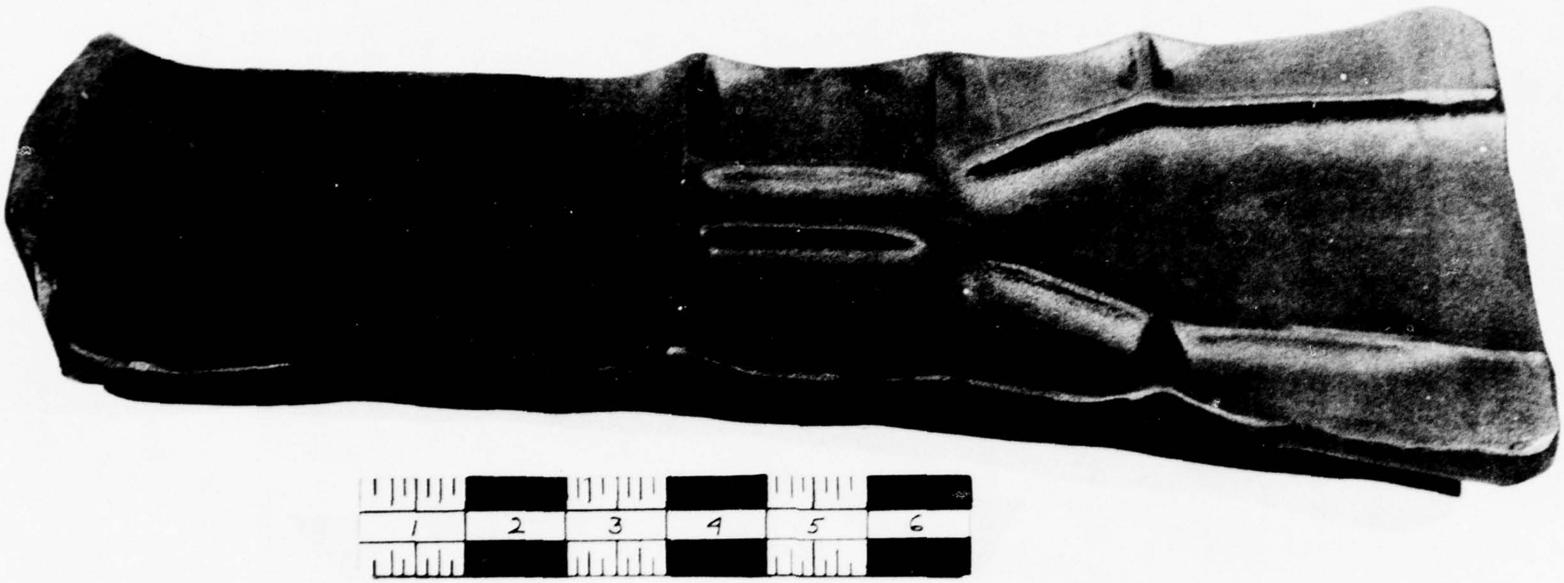


Figure10 Top view of blocker used for finish forging evaluations

TABLE 5

COMPOSITIONS OF ISOTHERMAL FORGING LUBRICANTS SELECTED AND USED FOR PHASE I (TASK I) EFFORT

Source	Lubricant Designation	Compositions and Formulations
TRW	GFBN-8*	850 Gram Batch: 300 gm of vitreous phase (31W/oSiO_2, 67W/oB_2O_3, 2.0W/oCaO, 1.0FeO, trace MgO, trace K_2O) 24 gm of BN (9-30 μ size) 446 gm of xylene 77 gm of acrylic emulsion
TRW	GFTC-8*	850 Gram Batch: 300 gm of vitreous phase (31W/oSiO_2, 67W/oB_2O_3, 2.0W/oCaO, 1.0FeO, trace MgO, trace K_2O) 24 gm of TiC 457 gm of xylene 78.1 gm of acrylic binder
Acheson Colloids Company	Delta-** glaze 69	water-based silicate glass compound
TRW	OPT-112**	14% Boron Nitride 86% Glass Glass Composition - 67% B_2O_3 33% Silica Glass Frit with 2% Transition Metal

* Lubricants recommended from AFML Contract F33615-74C-5059 (reference 5)

** Lubricants recommended from AFML Contract F33615-74-C-5011 (reference 1)

A series of forty-four (44) forgings were produced using three (3) lubrication practices [twenty (20) per lubricant for two newly developed lubricants ([5]) and four (4) for Acheson Deltaglaze-69]. They were forged in the R & D 1500-ton hydraulic press; the die set, heating assembly, and tooling system with top and bottom movable ejectors, are available at R & D of Wyman-Gordon for this program forging (Figure 2). The details of the processing variables for finish forging evaluations are listed in Table 6.

The main characteristics for the finish forging practice are given as follows:

a. Part/die temperature for the finish operation: 1750F and 1600F

   All the evaluation was made on isothermal conditions in order to eliminate or to reduce the chilling effect from the die. The two selected temperatures, 1750F and 1600F, fall within the optimized part-die temperature range specified in the recently completed AFML-sponsored contract F33615-74-C-5011 ([1]).

b. Strain rate in the finish operation; 0.1 inch/minute ram rate

   It has been experienced that the ram rate of ~0.1 inch/minute appears to be optimum condition from forge pressure standpoint for isothermal forging of this Ti-6Al-4V alloy component.

TABLE 6

PROCESSING VARIABLES FOR FINISH FORGING EVALUATIONS OF Ti-6Al-4V ALLOY FOR PHASE I (TASK I) EFFORT

Serial Number	Lubricant* (Coating)	Forge/ Die Temp. (F)	Ram Rate (in/min)	Furnace** Type	Average*** Pressure Applied (ksi)
1-3	GFBN-8	1750	0.1	Gas-fired	25
4-10	GFBN-8	1750	0.1	Electric	25
11-13	GFBN-8	1600	0.1	Gas-fired	37.5
14-20	GFBN-8	1600	0.1	Electric	37.5
21-23	GFTC-8	1750	0.1	Gas-fired	25
24-30	GFTC-8	1750	0.1	Electric	25
31-33	GFTC-8	1600	0.1	Gas-fired	37.5
34-40	GFTC-8	1600	0.1	Electric	37.5
41	Deltaglaze-69	1750	0.1	Gas-fired	25
42	Deltaglaze-69	1750	0.1	Electric	25
43	Deltaglaze-69	1600	0.1	Gas-fired	37.5
44	Deltaglaze-69	1600	0.1	Electric	37.5

* Coated for 6 mils by spray

** Furnace time ≈1-1/2 hours; transfer time from furnace to die ≈5 seconds

*** Dwell time =1 minute

c. Preform microstructure: $\alpha+\beta$

Recent results ([1], [10]) suggest that an ($\alpha+\beta$) preform followed by an ($\alpha+\beta$) finish should result in the lower pressure required and provide better die-fill, as compared to β-preform. It is anticipated that the residual β structure from billet conversion will be eliminated after considerable preliminary deformation has applied to the preform in the $\alpha+\beta$ field.

d. Preform preparation method and excess preform volume

The preforms were produced at 1750F in existing conventional blocker tooling in order that the basic preform volume and distribution can be controlled. An excess preform volume of $\sim$2% was used to eliminate possible forge pressure variations due to flash formation and were controlled by chem-milling.

e. Furnace Atmosphere

The initial attempt was to use gas-fired furnace as preheating furnace in order to simulate the atmosphere condition in the forge shop. However, it was discovered during early forging operations that the gas-fired environment had significantly reduced the metal flow characteristics and changed the coating appearance (see Figure 11). Therefore, both gas-fired and electric furnaces were then used for this evaluation.

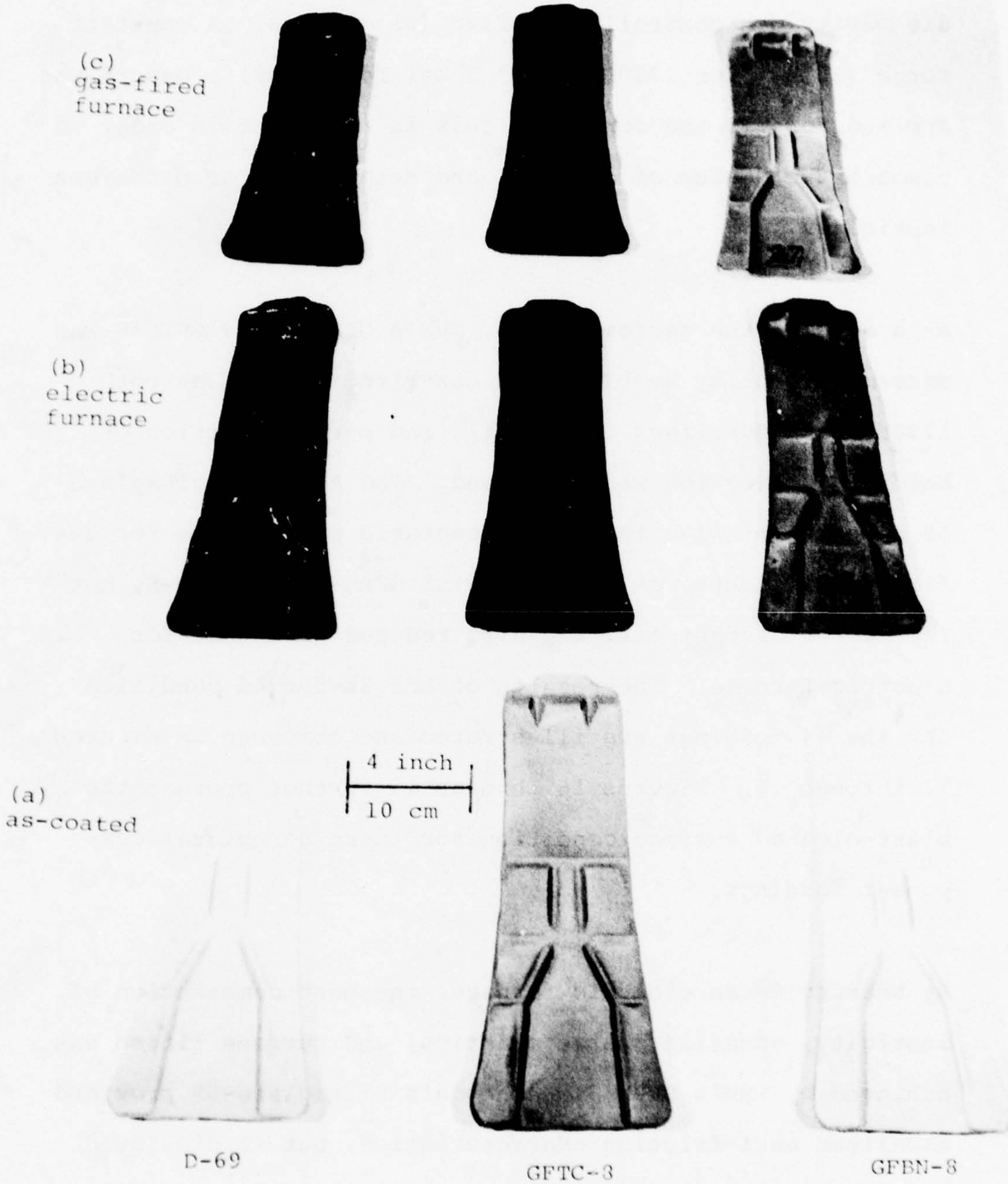


Figure 11 Change in coating appearance after 3 hours exposure at 1750F: (a) as-coated, (b) electric furnace, (c) gas-fired furnace

In addition, the transfer time for the part from furnace to die cavity was controlled at five (5) seconds. A constant forge ([illegible] ksi for 1750F and 37.5 ksi for 1600F) pressure was applied for all the forgings; this is important in order to compare the degree of die-fill and metal flow for different lubricants.

As a result, the performance of TRW's GFBN-8 and GFTC-8 was extremely poor by heating in a gas-fired furnace at both 1750F and 1600F; lack of rib-fill and part-distortion or bending on ejection were observed. The Acheson Deltaglaze-69 appeared to give the most acceptable performance for gas-fired environment, as compared with GFBN-8 and GFTC-8, but the degree of part-fill was also reduced from that for electric furnace. The results of the as-forged condition for the 44 forgings are illustrated and compared in Figures 12 through 15. Figures 16 through 19 further present the blast-cleaned surface condition for these structural component forgings.

By heating in an electric furnace, the best combination of lubricity, adhesion characteristics, and surface finish was achieved by TRW's GFBN-8. Acheson's Deltaglaze-69 provided excellent anti-friction characteristics, but it displayed unfavorable adhesion properties. TRW's GFTC-8 gave excellent adhesion characteristics, but it significantly reduced the degree of part-fill (see Figures 12 through 19).

Figure 12 Complete set of twenty-two structural component forgings produced by isothermal forging at 1750F

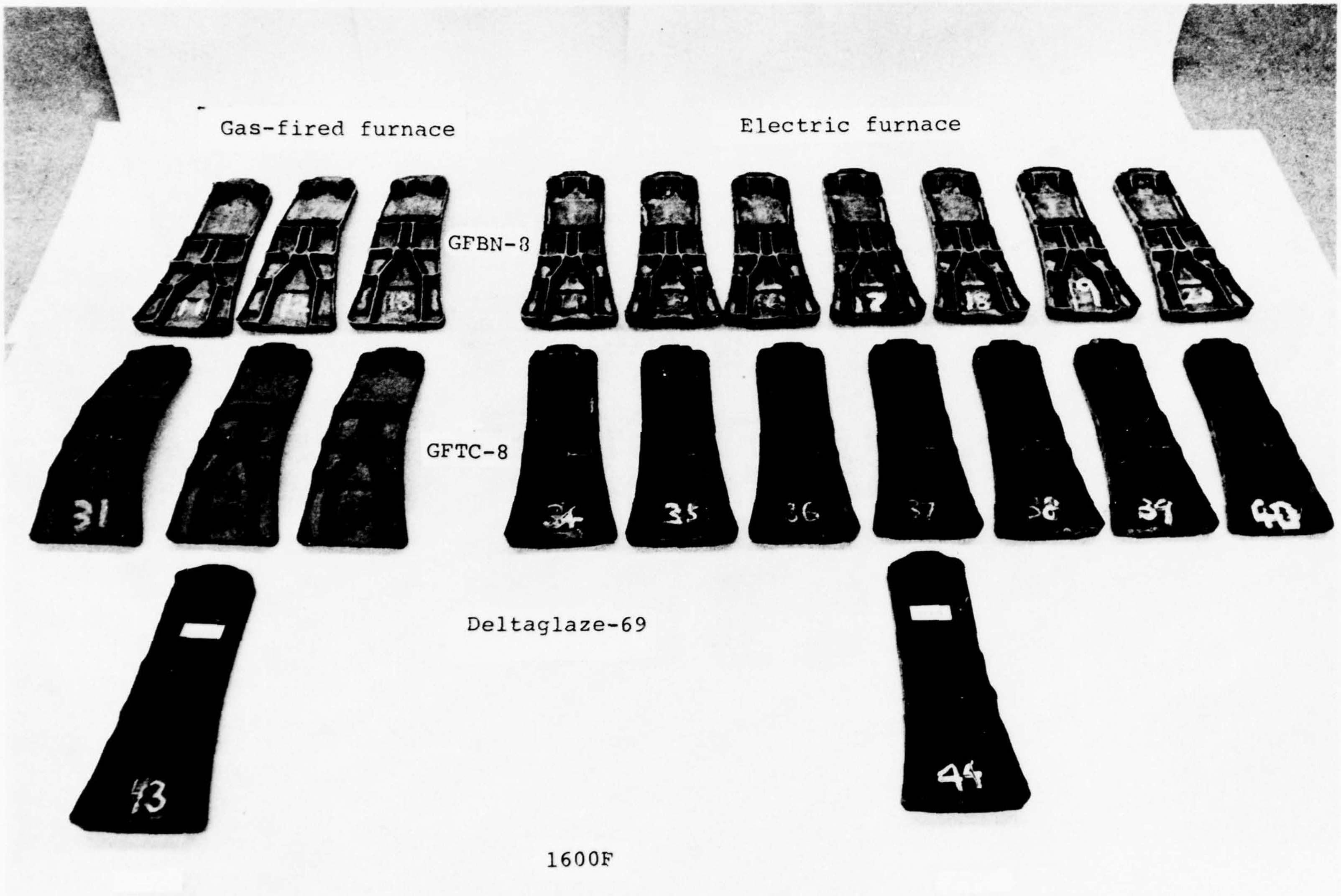


Figure 13 Complete set of twenty-two structural component forgings produced by isothermal forging at 1600F

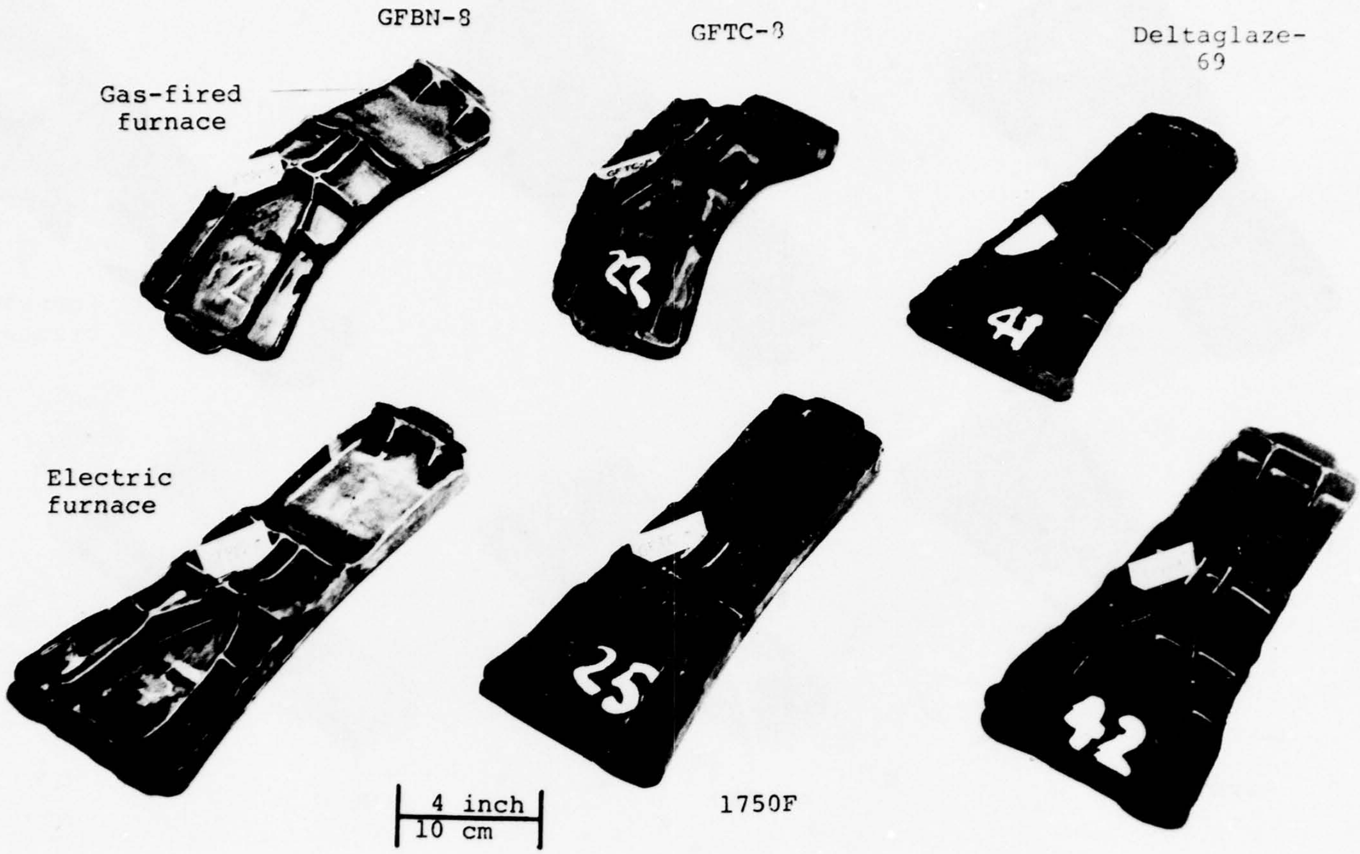


Figure 14 Closeup view of structural component forgings produced by isothermal forging at 1750F using three different lubricants

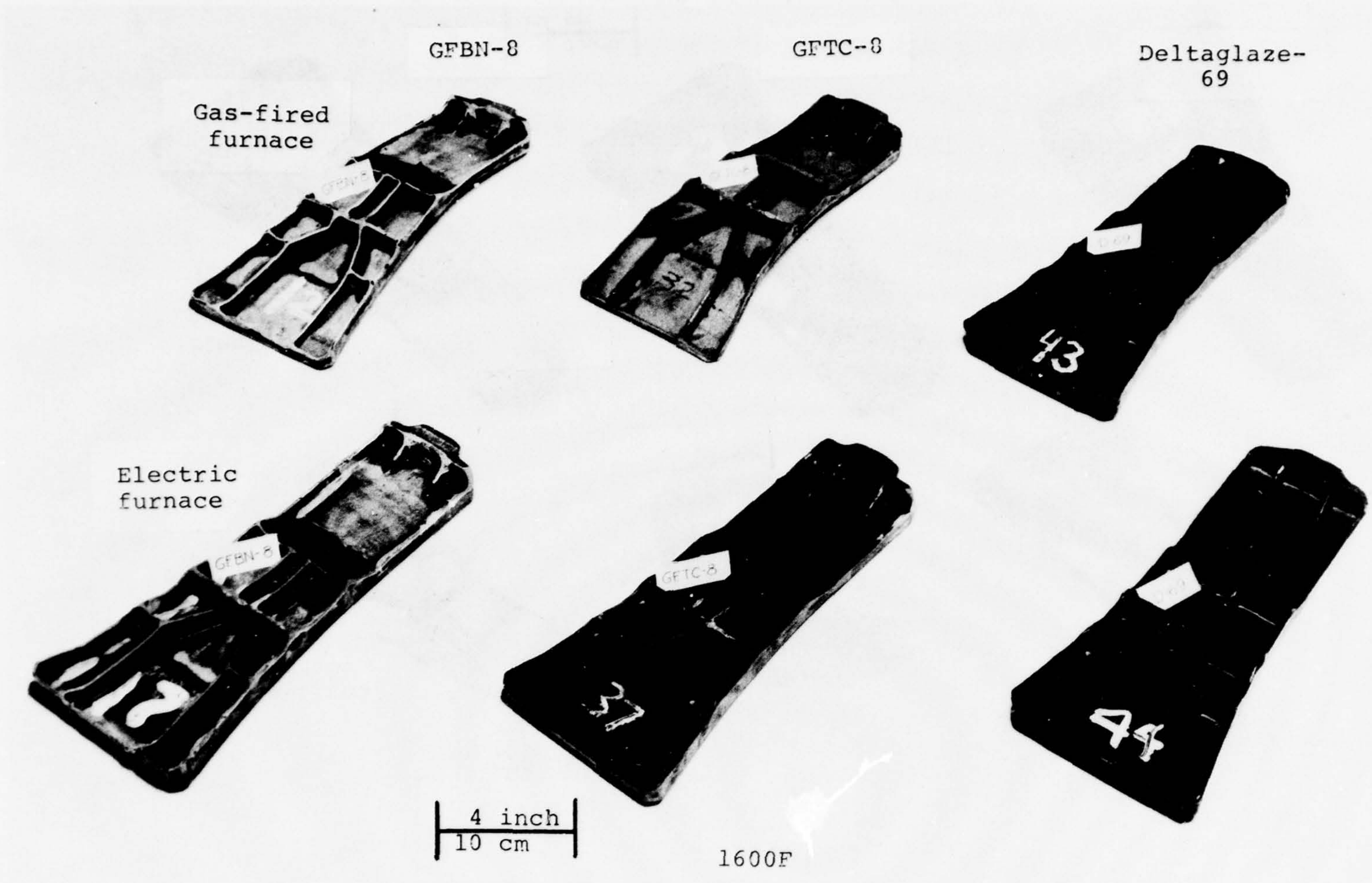


Figure 15 Closeup view of structural component forgings produced by isothermal forging at 1600F using three different lubricants

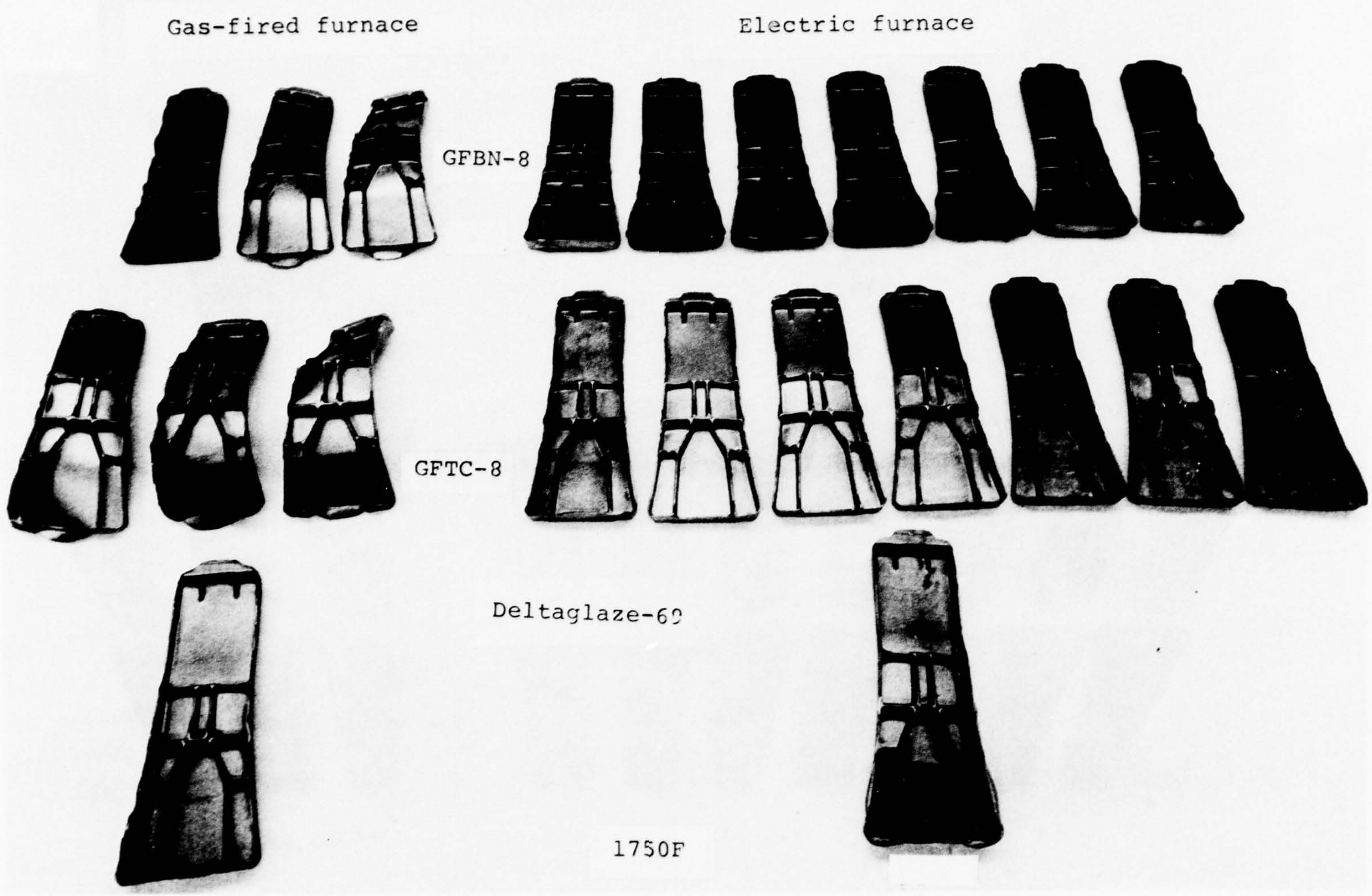


Figure 16 Complete set of twenty-two structural component forgings produced by isothermal forging at 1750F; blast-cleaned condition

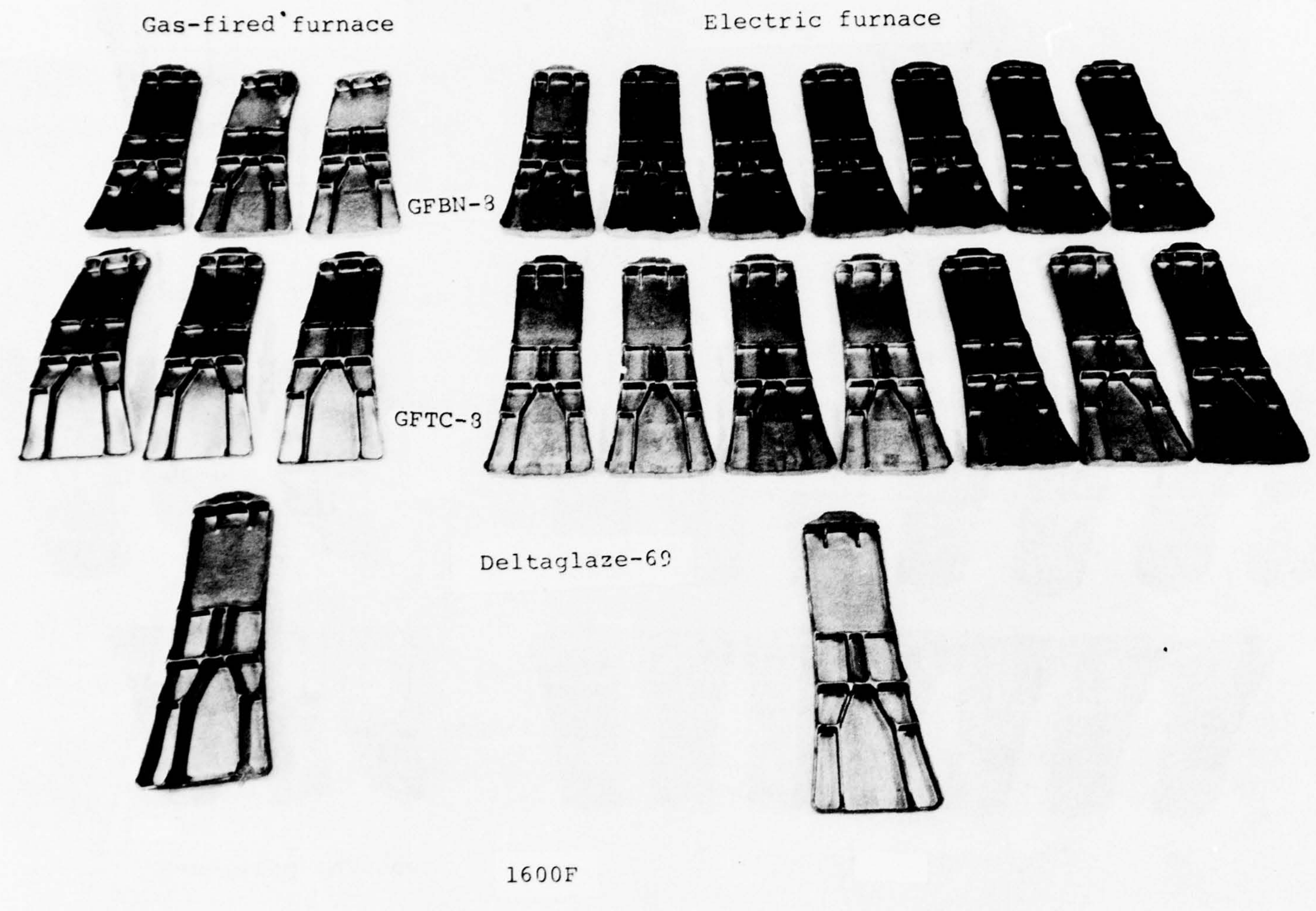


Figure 17 Complete set of twenty-two structural component forgings produced by isothermal forging at 1600F; blast-cleaned condition

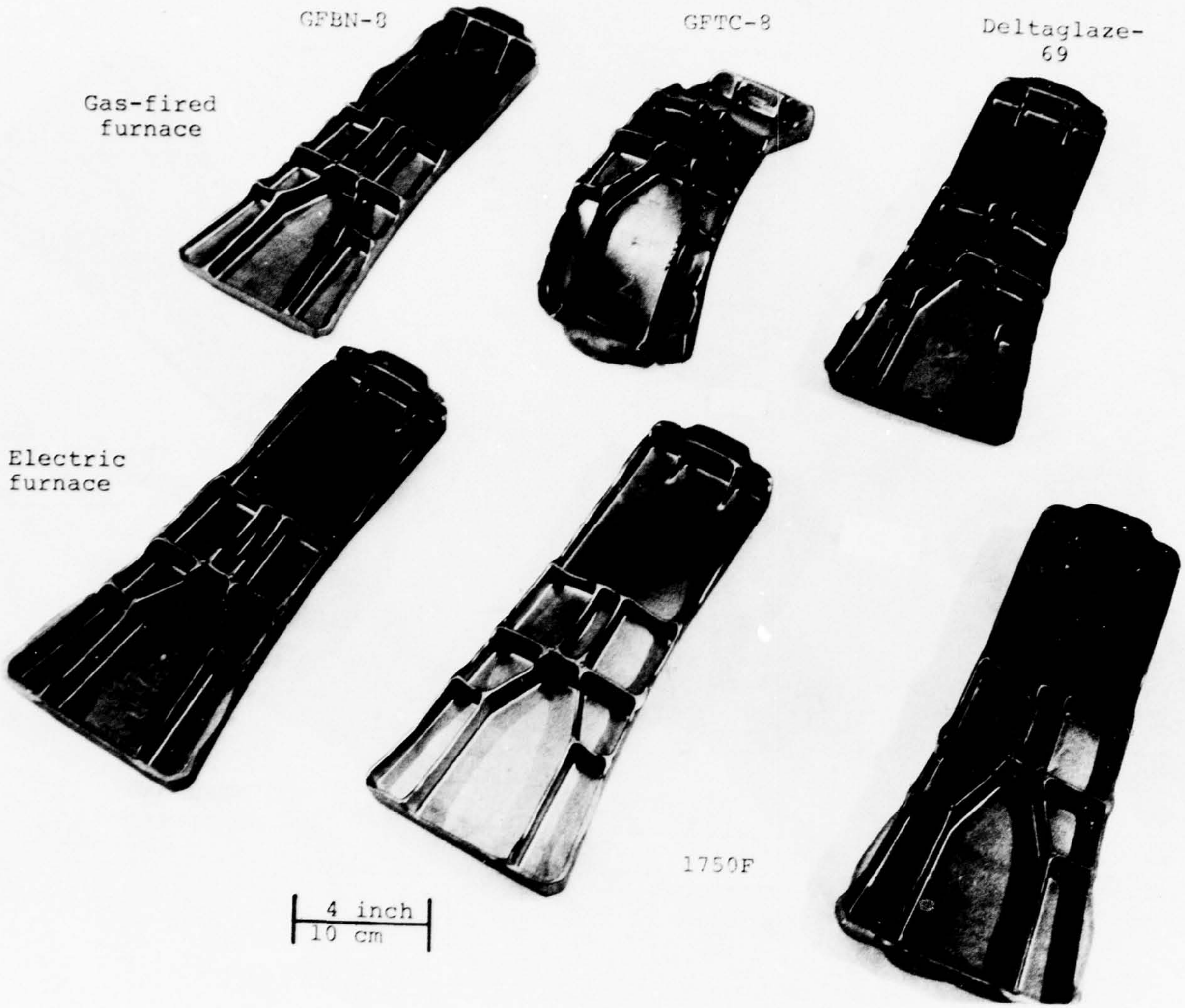


Figure 18a Closeup top view of structural component forgings produced by isothermal forging at 1750F using three different lubricants; blast-cleaned condition

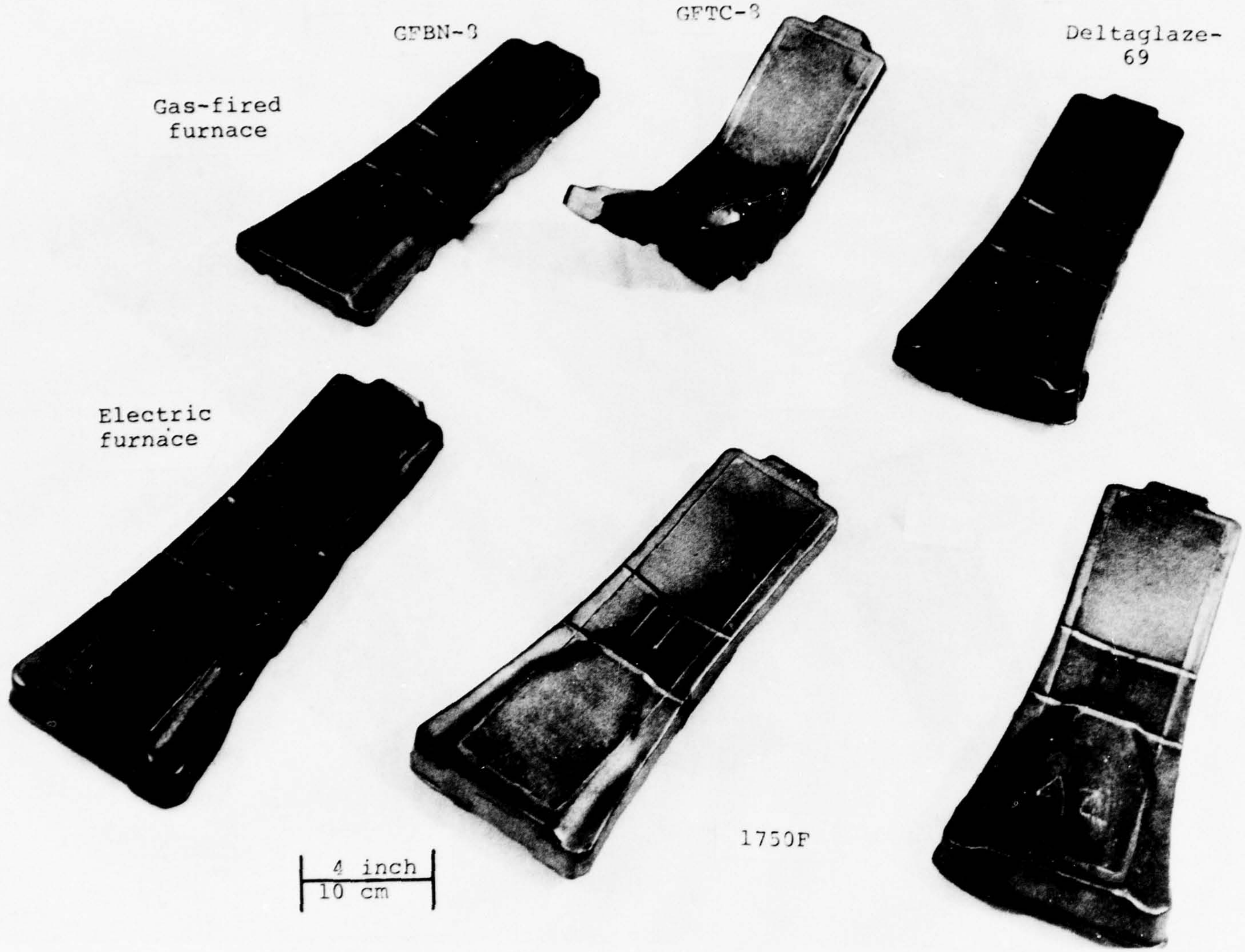


Figure 18b Closeup bottom view of structural component forgings produced by isothermal forging at 1750F using three different lubricants; blast-cleaned condition

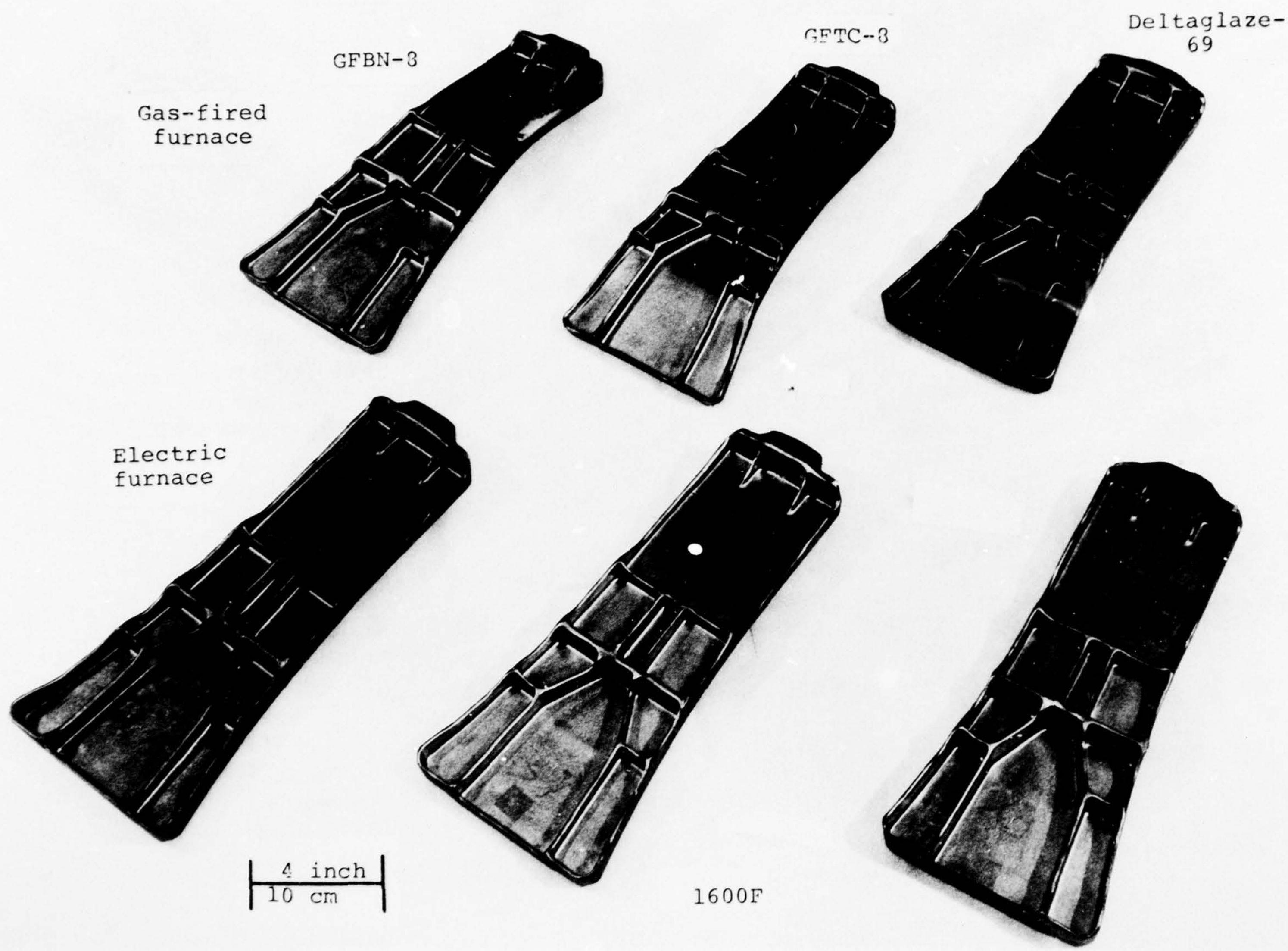


Figure 19a Closeup top view of structural component forgings produced by isothermal forging at 1600F using three different lubricants; blast-cleaned condition

Figure 19b Closeup bottom view of structural component forgings produced by isothermal forging at 1600F using three different lubricants; blast-cleaned condition

It should be particularly emphasized that the observation of the detrimental influence of gas-fired furnace on metal flow and adhesion strength within short-time furnace exposure ($\sim$1-1/2 hours) was surprising. Although the gas-fired furnace has been used often for comparing the thermal stability of the coatings on small-scale laboratory samples or forgings, the previous tests have been limited to thickness and weight changes of the lubricant films and visual examination of the film appearance and characteristics. Here the direct demonstration of the effect of gas-fired environment on both anti-friction and adhesion characteristics of the lubricants for producing an actual aircraft component forging may account for an important accomplishment of the Phase I efforts in the subject program.

Based on the above results, two essential considerations have to be taken in order to improve and to represent the state-of-the-art in isothermal forging lubricants. First, if the newly developed lubricants will become production lubricants, the use of an electric furnace as a preheat furnace prior to isothermal forging is necessary. This appears to be impractical since most of the forge shops use gas-fired furnaces as preheating furnaces due to economical reasons. Second, in order that the developed lubricants could be commercially acceptable in the forge shop, the future experimental effort on the evaluation of new lubricant formulations should use the gas-fired furnace.

2. Task II - Beta Titanium Alloy (1300-1550F Range)

As described earlier, the beta or near-beta titanium alloys are strong alloy candidates for future aircraft components from an economic reason for isothermal forging. The selected alloy system for this portion of evaluation was Ti-10V-2Fe-3Al alloy. The excellent combination of hot-die forgeability and strength-ductility-toughness relationships provides this alloy as a strong potential candidate for isothermal forging of titanium aircraft structural components. Wyman-Gordon has had considerable experience on hot-die forgeability, structure, and properties for this alloy ([6], [11]).

(a) Experimental Lubricants Recommended by AFML

The two AFML-recommended lubricants (TRW's LFC-8 and LFC-11)([5], [12]) for scale-up in isothermal forging of the Ti-10V-2Fe-3Al alloy over the 1300F to 1550F temperature range were formulated by TRW. A total of ten different lots of lubricants was ordered by Wyman-Gordon; five different lots per lubricant, and a half-gallon per lot. Details of the compositions and formulations for the lubricants are given in Table 7. It is seen that the LFC-8 is basically a borosilicate glass coating, while LFC-11 is a silicate type of lubricant. As described by the lubricant producer ([13]), these lubricants were formulated for spray application; LFC-11 was diluted with isopropyl alcohol, and LFC-8 was diluted with xylene. They should be thoroughly mixed and agitated during application.

TABLE 7

COMPOSITIONS AND GENERAL DESCRIPTION OF ISOTHERMAL FORGING LUBRICANTS SELECTED FOR PHASE I (TASK II) EFFORT: FOR BETA TITANIUM ALLOY USE AT 1300 TO 1550F TEMPERATURE RANGE

Source	Lubricant Designation	Compositions and Formulations	General Description
TRW	LFC-8*	Vitreous phase: 60% B_2O_3, 31% SiO_2 7% K_2O, 2% CoO particulate phase: 3.7 wt.% TaC	1. Experimental lubricant recommended for service at 1350-1500F with Ni-alloy dies 2. An excellent wide-thermal-spectrum isothermal forging coating for beta Ti-alloys
TRW	LFC-11*	Vitreous phase: 42% SiO_2, 2% Na_2O 6% K_2O, 49% PbO 1% LiO Particulate phase: 4.5 wt.% CrC	1. Experimental lubricant recommended for service at 1350F with ferrous alloy dies 2. ease in application, superior in compatibility, stability, and adhesion, but a somewhat high in adhesion load
Acheson Colloids Company	Deltaglaze-149	Water-based silicate, glass and organic resin	1. Commercial lubricant for isothermal forging uses 2. Excellent lubricacation, protection, and viscosity in the temperature range of 1300 to 1550F

* Recommended lubricant from AFML Contract F33615-74-C-5059 (reference 5)

(b) Scaled-up Evaluations for Beta Titanium Alloy

Finish forging evaluations for the forty-four Ti-10V-2Fe-3Al alloy blockers were completed using two experimental isothermal forging lubricants developed under AFML Contract F33615-74C-5059, i.e., TRW's LFC-8 and LFC-11, and the "control" lubricant Acheson Deltaglaze-149. As stated earlier in Task I effort, the forge variables were closely controlled and applied in a consistent manner for insuring the constancy of forge operations. It was revealed in the preliminary rib-and-web forging trials and under AFML Contract F33615-74C-5011 work at Wyman-Gordon ([1]) that the Acheson Deltaglaze-149 had excellent lubrication efficiency in the temperature range of 1300 to 1550F. The Deltaglaze-149 should also have a more adequate viscosity than Deltaglaze-69 at 1300 to 1550F temperature range ([8]). Table 8 lists the details of the processing variables used for this effort.

(1) Starting Forging Stocks

The Ti-10V-2Fe-3Al alloy of 8 inch round stock was purchased from TMCA. The chemical composition (Table 2) of the as-received Ti-10V-2Fe-3Al stock (TMCA heat V-5145) is within the proposed chemistry limit for this alloy formulation ([14]) and the starting stock was sonic inspected to acceptance standard by ingot producer.

TABLE 8

PROCESSING VARIABLES FOR FINISH FORGING EVALUATIONS OF Ti-10V-2Fe-3Al ALLOY FOR PHASE I (TASK II) EFFORT

Serial Number	Lubricant* (Coating)	Forge/ Die Temp. (F)	Ram Rate (in/min)	Furnace** Type	Average*** Pressure Applied (ksi)
1-7	LFC-8	1550	0.5	Electric	35
8-10	LFC-8	1550	0.5	Gas-fired	35
11-17	LFC-8	1400	0.5	Electric	37.5
18-20	LFC-8	1400	0.5	Gas-fired	37.5
21-27	LFC-11	1550	0.5	Electric	35
28-30	LFC-11	1550	0.5	Gas-fired	35
31-37	LFC-11	1400	0.5	Electric	37.5
38-40	LFC-11	1400	0.5	Gas-fired	37.5
41	Deltaglaze-149	1550	0.5	Electric	35
42	Deltaglaze-149	1550	0.5	Gas-fired	35
43	Deltaglaze-149	1400	0.5	Electric	37.5
44	Deltaglaze-149	1400	0.5	Gas-fired	37.5

* Coated for 6 mils by spray

** Furnace time ≃1-1/2 hour; transfer time from furnace to die ≃5 seconds

*** Dwell time = 1 minute

(2) Preparations for Forging Blockers

The preliminary cogging and drawing processings for Ti-10V-2Fe-3Al forging stock were done at 1550F using press forging. They were then sectioned to 2-1/4 inches round x 11-3/8 inches long multiples. The multiples were blasted, ground to remove minor wrinkles, and chem-milled to remove surface layers. The fullering, flattening, and blocking were made on the 2-1/4 inch round x 11-3/8 inch long multiples at 1550F using drop hammer. Unlike other beta titanium alloys, the forgeability of Ti-10V-2Fe-3Al alloy under hammering was extremely good at 1550F. No evidence of surface cracking was shown and surface wrinkling of Ti-10V-2Fe-3Al blockers was less than that on Ti-6Al-4V blockers. The forging blockers were blast-cleaned, ground to remove minor defects, and chem-milled to remove surface alpha case.

(3) Finish Forging Evaluations

The forge practice and the tooling systems used for the Ti-10V-2Fe-3Al alloy are basically the same as those described for Task I approach. However, three exceptions should be noted:

a. Forge/Die Temperature for the Finish Operation: 1550F and 1400F

The selection of these two temperatures was based on our experience at Wyman-Gordon for the opti-timized part-die temperature range. This should also give the comparison of the difference in die fill between beta and alpha-beta forging operations.

b. Strain Rate and Dwell Time in the Finish Operation

Our experience demonstrated that optimum strain rate for hot-die forging at part/die temperature of 1550/1400F is 0.5∿1 inch/minute ram rate ([6]). A dwell time of 60 seconds was used to help die fill for this alloy.

c. Preform Microstructure: β-Preform

Unlike (α+β) preform microstructure for Ti-6Al-4V alloy stock used in Task I, the preliminary and blocking operations for Ti-10V-2Fe-3Al stocks were performed at 1550F to establish the same β-preform microstructure in all preforms.

Figures 20 through 27 illustrate the visual appearance of isothermally forged Ti-10V-2Fe-3Al alloy structural components at as-forged and blast-cleaned conditions. The results demonstrated that the LFC-11 gave the best combination of lubricity and adhesion characteristics in both electric and gas-fired furnaces. LFC-8 provided excellent adhesion properties, but it displayed comparably poor lubricity and stability. The Acheson's Deltaglaze-149 had excellent anti-friction characteristics; however, it gave unfavorable adhesion strength. Although the gas-fired environment appeared to give an effect on both metal flow and adhesion strength of the coating, the degree of influence for these beta-titanium alloy lubricants was considerably smaller, as compared with the lubricants (i.e., GFBN-8 and GFTC-8) for alpha-beta titanium alloys.

Another important observation for this portion of the program is the direct demonstration of the excellent isothermal forgeability of Ti-10V-2Fe-3Al alloy for producing an actual aircraft component forging. As previously reported by Wyman-Gordon ([6]), the use of Ti-10V-2Fe-3Al alloy may have major impact on the cost-effectiveness for the current isothermal forging technology of titanium alloy; isothermal forging of this alloy at 1300-1550F temperature range would possess significant advantages in reduced die materials and tooling costs, simplified handling, and energy savings over isothermal forging of Ti-6Al-4V alloy.

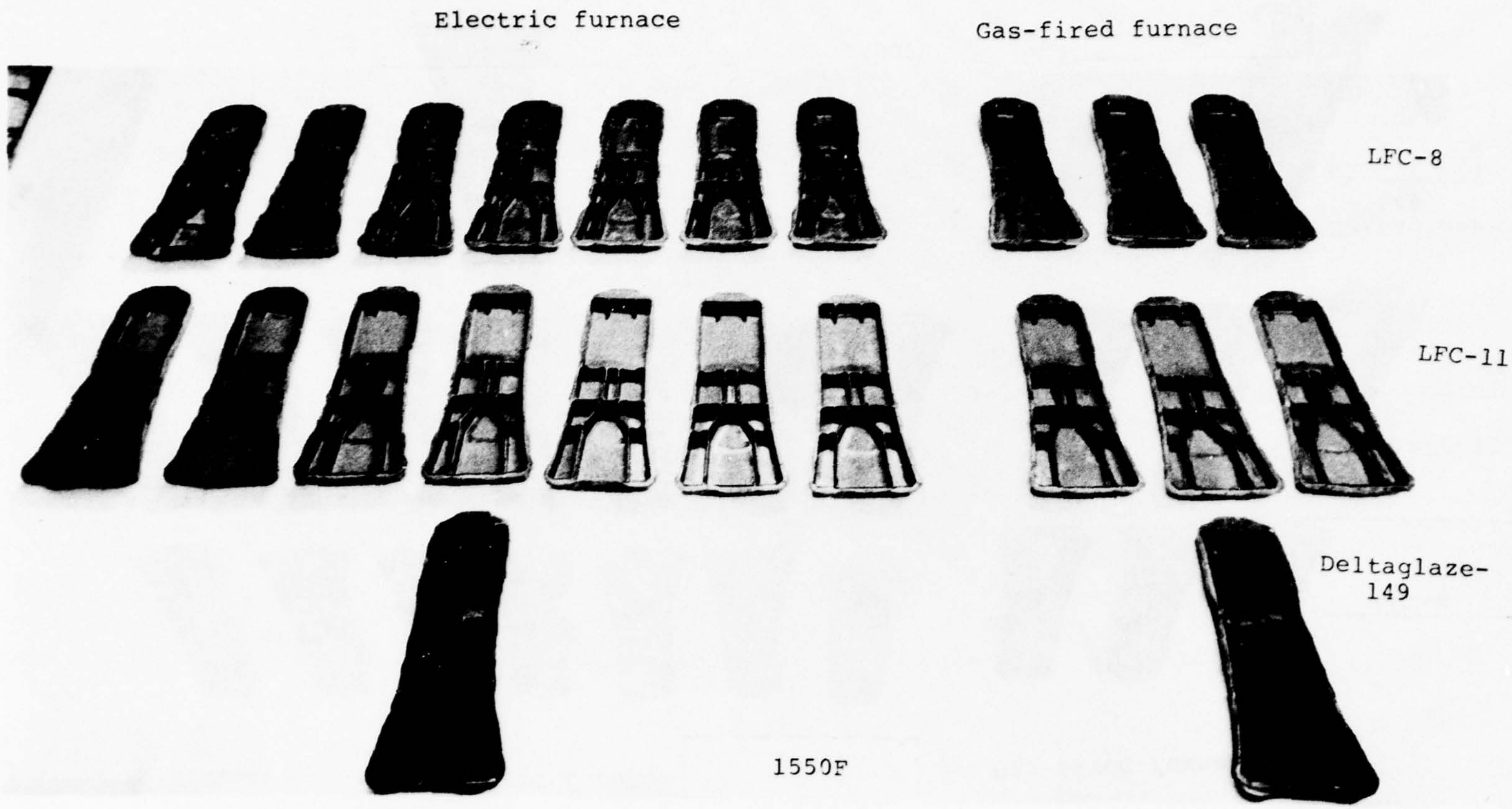


Figure 20 Complete set of twenty-two structural component forgings produced by isothermal forging at 1550F

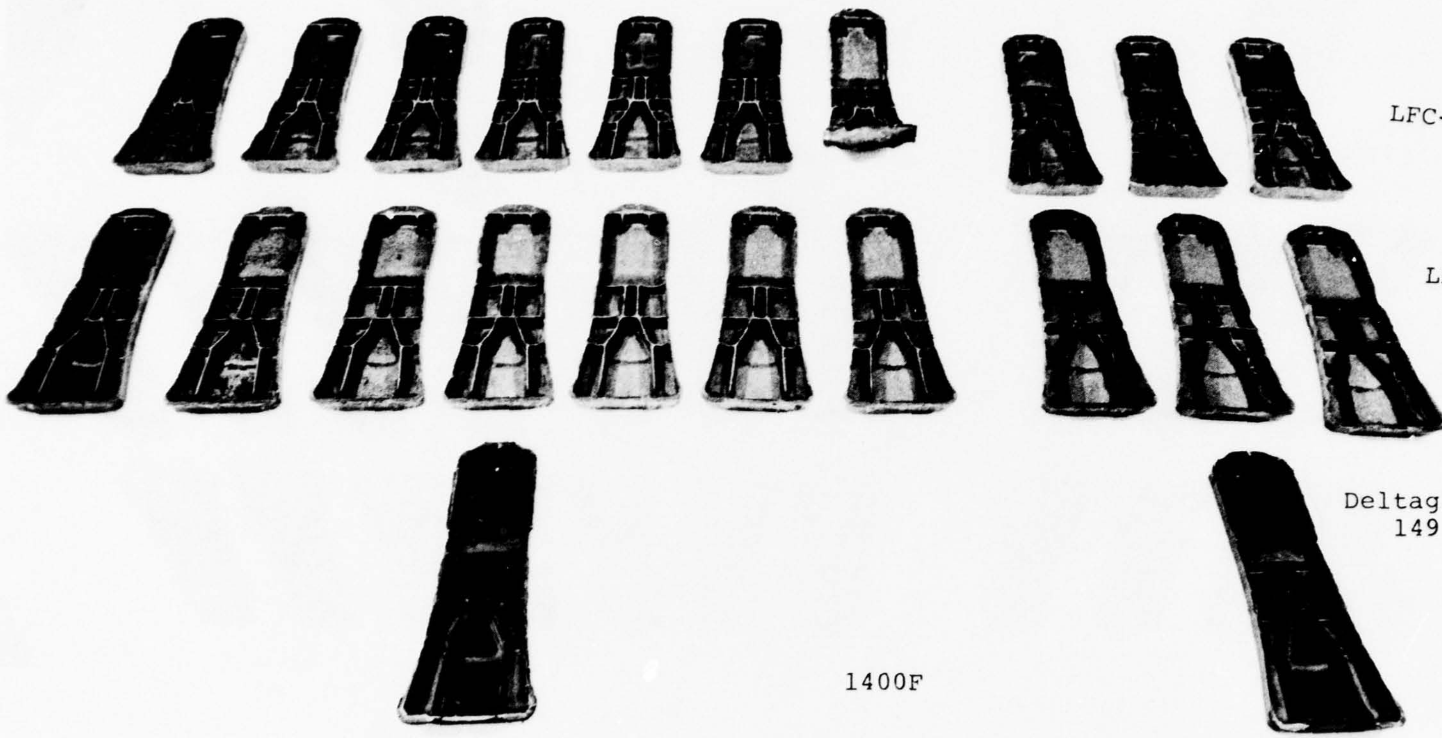


Figure 21 Complete set of twenty-two structural component forgings produced by isothermal forging at 1400F

Figure 22 Closeup view of structural component forgings produced by isothermal forging at 1550F using three different lubricants

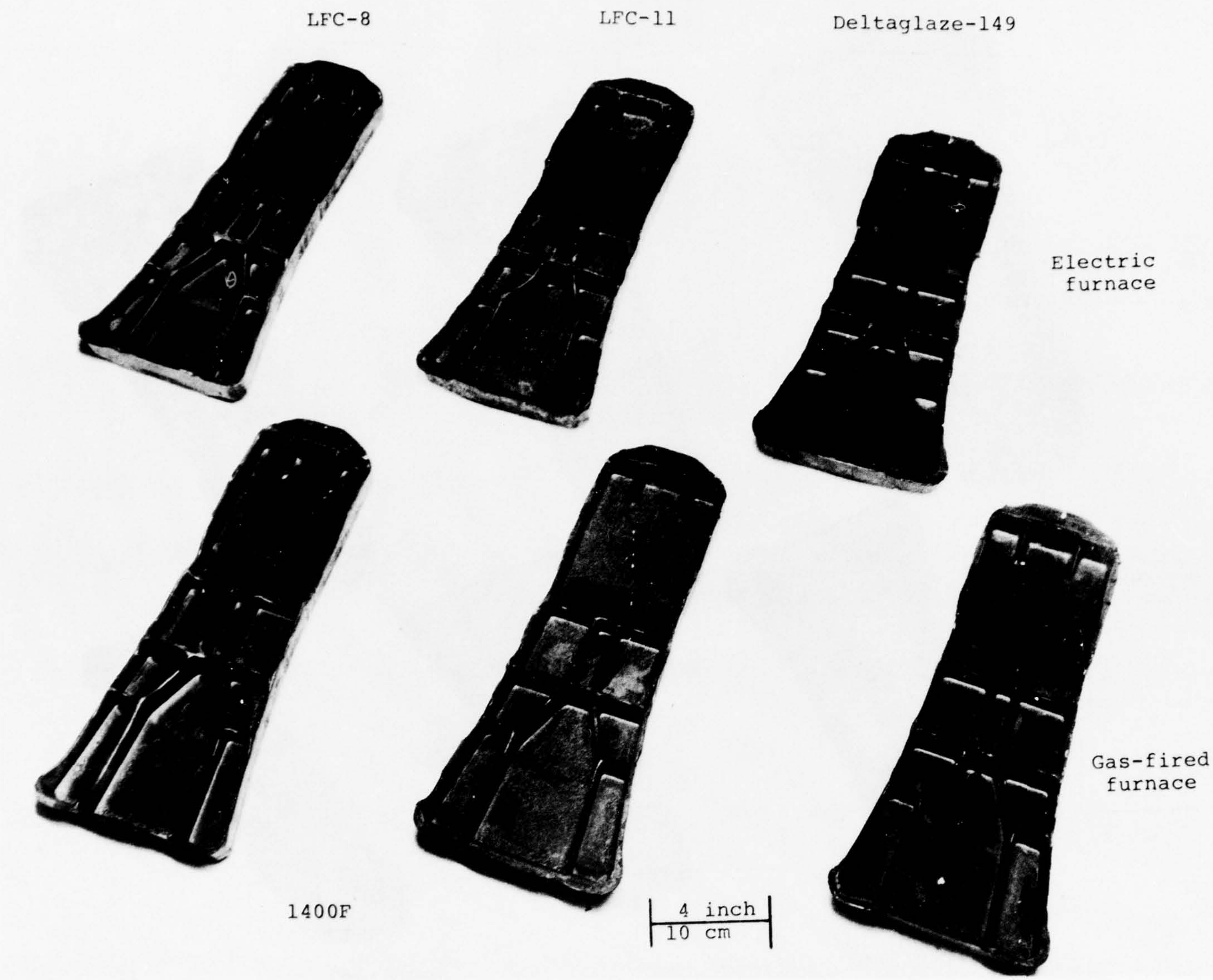


Figure 23 Closeup view of structural component forgings produced by isothermal forging at 1400F using three different lubricants

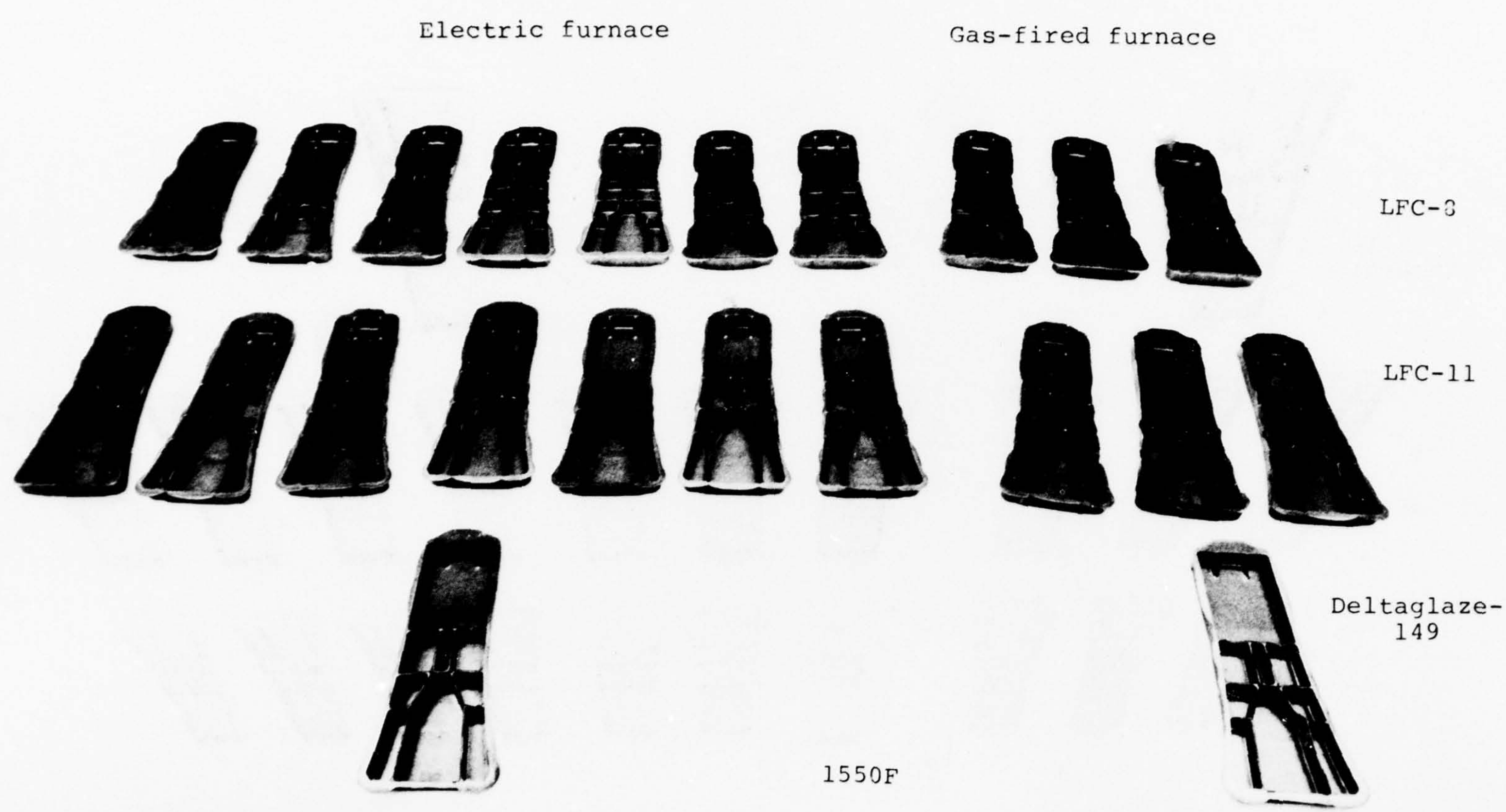


Figure 24 Complete set of twenty-two structural component forgings produced by isothermal forging at 1550F; blast-cleaned condition

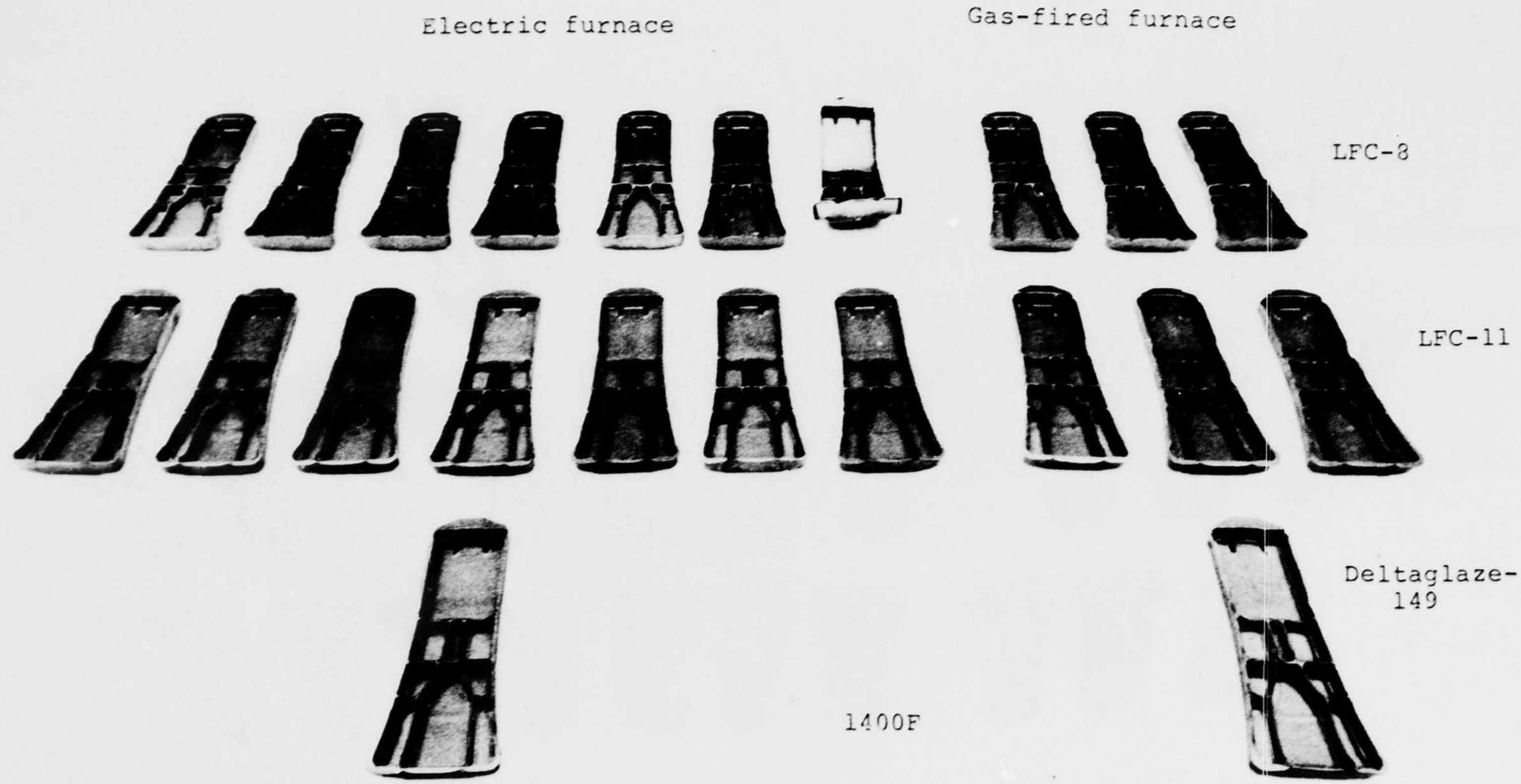


Figure 25 Complete set of twenty-two structural component forgings produced by isothermal forging at 1400F; blast-cleaned condition

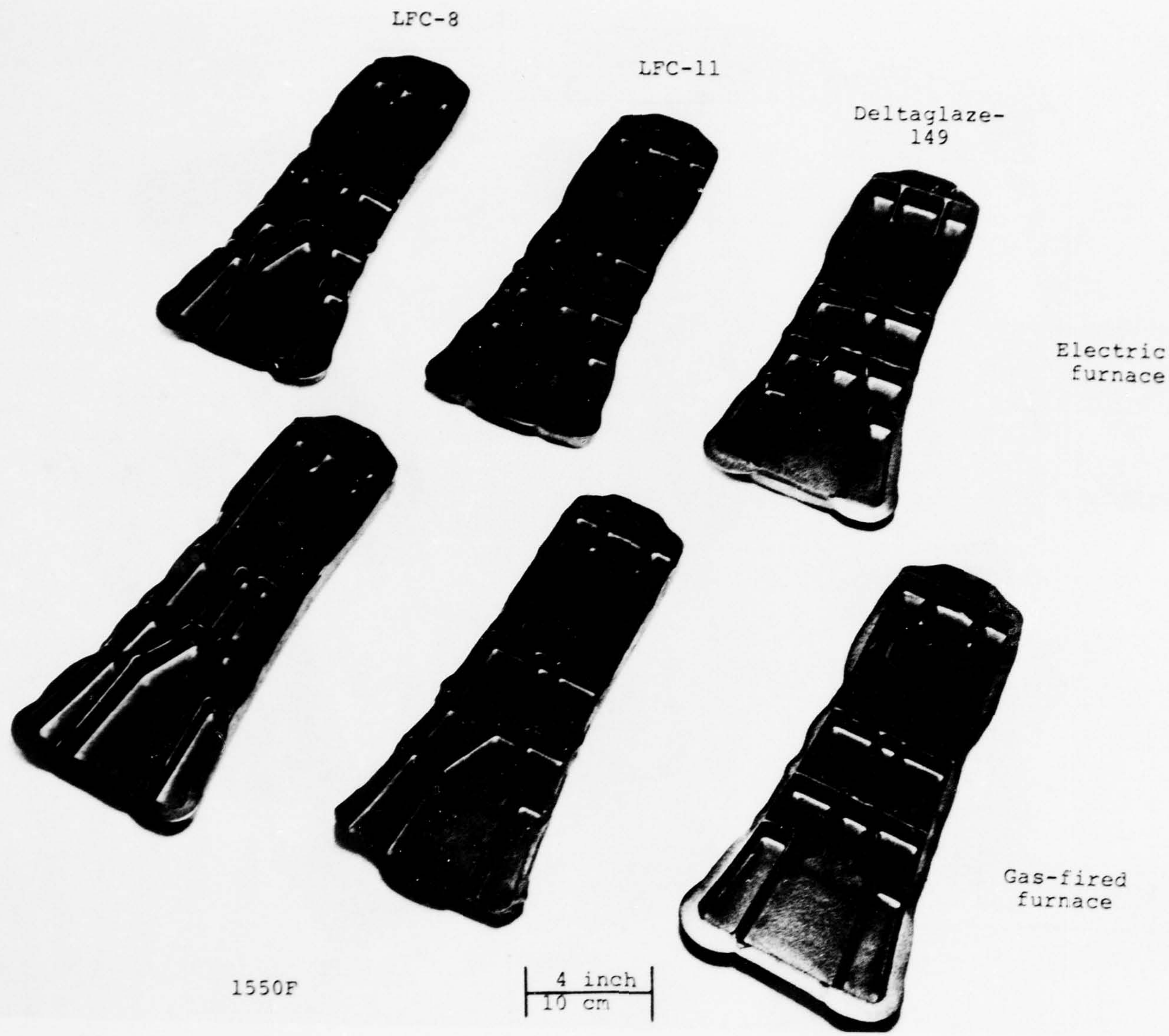


Figure 26a Closeup top view of structural component forgings produced by isothermal forging at 1550F using three different lubricants; blast-cleaned condition

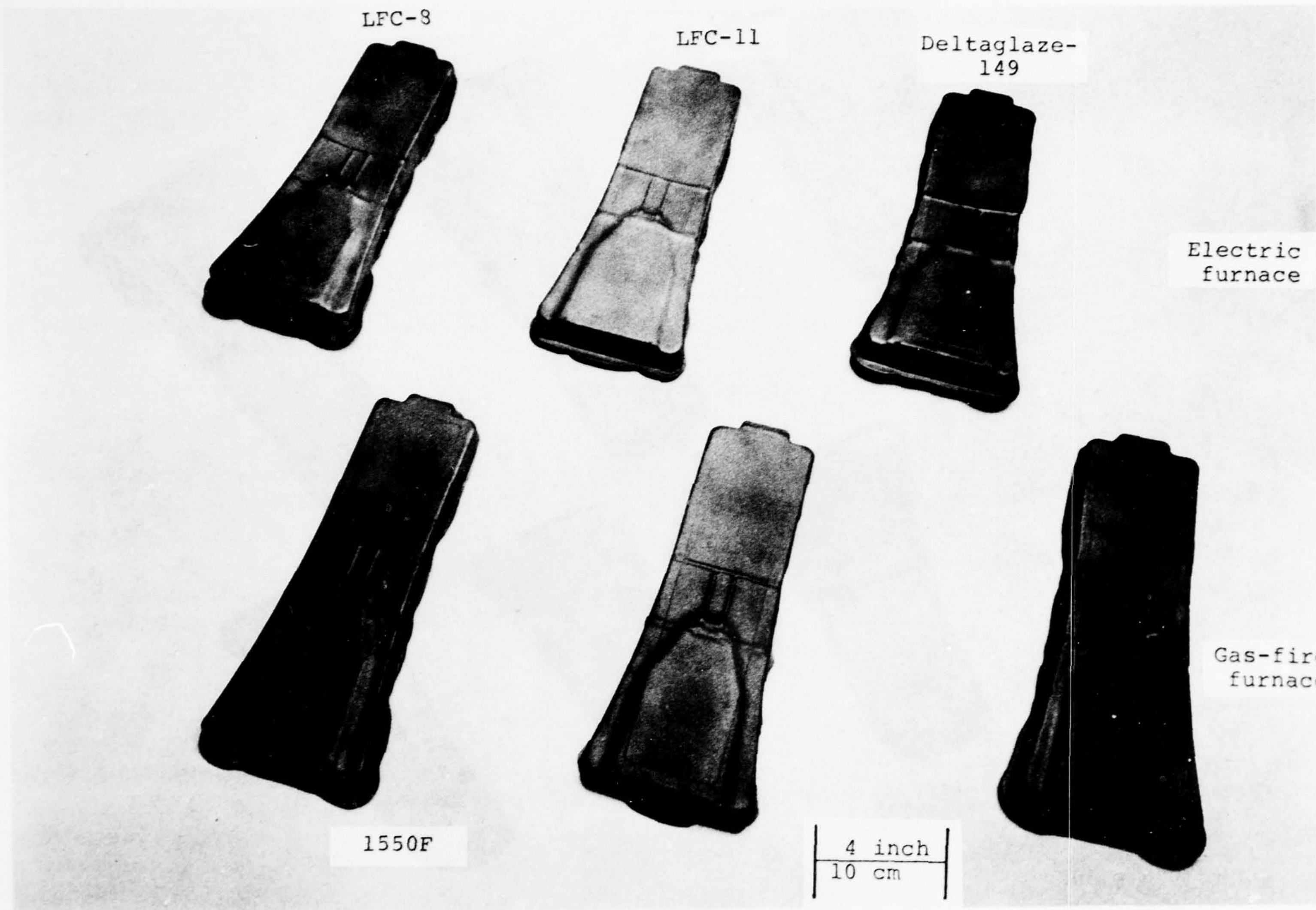


Figure 26b Closeup bottom view of structural component forgings produced by isothermal forging at 1550F using three different lubricants; blast-cleaned condition

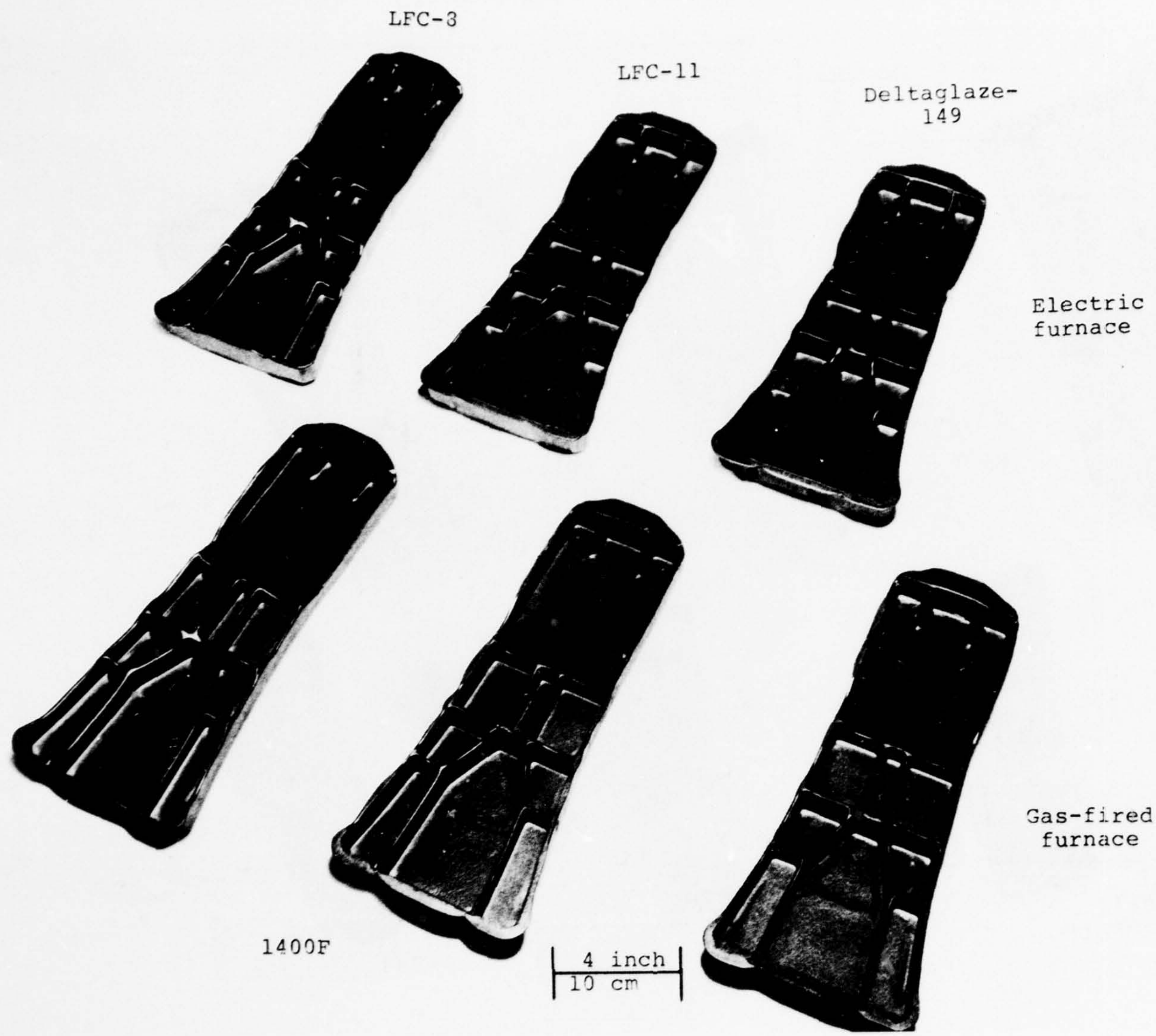


Figure 27a Closeup top view of structural component forgings produced by isothermal forging at 1400F using three different lubricants; blast-cleaned condition

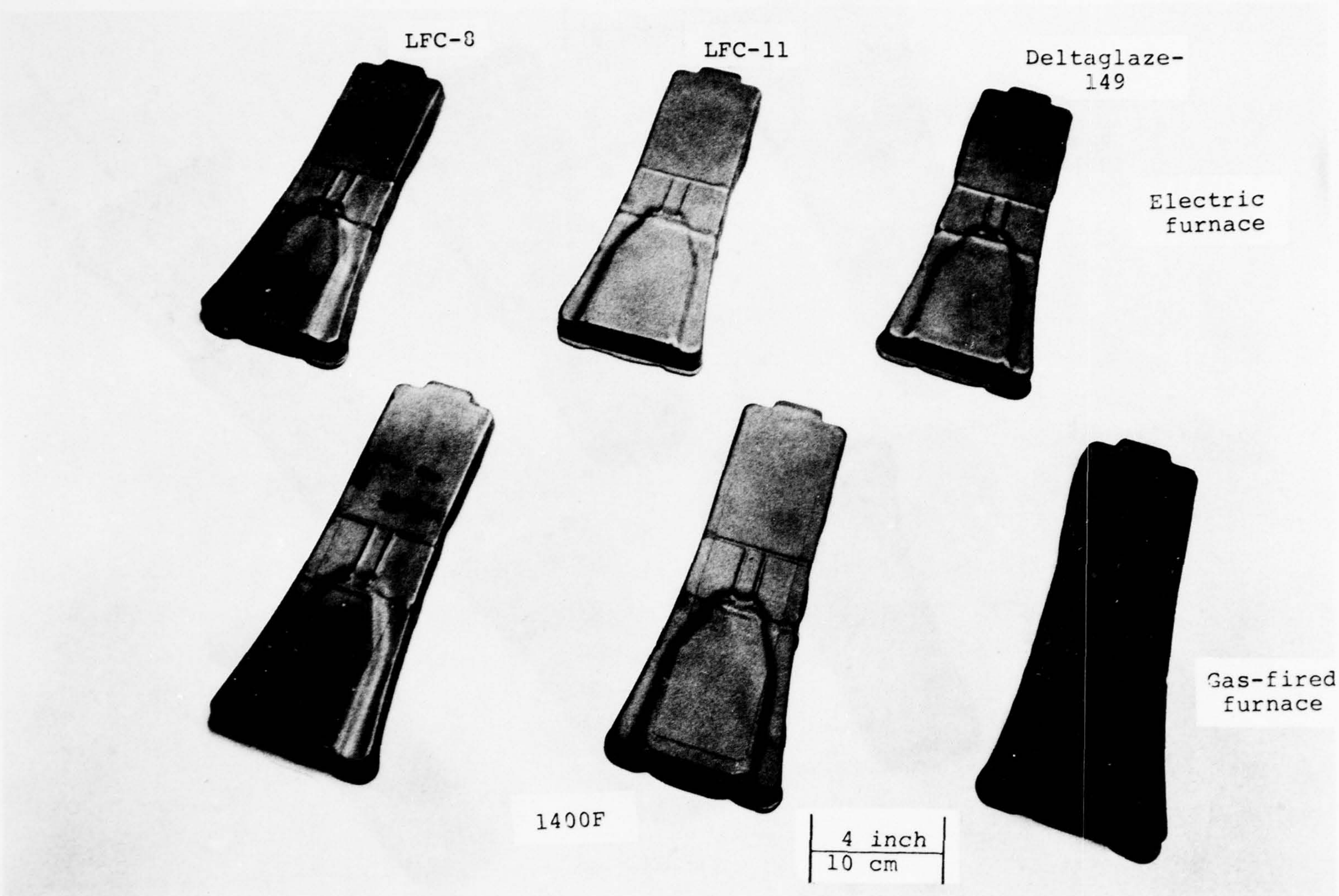


Figure 27b Closeup bottom view of structural component forgings produced by isothermal forging at 1400F using three different lubricants; blast-cleaned condition

B. Phase II - Lubricant Development

The Phase II effort aims at searching for an improved lubricant for isothermal forging application. The basic development concept concentrates on the lubricant formulations capable of providing effective lubrication, while meeting environmental and safety requirements. This program attempted to maximize the lubrication effectiveness for the water-based lubricants by optimizing the dispersed powder compounds and vitreous inorganic binders.

1. Continuous Investigations in the Improved Lubricants

The selected most promising lubricants for isothermal forging of titanium alloys from AFML Contract F33615-74C-5011 and Contract F33615-76C-5059 allow good performance for laboratory-size forging examination, but the choice among the lubricants to manufacturing applications is still dependent on the relative virtues and limitations. It appears highly desirable if a new lubricant formulation, which would provide the combined advantages of lubrication effectiveness and environmental and safety objections, could be developed.

The most favorable and logical formulation, capable of providing the combined requirements of effective lubrication and environmental and safety consequences, will be the water-based one, because of its satisfaction to the EPA and OSHA environmental safety and health requirements. However, the acceptable and successful performance of the water-based lubricants to manufacturing applications will require an improvement in the lubrication effectiveness.

2. Water-Based Lubricant Formulations

Examination of the chemical ingredients in Acheson Deltaglaze-69 indicates that there are at least two modifications which could be made in order to improve the lubrication effectiveness without sacrificing the practical advantages imposed by water-base lubricants: (1) addition of boron nitride (BN) powders to increase the lubrication efficiency, and (2) use of potassium glasses to increase the protective action of the titanium part, to reduce corrosive activity of the coating on both the titanium stock and the nickel-base alloys, and also to enhance the viscosity of the coating.

BN powder is a unique lubricant additive which combines outstanding thermal stability and inertness to both nickel-base and titanium-base alloys. It is nontoxic, highly resistant to thermal shock, and insoluble in water. Its thermal stability and oxidation resistance are much better than graphite in the temperature range of 1300 to 1800F. In addition, it possesses excellent density and lamellar structure which should contribute to effective lubrication and interface separation. It has been demonstrated that the addition of BN into xylene-base lubricant significantly helps on lubricity, reduces in lubricant accumulation in the cavity, and improves release action from the die ([1]).

Another factor of major importance in determining a successful lubricant-coating for hot-die forging systems is the protective action and the corrosive activity of the coating. This implies that the vitreous components in the lubricant should contain the ingredient which could provide excellent surface protection and less corrosive activity on both titanium parts and nickel-base die alloy during long-term, high temperature in air. Recent work ([15]) has shown that, among various binary alkali silicate and alkali borate glasses used for coating titanium during heating in air, the potassium glasses showed the highest viscosity of the melt, thus providing the best protective properties and the least corrosive activity for titanium. As the alkali metal oxide content in the coating decreases, the viscosity of the coating increases, and the protective action increases and the corrosive activity decreases. It is very likely that the above basic principles can be used in improving the effectiveness of water-based lubricants for isothermal forging of titanium alloys.

3. Lubricant Variables Proposed

As mentioned previously, one of the soundest approaches to maximizing the lubrication effectiveness for the water-based lubricants involves optimizing the compounds of dispersed powder and vitreous inorganic binder. The BN will be used as dispersed phase additives; the addition of proper composition of BN is expected to promote effective lubrication and interface separation.

In addition to the BN addition, the vitreous components consisted of potassium glasses; this glass should provide high viscosity, excellent protective action, and low corrosive activity of the lubricant coating. The optimum quantities for each component in the vitreous components required experimental determinations.

The basic constituents and the weight percentages of the components for the experimental lubricant formulations are given below:

(a) Boron Nitride (BN): BN is commercially available in various particle sizes. The proposed powder will be HCP grade which is finest powder and also the least expensive. Previous experience indicated that the BN requires careful storage and protection from atmospheric contamination before application. The weight percentages of the BN used were 10, 15, and 30%.

(b) Potassium glasses: The K_2O proportions in K_2O-B_2O_3-SiO_2 vitreous components were 10, 20, and 30% because this range of K_2O was shown to possess a desirable viscosity of the vitreous coating ([15]). The addition of B_2O_3 in the vitreous components will lower the melting point and increase the viscosity of the silicate coating. It also provides oxidation protection for BN powders.

(c) A small amount (1%) of acrylic emulsion (acrysol liquid) was added as a resin binder in order to facilitate the film strength. The acrysol liquid is emulsifiable with water. It was compared to a zero level.

(d) A 1% cobalt oxide was added to increase the thermal stability and to reduce the radiation losses of the heat during transferring the preform from the furnace to the die. It was compared to a zero level.

Thirty-six (36) lots of new water-based lubricant formulations were prepared by varying the amount of dispersed BN powders (10, 15, and 30%) and K_2O in vitreous components (10, 20, 30% K_2O in K_2O-$B_2O_3SiO_2$), and with the addition of acrysol liquid and/or cobalt. The borosilicate composition was 65% B_2O_3 and 35% SiO_2.

4. Lubricant Performance Testing

The proposed lubricant formulations were tested experimentally to determine their lubrication efficiency as a potential candidate for isothermal forging applications. The information regarding the friction, adhesion, protective action, corrosive activity in both gas-fired and electric furnaces provided by these coatings were analyzed.

The application procedure for preparing the test samples in this program is the same as that previously reported for water-based lubricants ([1]). The samples were cleaned by chem-mill followed by sandblast, preheat at 150F, coat the lubricant with air spray gun for about six (6) mils, allow film to dry completely. In order to develop lubricants acceptable for manufacturing applications, both gas-fired and electric furnaces were used for these tests.

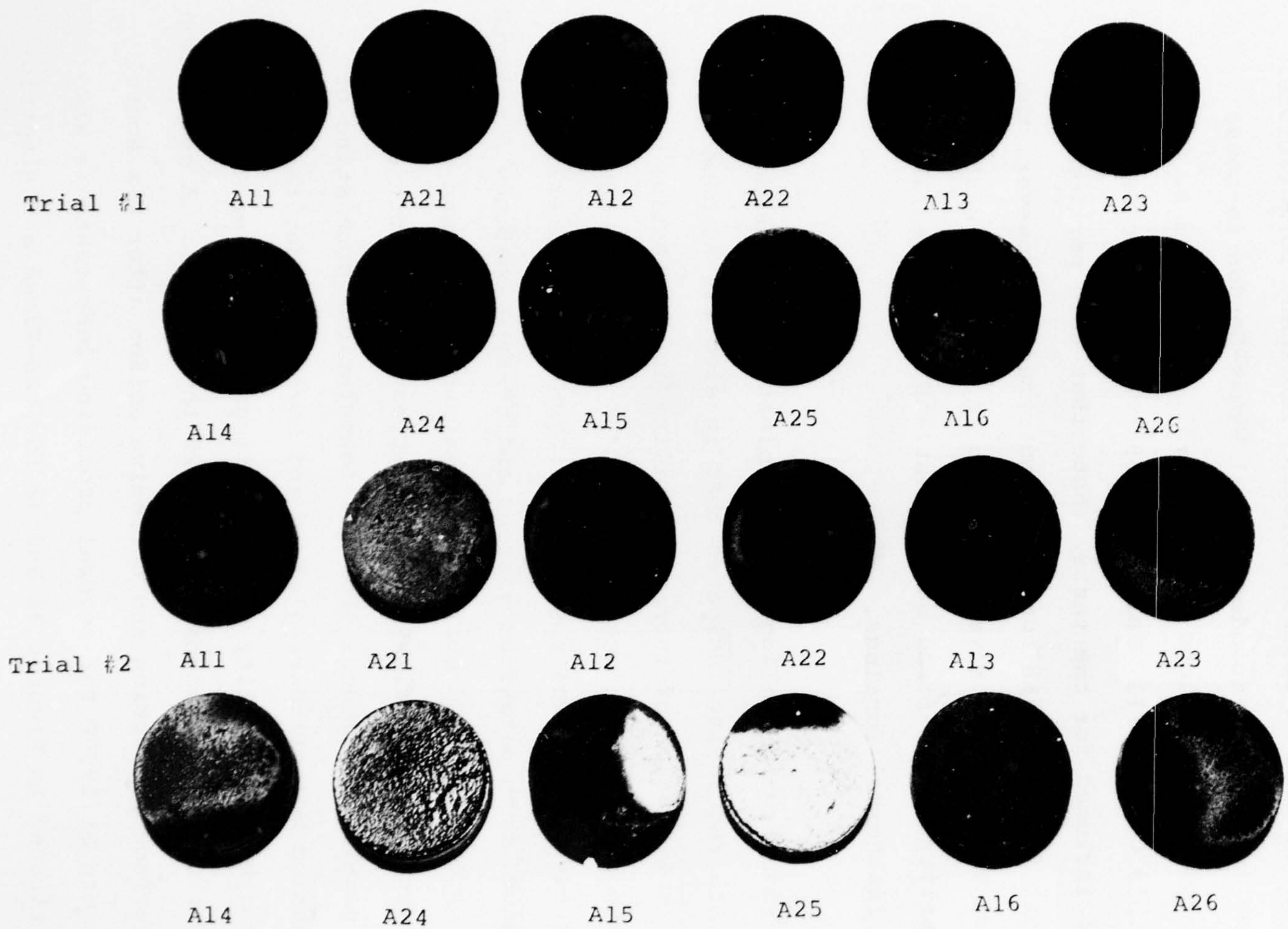
(a) Thermal Stability Tests

Several sections of the 4-9/16 inch round bar of Ti-6Al-4V alloy were cogged and drawn to about 3 inch diameter by 200 inch long at 1750F. They were chem-milled to remove 20 mils per side of the surface, and cut into 3 inch diameter by 3/4 inch multiples.

One hundred (100) samples were prepared and machined to 2-3/4 inch diameter x 1/2 inch thick for thermal stability tests. The 100 coating and heating tests for about 50 lots of lubricants were carried out in both gas-fired and electric furnaces. The tests were made at 1750F for six (6) hours. Both thickness and weight changes of the lubricant films were measured and visual changes of the film appearance were characterized. Some of the samples were also cut for metallographic examinations.

Based on the results of Phase I (Task I) lubricant evaluations it was decided that, in order to develop a more successful lubricant for the Phase II effort, an additional effort should be made on several existing lubricant formulations. These lubricants included several Wyman-Gordon in-house developed formulations (CP-22, CP-31, et al) and A. O. Smith's CG-54 ([16]). Deltaglaze-69, OPT-112, and GFBN-8 were also included for the tests. Note that this portion of the effort is beyond the contract requirements. However, the above coatings may have advantages in achieving better stability in gas-fired environment and effective lubricity for isothermal forgings.

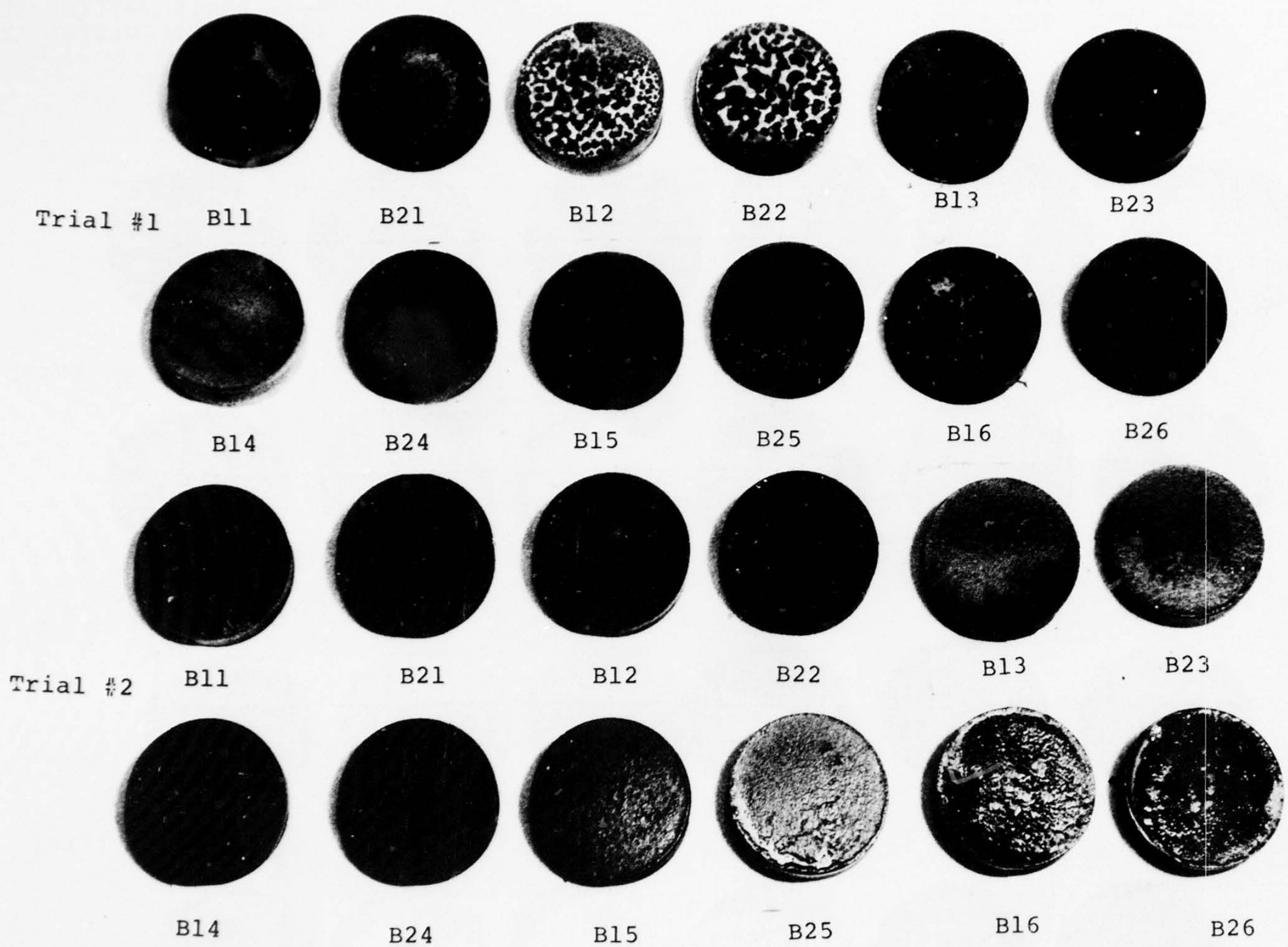
The results of metallographic examinations on the sample surface regularity indicated that in electric furnace the best combination of thermal stability and protective action of the coatings was achieved by CG-54 and D-69. Severe corrosive attack was observed for GFBN-8. In gas-fired furnace, both potassium glasses and CP-type coatings displayed good protection and corrosion resistance. D-69 and CG-54 had excellent stability and film appearance in both electric and gas-fired furnace. For the formulations consisting of potassium borosilicate glasses and boron nitride, the film strength and stability of the coatings increase as the amount of K_2O increases (Figures 28 through 30). A comparison of surface protection and corrosive action after six hours' exposure at 1750F for several promising lubricants is also illustrated in Figures 31 and 32 for gas-fired and electric furnaces, respectively.



A1: silica glass frit
A2: silica glass frit with 1% CoO

A11, A21, A12, A22: 10% BN
A13, A23, A14, A24: 15% BN
A15, A25, A16, A26: 30% BN

Figure 28a Film appearance of thermal stability tested samples with lubricant coatings containing a vitreous component of 10% K_2O - 90% (65% B_2O_3 + 35% SiO_2); after six (6) hours at 1750F in gas-fired furnace



B1: silica glass frit
B2: silica glass frit with 1% CoO

B11, B21, B12, B22: 10% BN
B13, B23, B14, B24: 15% BN
B15, B25, B16, B26: 30% BN

Figure 28b Film appearance of thermal stability tested samples with lubricant coatings containing a vitreous component of 20% K_2O - 80% (65% B_2O_3 + 35% SiO_2); after 6 hours at 1750F in gas-fired furnace

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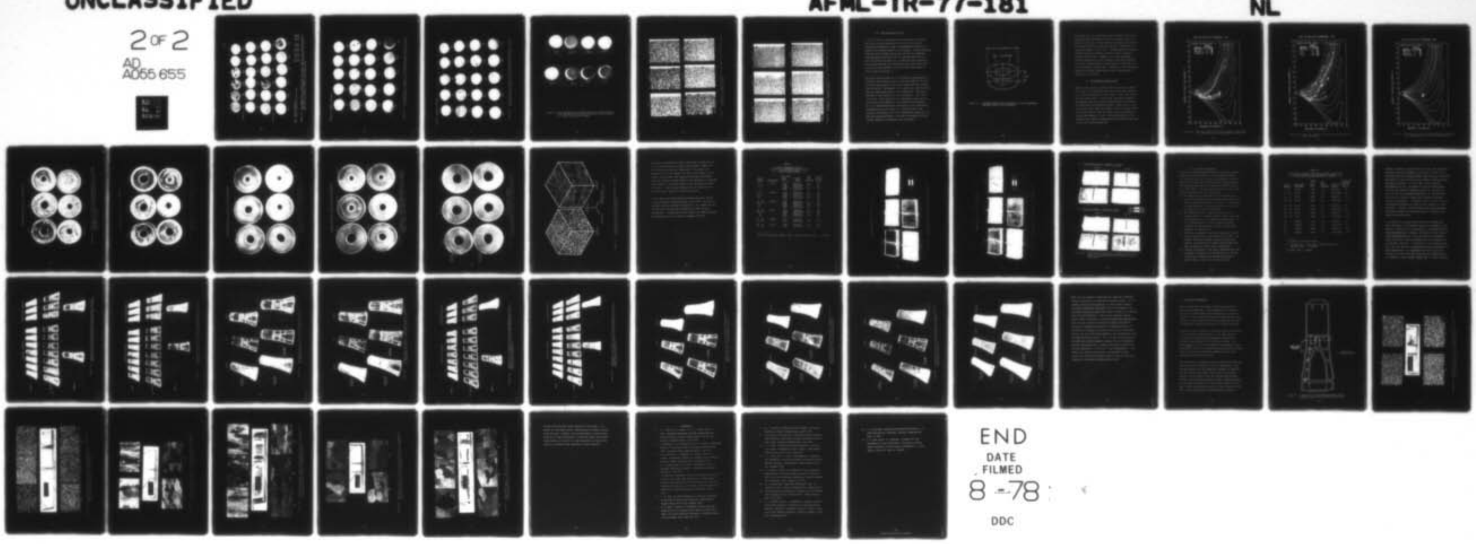

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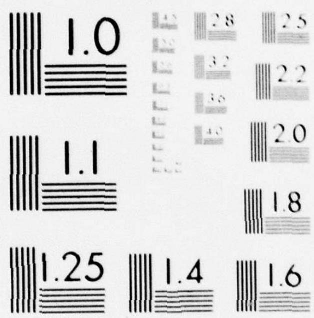
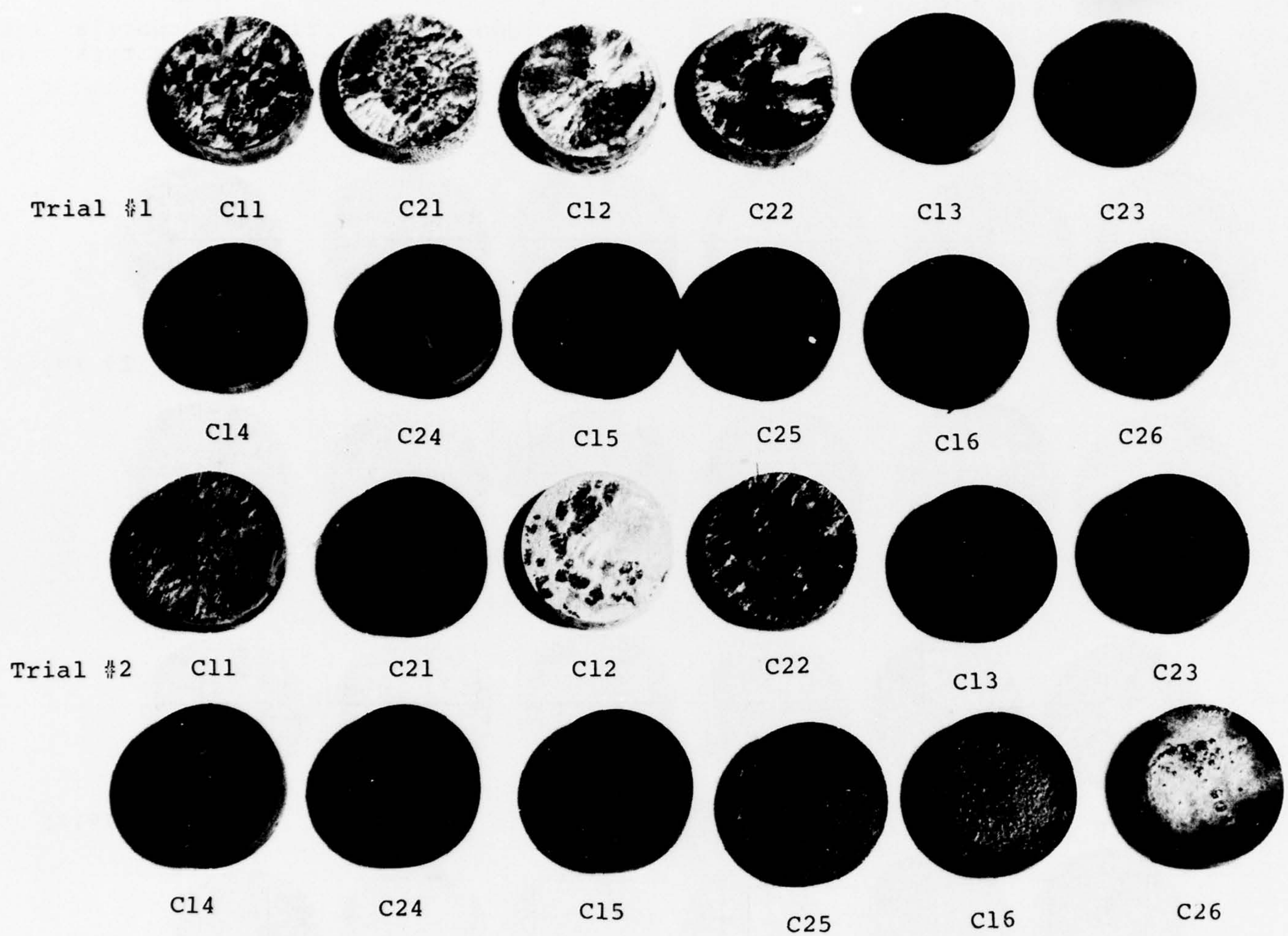


MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A



C1: silica glass frit
C2: silica glass frit with 1% CoO

C11, C21, C12, C22: 10% BN
C13, C23, C14, C24: 15% BN
C15, C25, C16, C26: 30% BN

Figure 28c Film appearance of thermal stability tested samples with lubricant coatings containing a vitreous component of 30% K_2O - 70% (65% B_2O_3 + 35% SiO_2); after six (6) hours at 1750F in gas-fired furnace

Trial 1: Electric furnace

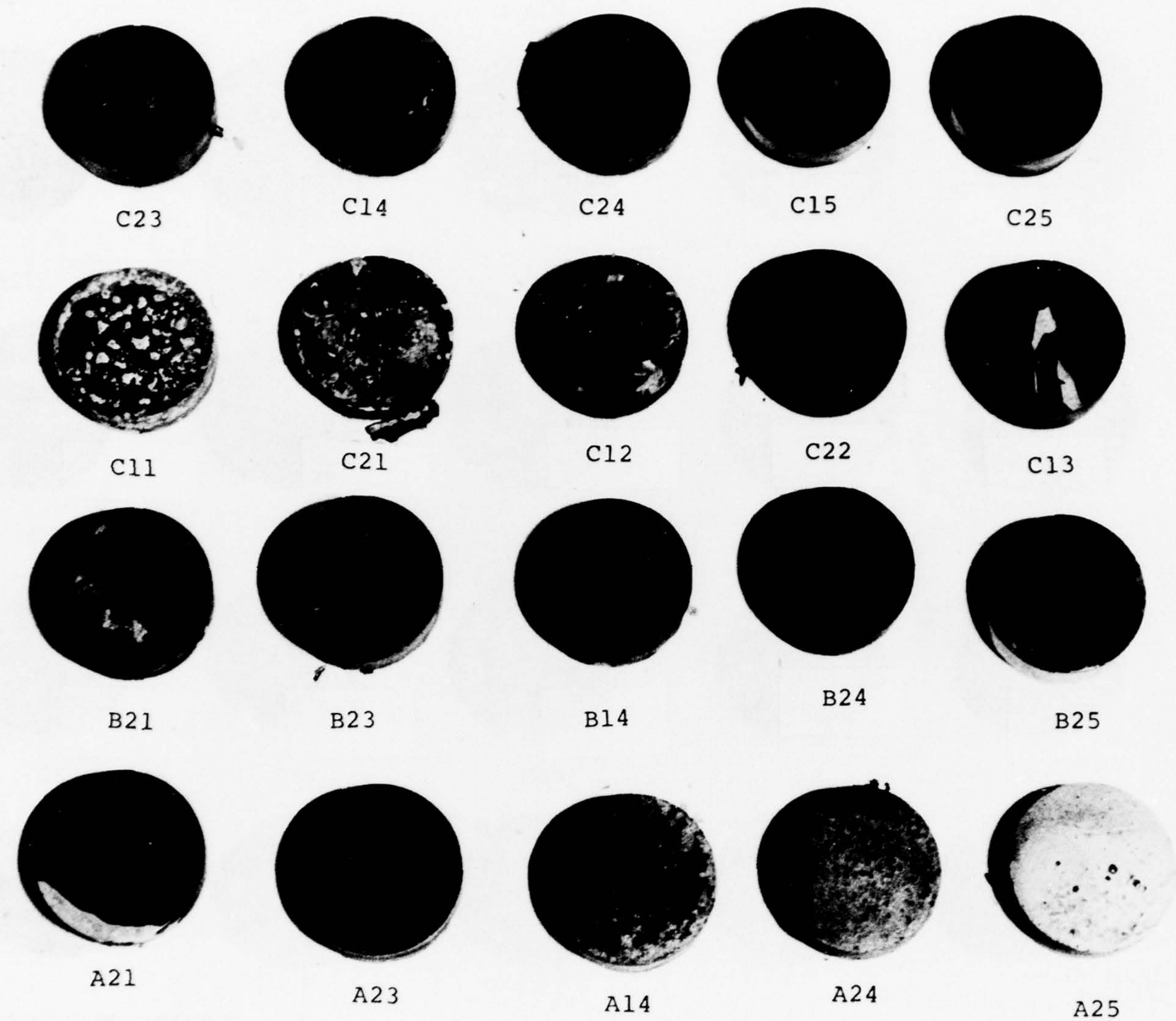


Figure 29a Film appearance of thermal stability tested samples with various lubricant coatings after six (6) hours at 1750F in electric furnace

Trial 2: Electric furnace

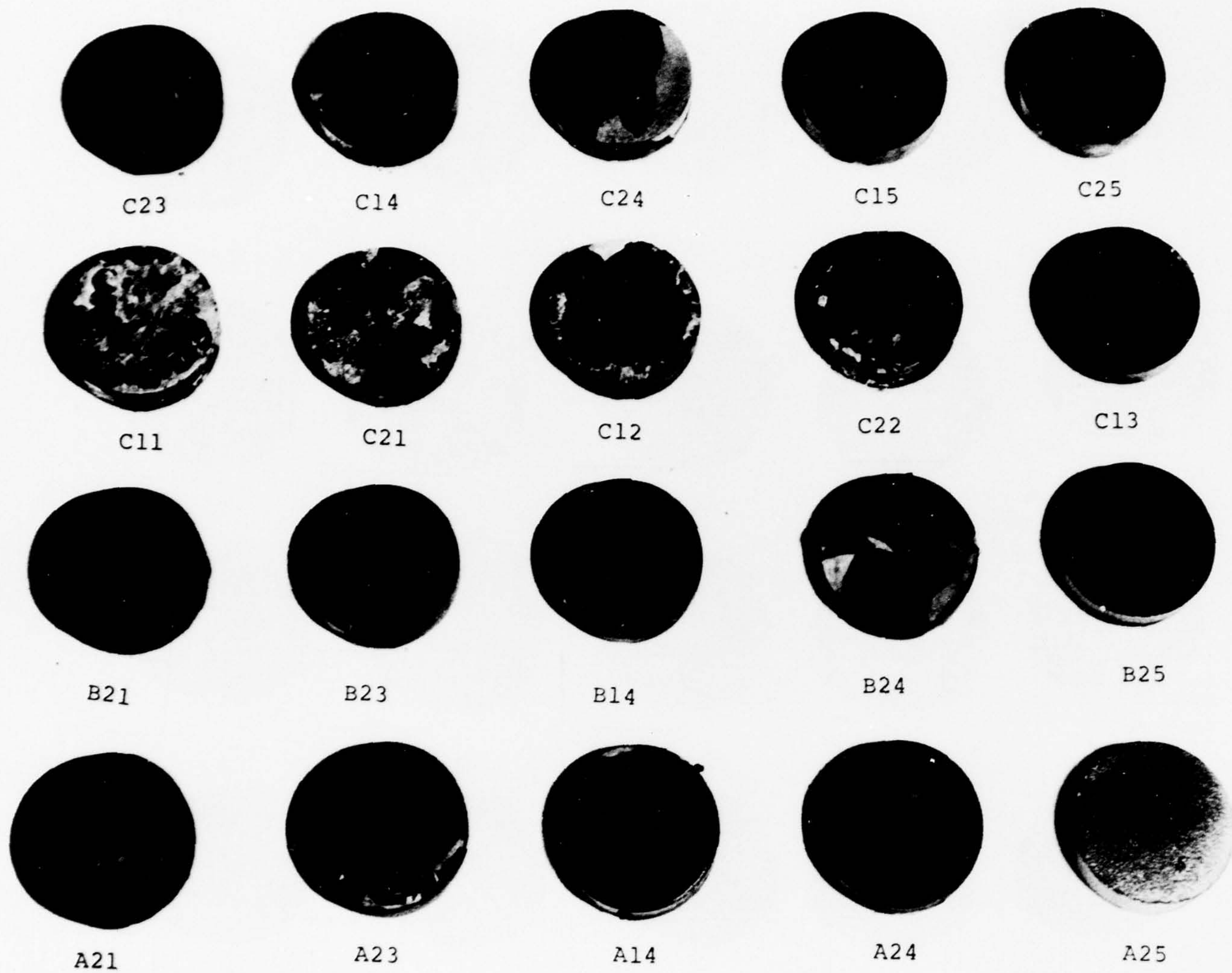


Figure 29b Film appearance of thermal stability tested samples with various lubricant coatings after six (6) hours at 1750F in electric furnace

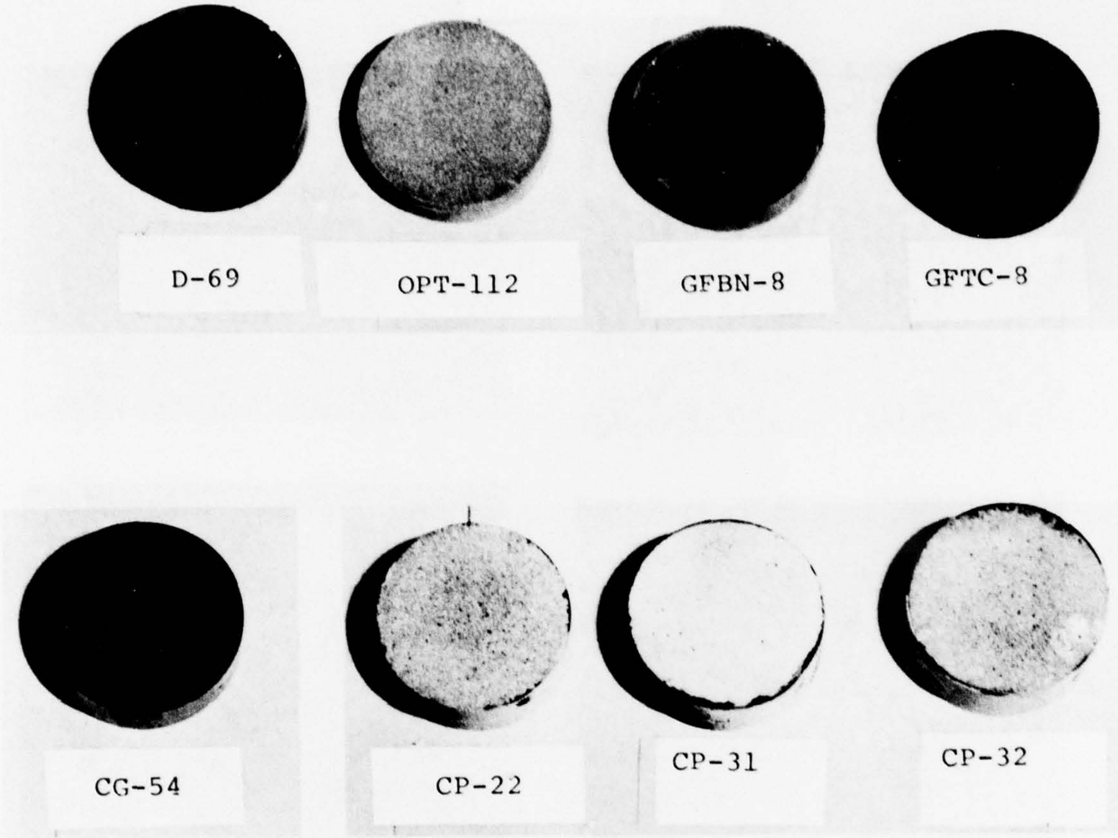


Figure 30 Film appearance of thermal stability tested samples with various lubricant coatings after six (6) hours at 1750F in gas-fired furnace

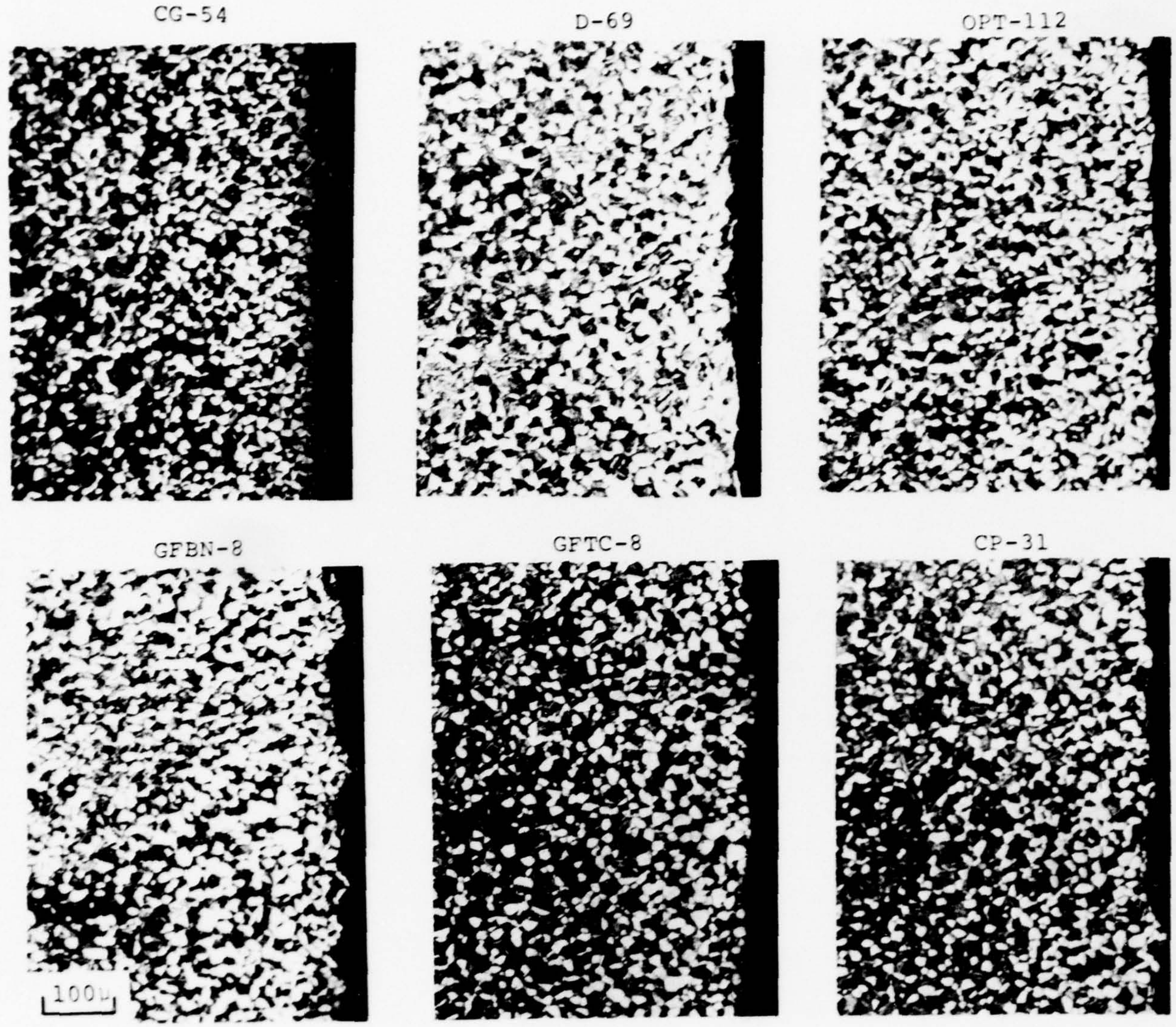


Figure 31 Comparison of surface protection and corrosive action after six hours at 1750F in gas-fired furnace

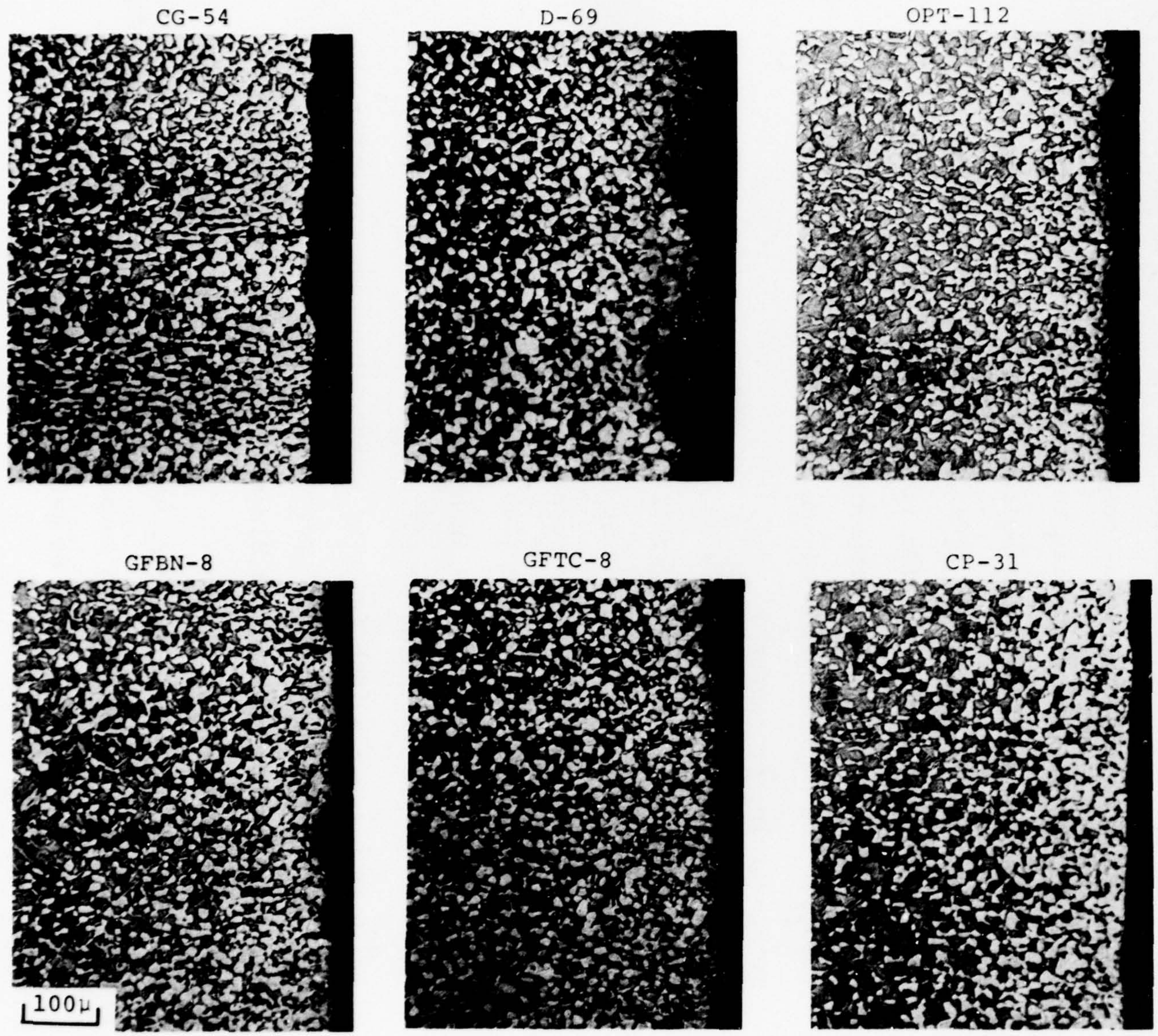


Figure 32 Comparison of surface protection and corrosive action after six hours at 1750F in electric furnace

(b) Ring Compression Tests

A total of 100 ring compression tests were made to evaluate the anti-friction characteristics for the 20 different lubricant combinations; these compositions were selected based on the thermal stability test results. Several promising coatings such as GFBN-8, Deltaglaze OPT-112 for alpha-beta titanium alloys, and LFC-8, LFC-11 and Deltaglaze-149 for beta titanium alloys were also included for this evaluation. It is noted that the ring compression tests have often been used for the determination of the friction coefficient in metal-working processes ([1], [17]).

The test conditions were at 1750F forge/die temperatures for Ti-6Al-4V alloy coatings, and at 1550F and 1400F for Ti-10V-2Fe-3Al alloy coatings. The percent reductions were ranged from 20 to 80%. One hundred (100) samples of 1 inch thickness were cut and prepared from 3 inch round stock. They were machined to the dimension of OD:ID:thickness = 2.620 inch : 1.310 inch : 0.875 inch for ring compression test preforms; this gives a thick washer of proportions OD:ID:thickness = 6:3:2. A sketch showing the dimensions of ring compression specimens is given in Figure 33. After the tests, the internal ring diameter and ring thickness were measured, and both the percent decrease in internal ring diameter and the percent reduction in thickness were calculated.

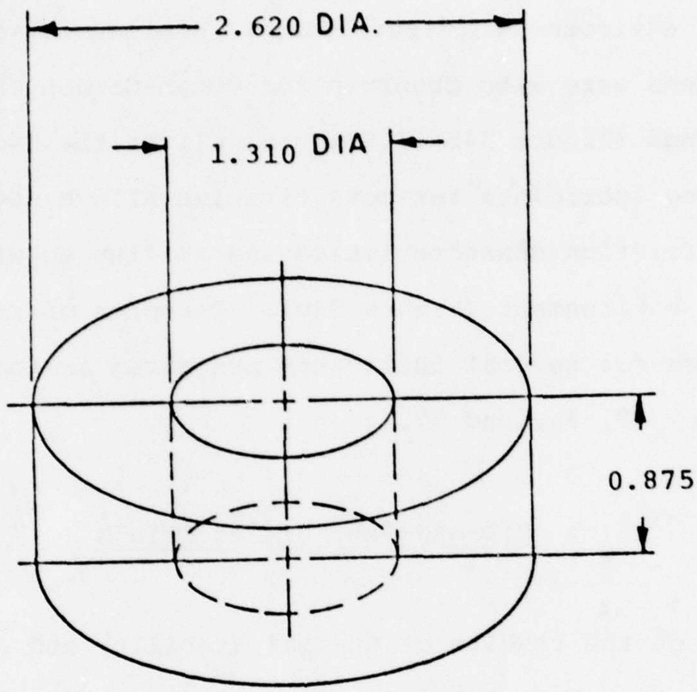


Figure 33 A sketch showing the dimensions of ring compression specimens used on this program

The results of ring compression tests (Figures 34 through 37) showed that the Deltaglaze-69 coating provided a very high degree of lubricity, in both electric and gas-fired furnaces, but GFBN-8 and OPT-112 have poor ability to withstand gas-fired environment (Figure 34a) . Similar gas-fired stability problems were also observed for Wyman-Gordon CP-types of coatings (Figure 34b). However, all of the isothermal forging lubricants for beta titanium alloys gave excellent anti-friction characteristics and ability to withstand gas-fired environment (Figure 34c). Examples of ring compression samples for several lubricants are given and compared in Figures 35, 36, and 37.

(c) Rib-and-Web Forging Trials

Based on the results of thermal stability and ring compression tests, four lubricant formulations were then selected for further rib-and-web forging tryouts. Here, the rib-fill forging tests served to provide the information regarding the adhesion and anti-friction characteristics provided by the lubricants from laboratory scale. Again, the 0.5 inch thick plate stock (TMCA heat number N-7628) was used in this rib-and-web forging test; the plate stock was produced by cogging and drawing at 1750F. The microstructure of the starting plate stock is characterized by finish forging high in the $(\alpha+\beta)$ field (Figure 38).

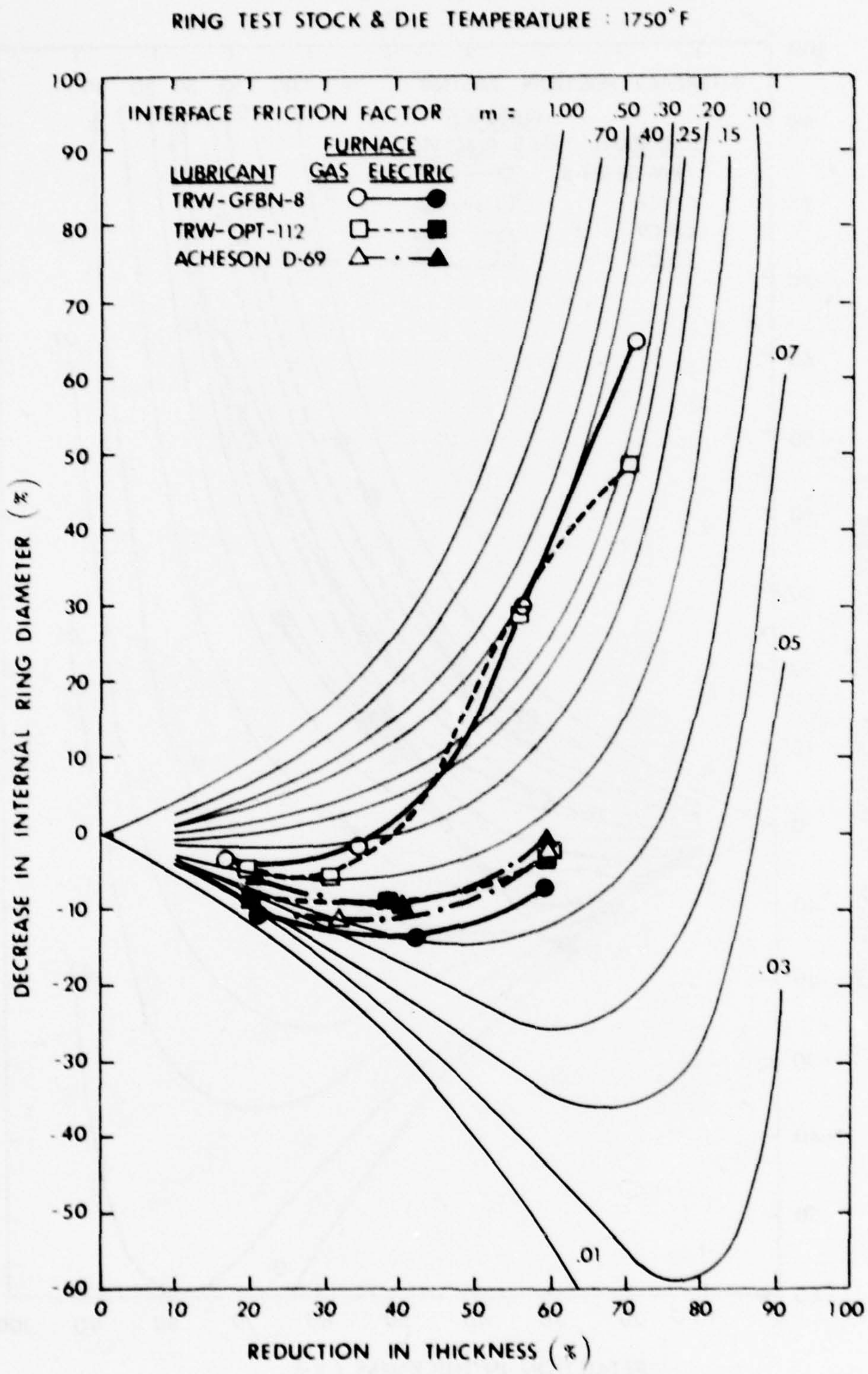


Figure 34a Ring test results for several candidate lubricants for isothermal forging of alpha-beta titanium alloy

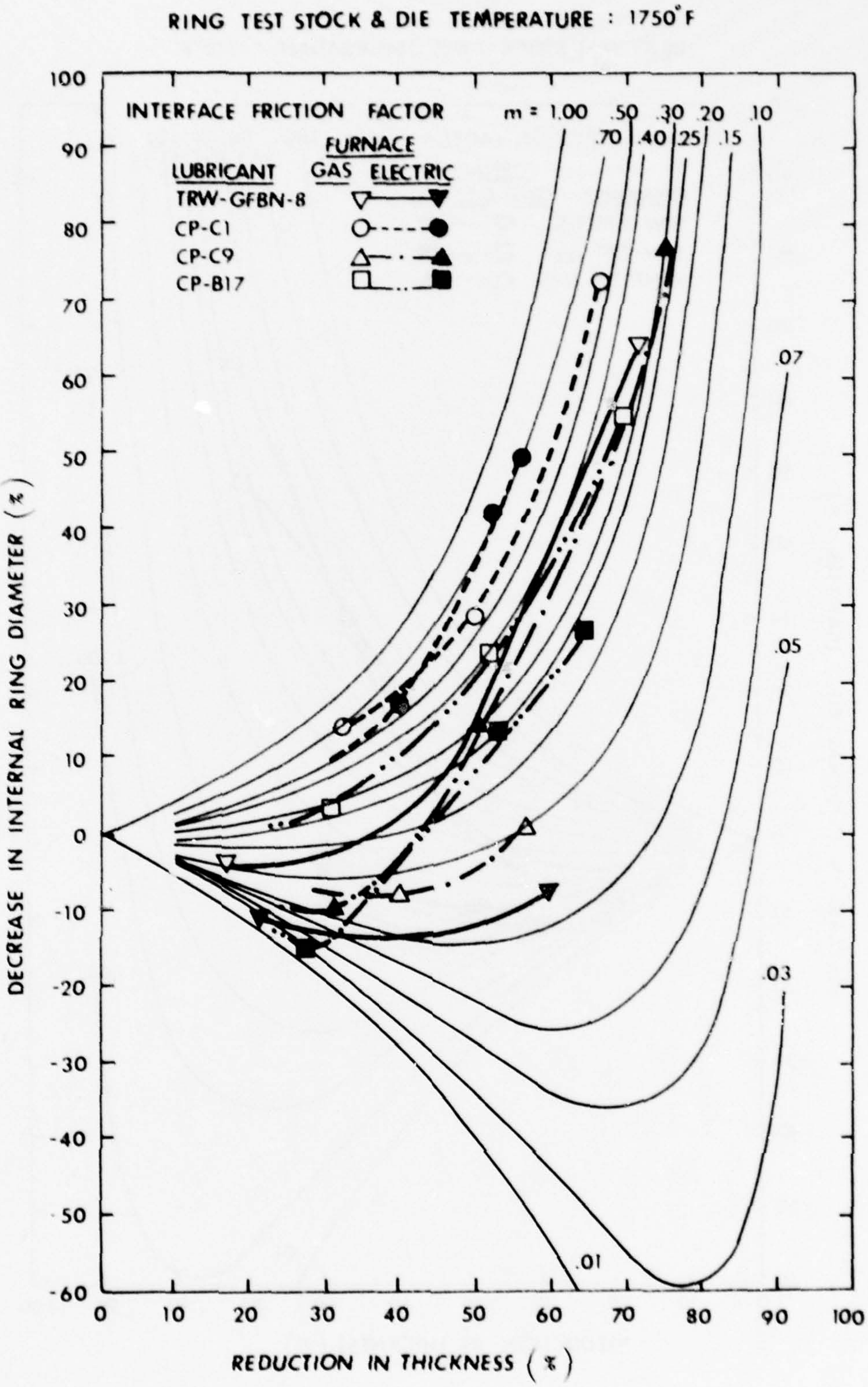


Figure 34b Ring test results for several lubricants used in Phase II effort

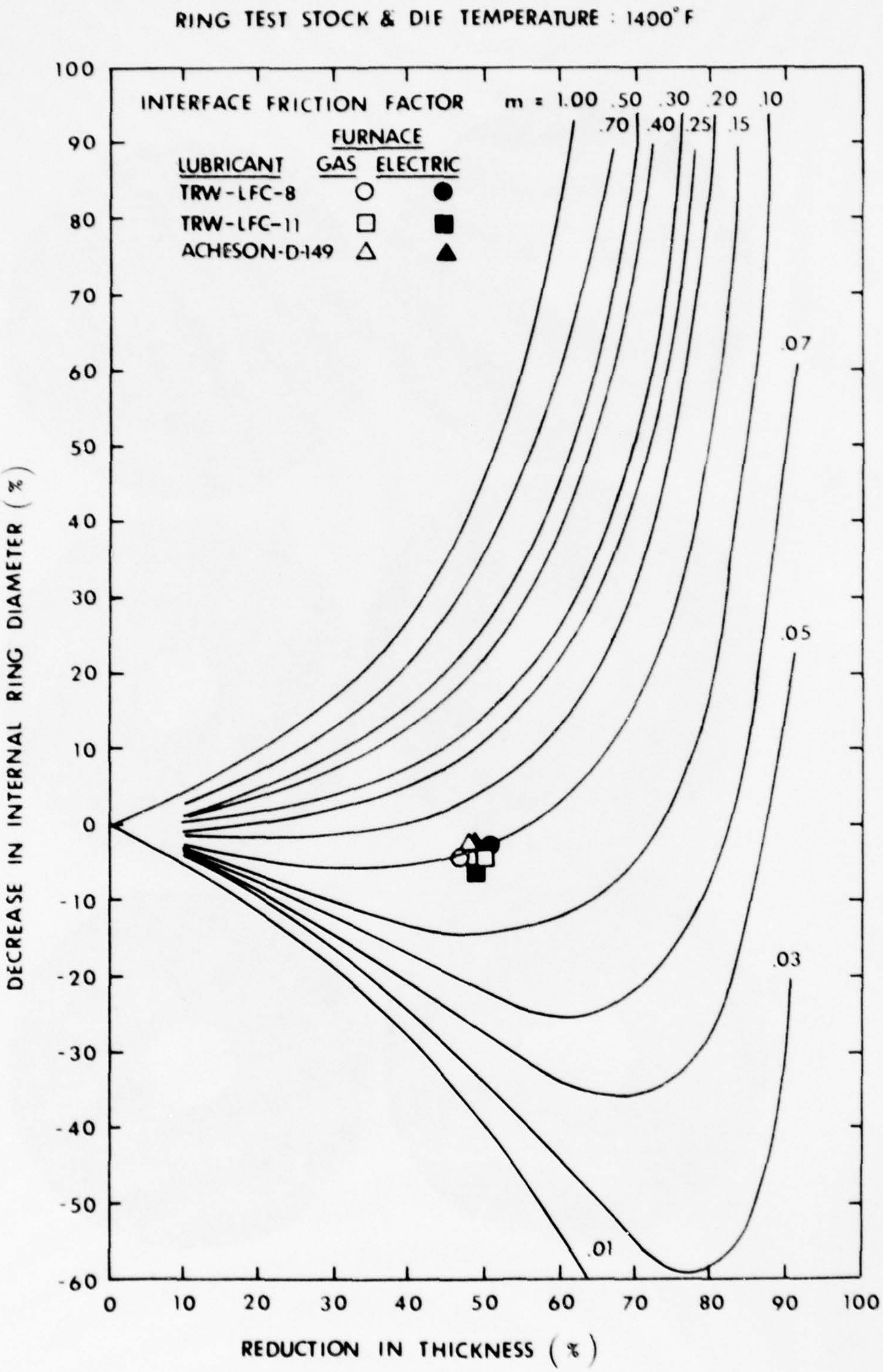


Figure 34c Ring test results for several candidate lubricants for isothermal forging of beta titanium alloy

Gas-fired Furnace (1750F): 60% reduction

Figure 35a Top view of ring compression samples produced by isothermal compression for several alpha-beta titanium alloy lubricants after three (3) hours at 1750F in gas-fired furnace; ram rate = 3 in/min.

Electric Furnace (1750F): 60% reduction

Figure 35b Top view of ring compression samples produced by isothermal compression for several alpha-beta titanium alloy lubricants after three (3) hours at 1750F in electric furnace; ram rate = 3 in/min.

Gas-fired Furnace: 1750F/3 in/min/~60% reduction

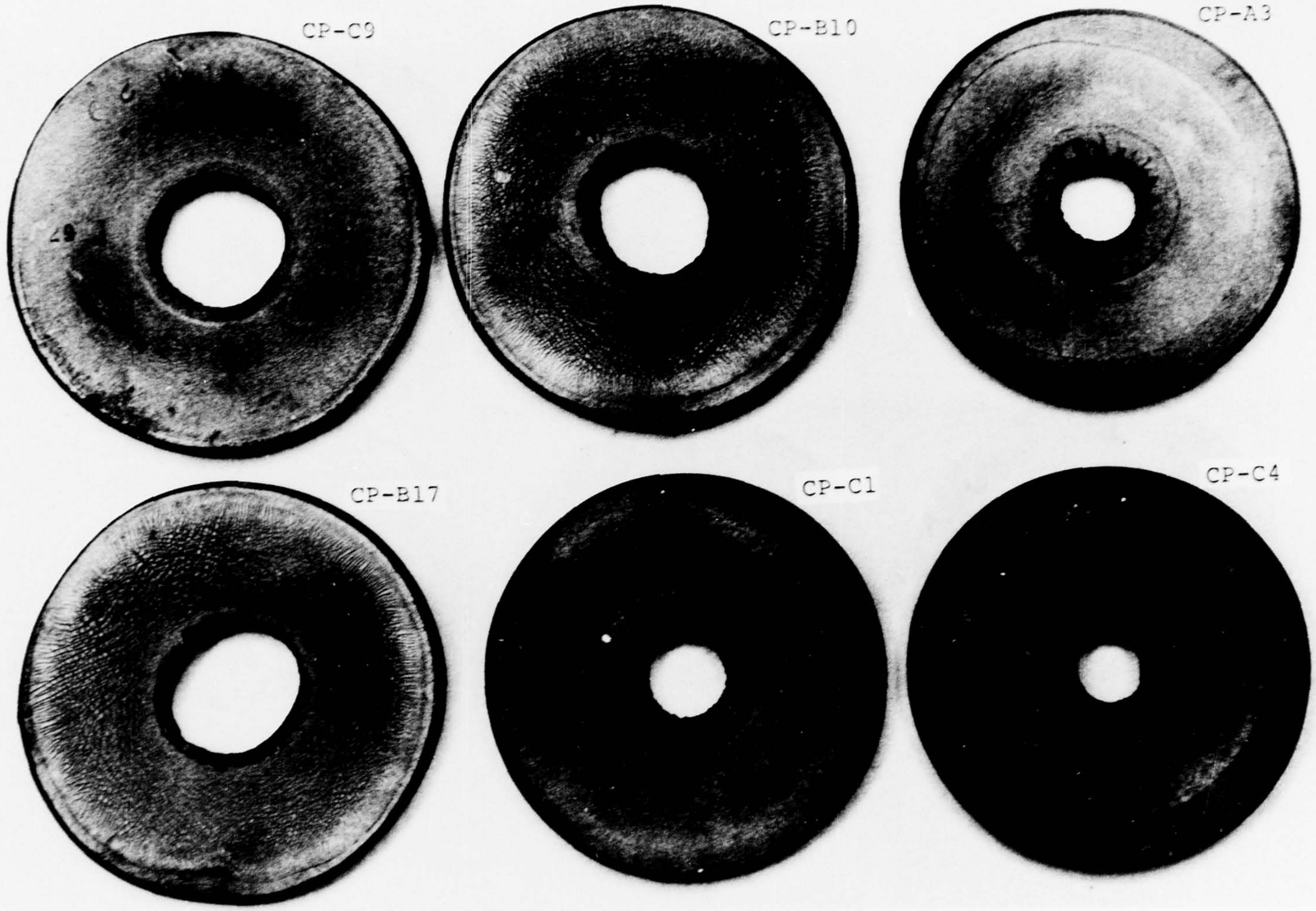


Figure 36a Top view of ring compression samples (Ti-6Al-4V) produced by isothermal compression for several alpha-beta titanium alloy lubricants used in Phase II after three (3) hours at 1750F in gas-fired furnace. Blast-cleaned condition.

Electric Furnace: 1750F/3 in/min/∿60 reduction

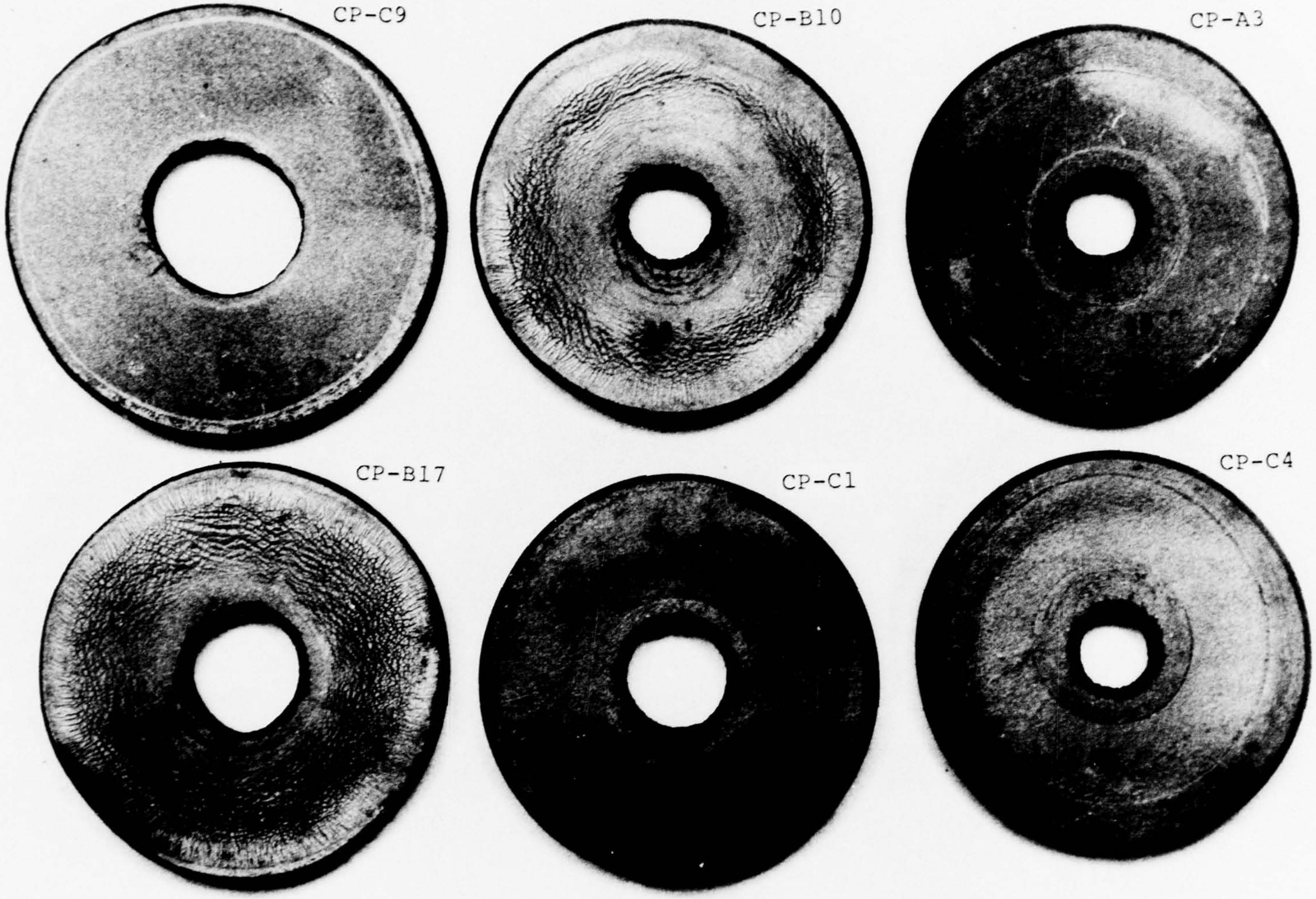
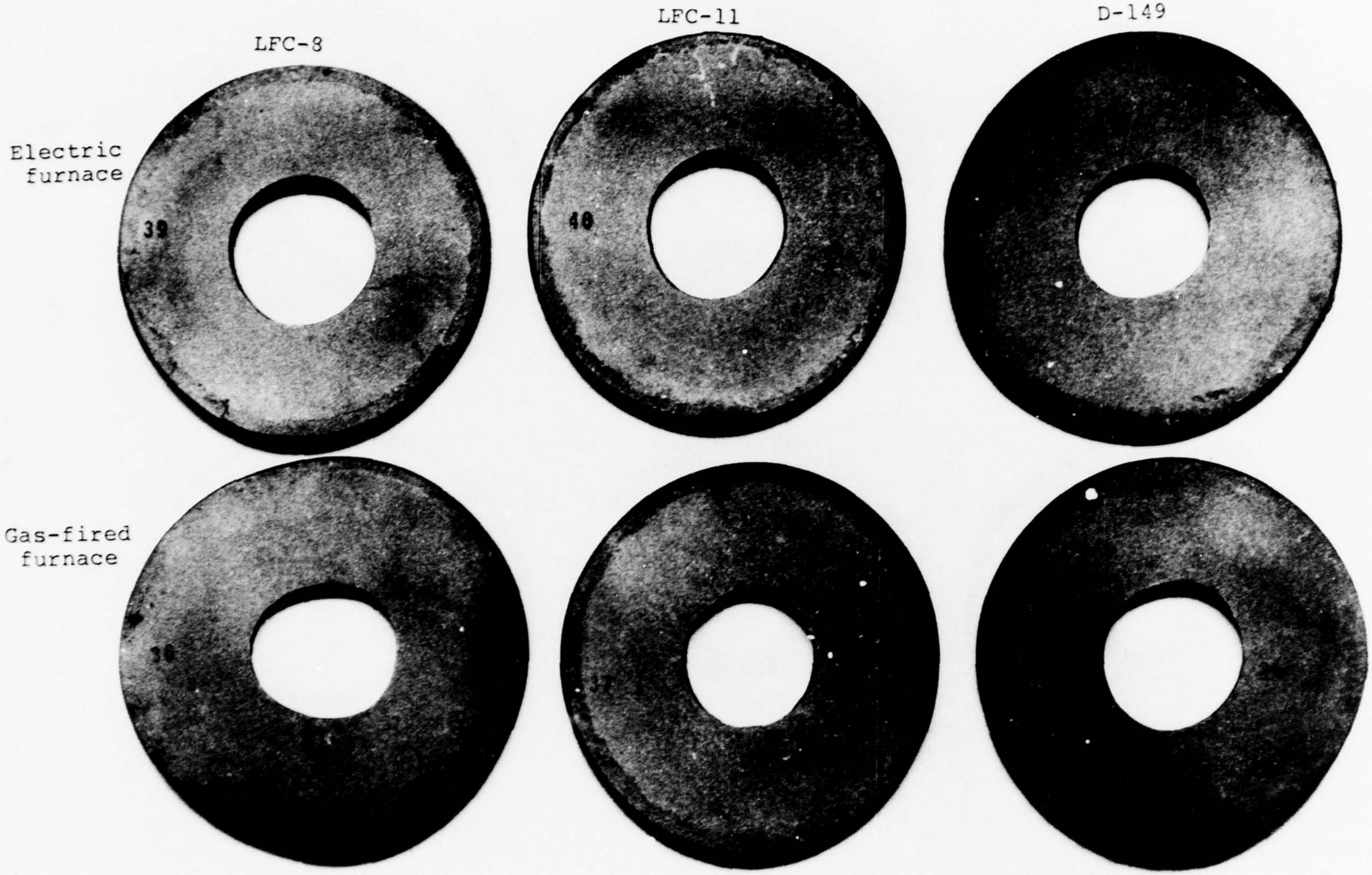


Figure 36b Top view of ring compression samples produced by isothermal compression for several alpha-beta titanium alloy lubricants used in Phase II after three (3) hours at 1750F in electric furnace. Blast-cleaned condition.



1400F/3 in/min/50% reduction

Figure 37 Top view of ring compression samples (Ti-6Al-4V) produced by isothermal compression at 1400F for several beta-titanium alloy lubricants after three (3) hours. Blast-cleaned condition.

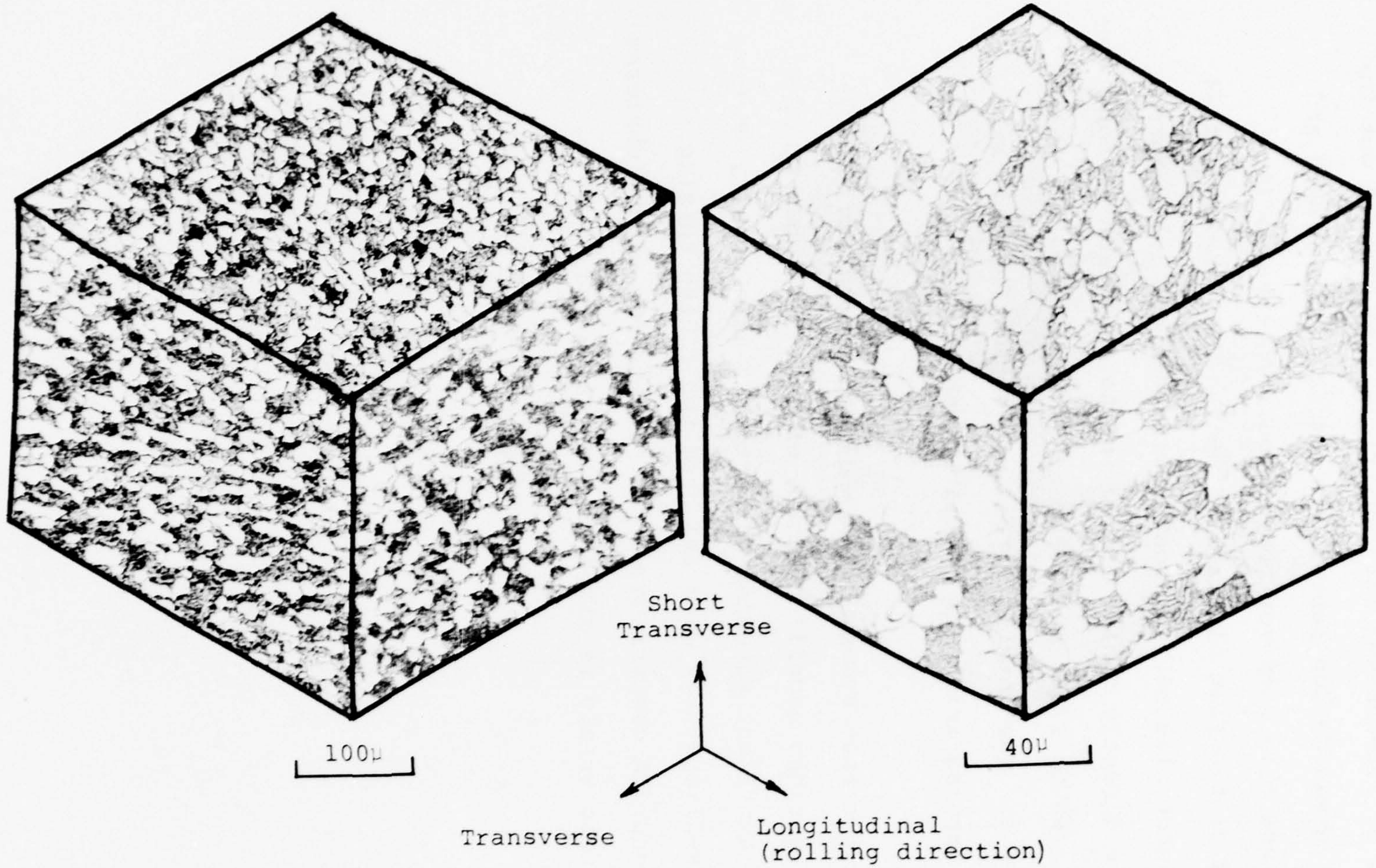


Figure 38 Microstructure of Ti-6Al-4V plate stock used in Phase II rib-and-web lubrication evaluations

A series of rib-and-web forging trials were carried out for four (4) Wyman-Gordon lubricant formulations. GFBN-8 and LFC-11 were also used for comparison. Thirty-two (32) machined Ti-6-4 flat blanks (0.5 inch x 2.65 inches x 4.64 inches) were blasted, and coated with various lubricants. They were directly finish forged in one operation at forge/die temperatures of 1750F and 1600F to the configuration shown in Figure 3. The forging variables for the Phase II rib-and-web forging trials is listed in Table 9.

It was shown that Wyman-Gordon modified waterglass (CP-C9) coating provided excellent degree of part fill, but WG CP-C1 provided excellent adhesion properties. As a result, WG CP-C9 and CP-C1 coatings were selected for finish forging evaluations. A comparison of the results for these lubricant optimization trials is given in Figures 39 and 40.

TABLE 9

FORGING VARIABLES FOR THE PHASE II RIB-AND-WEB FORGING TRIALS USING Ti-6Al-4V ALLOY

Serial Number	Lubricant*	Stock/die Temp. (F)	Furnace Type	Ram Rate (in/min)	Load Applied (tons)
1, 2	CP-C9	1750	Electric	0.2	225
3, 4		1750	Gas-fired	0.2	225
5		1600	Electric	0.2	325
6		1600	Gas-fired	0.2	325
7, 8	CP-B10	1750	Electric	0.2	225
9, 10		1750	Gas-fired	0.2	225
11		1600	Electric	0.2	325
12		1600	Gas-fired	0.2	325
13, 14	CP-B17	1750	Electric	0.2	225
15, 16		1750	Gas-fired	0.2	225
17		1600	Electric	0.2	325
18		1600	Gas-fired	0.2	325
19, 20	CP-C1	1750	Electric	0.2	225
21, 22		1750	Gas-fired	0.2	225
23		1600	Electric	0.2	325
24		1600	Gas-fired	0.2	325
25, 26	GFBN-8	1750	Electric	0.2	225
27, 28		1750	Gas-fired	0.2	225
29, 30	LFC-11	1750	Electric	0.2	225
31, 32		1750	Gas-fired	0.2	225

*coated for 6 mils; furnace time = 1 hour; transfer time = 5 seconds

Gas-fired Furnace: 1750F/0.2 in/min.

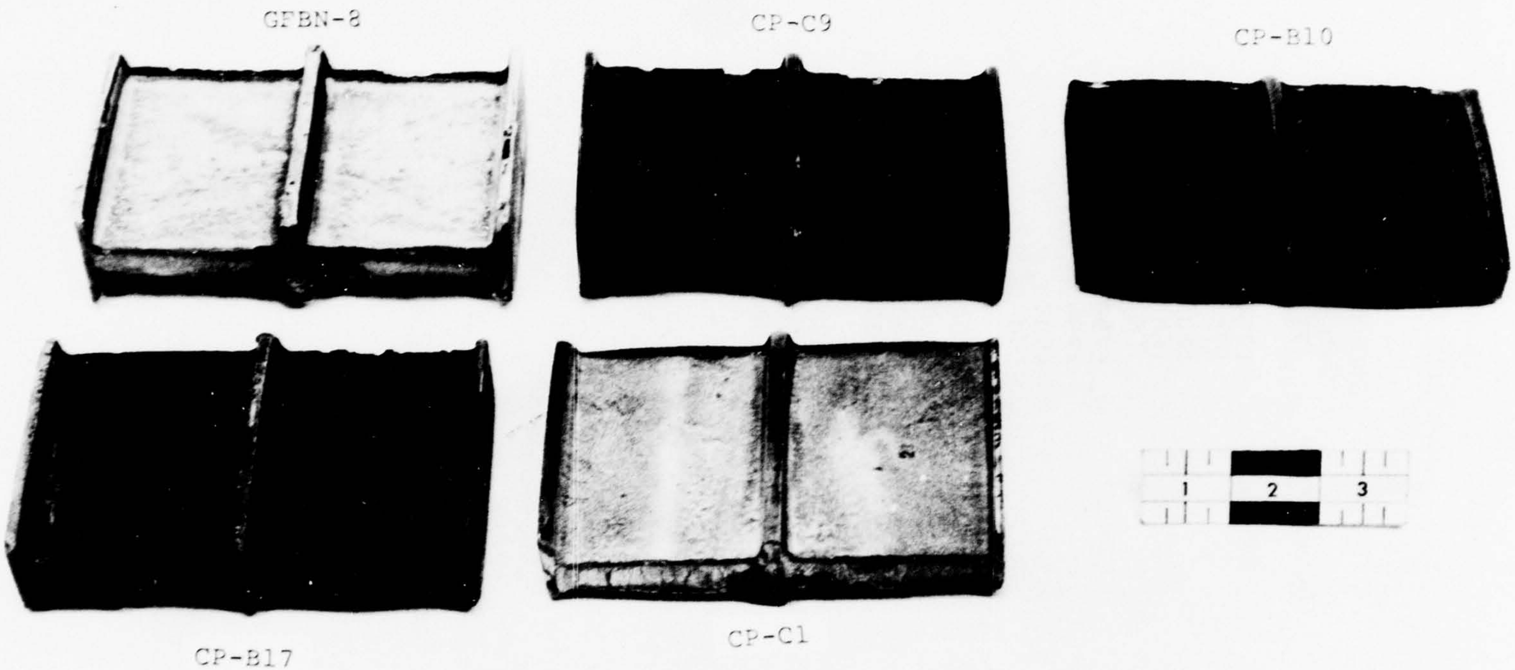


Figure 39a Side view of rib-and-web forgings produced from Phase II rib-and-web forging trials for several lubricants

Electric Furnace: 1750F/0.2 in/min.

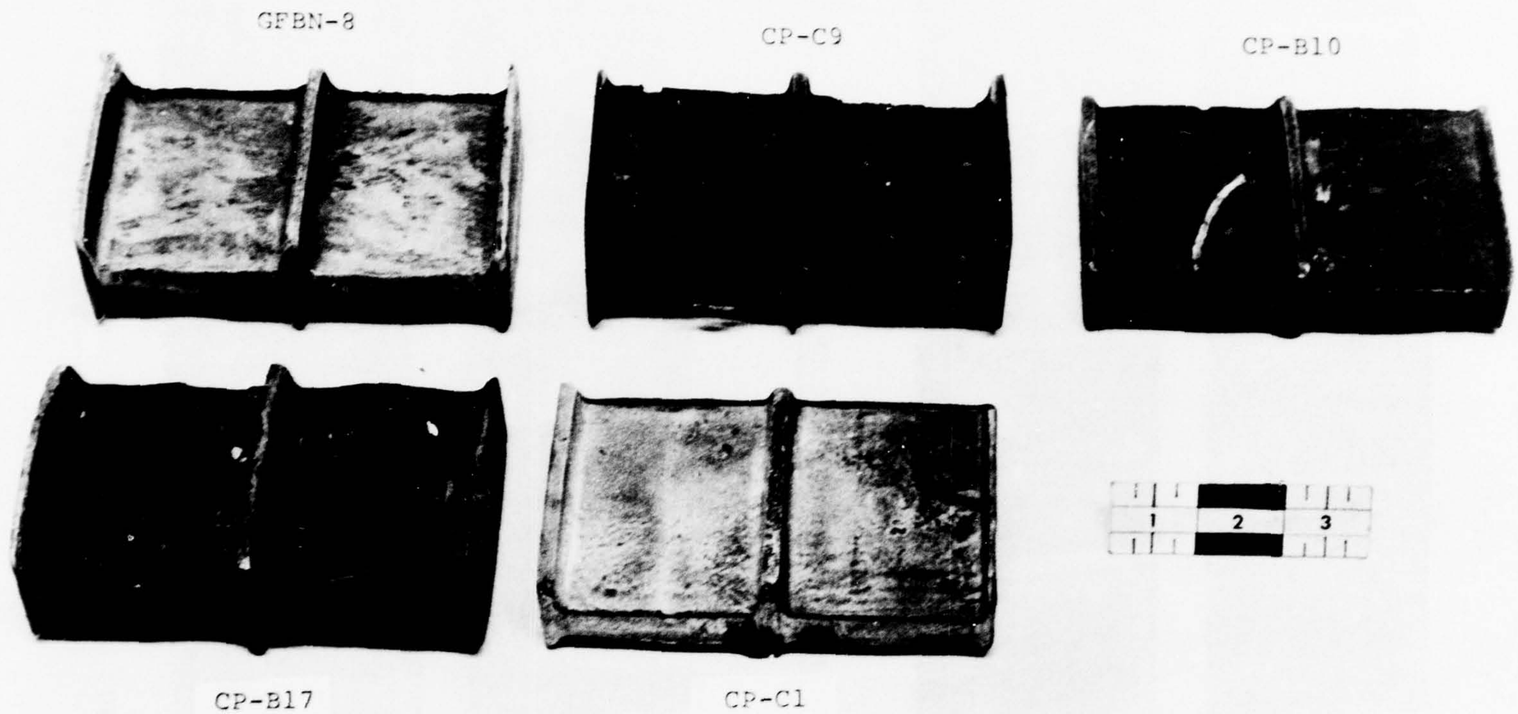
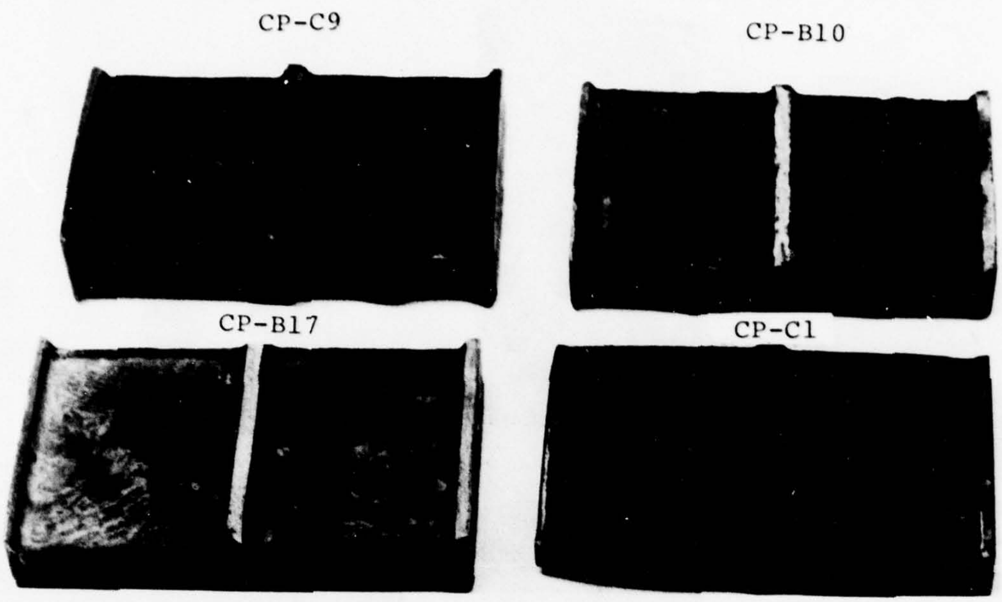
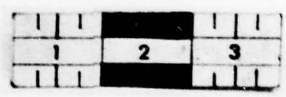


Figure 39b Side view of rib-and-web forgings produced from Phase II rib-and-web forging trials for several lubricants

(a) Gas-fired furnace: 1600F/0.2 in/min.



(b) Electric furnace: 1600F/0.2 in/min.



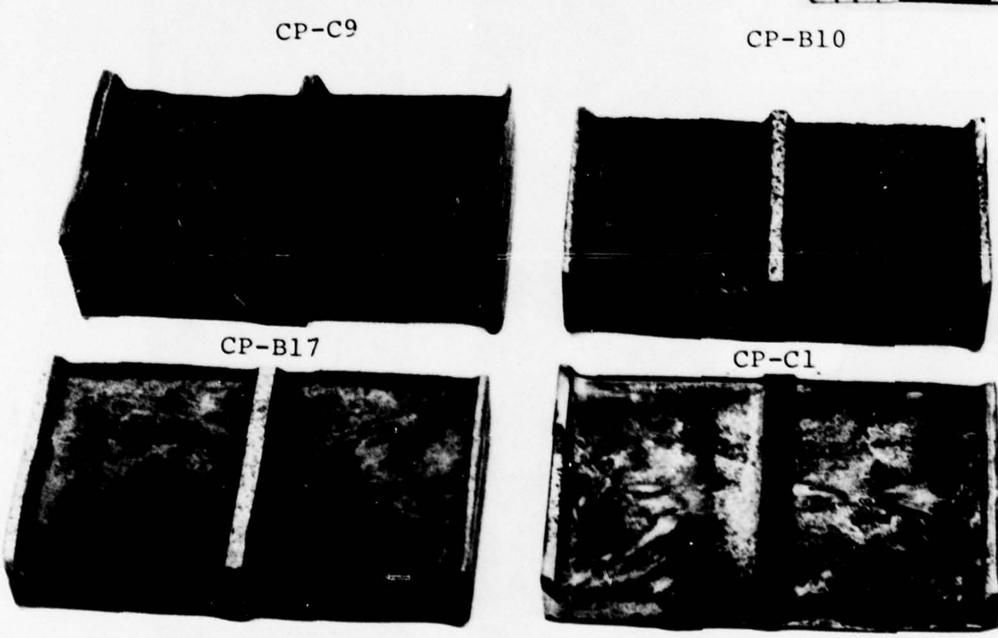


Figure 40 Side view of rib-and-web forgings produced from Phase II rib-and-web forging trials for several lubricants.

(d) Scaled-up Evaluations

A series of lubricant scaled-up forging tryouts using the WG 25046 die set were performed for two selected lubricants, i.e., WG CP-C9 and CP-C1 coatings. The lubricant effectiveness for these lubricant formulations were further compared with those obtained from the lubricants selected in Phase I, i.e., TRW's GFBN-8. The processing variables for the finish forging evaluations are given in Table 10.

(1) The Ti-6Al-4V alloy material for this portion of the program was obtained from the same bar stock (TMCA heat N-8554) as that used in Task I of Phase I. The chemistry and microstructure of the as-received stock were given in Table V and Figure 4, respectively.

(2) The forging stock was cogged and drawn from 4-9/16 inches round to 2-1/4 inches round at 1750F. They were then sectioned into 11-3/8 inches long multiples. The 2-1/4 inches diameter x 11-3/8 inches long forging multiples were blast-cleaned, ground to remove minor wrinkles, and chem-milled.

(3) The fuller, preblocker, and blocker operations for the forging multiples were also carried out at 1750F. The blockers were blast-cleaned, ground to remove minor defects, and chem-milled to remove surface alpha case. They are ready for finish forging evaluations.

(4) Scale-up evaluations of the select lubricants were then performed to determine the reproducibility of the new formulations, following the approach described in section Phase I (Task I) for Ti-6Al-4V alloy.

TABLE 10

PROCESSING VARIABLES FOR FINISH FORGING EVALUATIONS OF Ti-6Al-4V ALLOY FOR PHASE II EFFORT

Serial Number	Lubricant* (Coating)	Forge/ Die Temp. (F)	Ram Rate (in/min)	Furnace** Type	Average*** Pressure Applied (ksi)
1 - 17	CP-C9	1750	0.1	Electric	25
8 - 10	CP-C9	1750	0.1	Gas-fired	25
11 - 17	CP-C9	1600	0.1	Electric	37.5
18 - 20	CP-C9	1600	0.1	Gas-fired	37.5
21 - 27	CP-Cl	1750	0.1	Electric	25
28 - 30	CP-Cl	1750	0.1	Gas-fired	25
31 - 37	CP-Cl	1600	0.1	Electric	37.5
38 - 40	CP-Cl	1600	0.1	Gas-fired	37.5
41	GFBN-8	1750	0.1	Electric	25
42	GFBN-8	1750	0.1	Gas-fired	25
43	GFBN-8	1600	0.1	Electric	37.5
44	GFBN-8	1600	0.1	Gas-fired	37.5

* Coated for 6 mils by spray

** Furnace time ≃ 1-1/2 hour; transfer time from furnace to die ≃ 5 seconds

*** Dwell time = 1 minute

Figures 41 through 45 present the forty-four (44) structural component forgings produced for the Phase II effort; both as-forged and blast-cleaned surface conditions are illustrated. The results of this portion of the evaluation can be briefly outlined as follows: (1) CP-C9 (WG) offers stability advantages over CP-Cl and GFBN-8 in gas-fired environment, (2) CP-Cl has excellent adhesion properties, but poor in anti-friction and atmosphere stability, (3) Each lubricant still has its relative virtues and limitations in manufacturing performance. An adequate balance of the lubricity and adhesion properties is still a major problem for these lubricants. However, among the three lubricants evaluated, the GFBN-8 displays the best combination of lubricity and adhesion characteristics.

It is generally acceptable that the glass coatings have major advantages for isothermal forging in providing a high degree of lubricity and in maintaining a continuous film for excellent protection. However, the results of this investigation demonstrated that, from a manufacturing viewpoint, there are several limiting features with glass coatings for a successful lubricant: (a) sticking of the forging in the dies, (b) poor ability to withstand gas-fired environment at high temperatures, (c) accumulation or build-up in die cavities, (d) some corrosive activities on titanium alloys, (e) relatively rough surface finish, and (f) glass stringers.

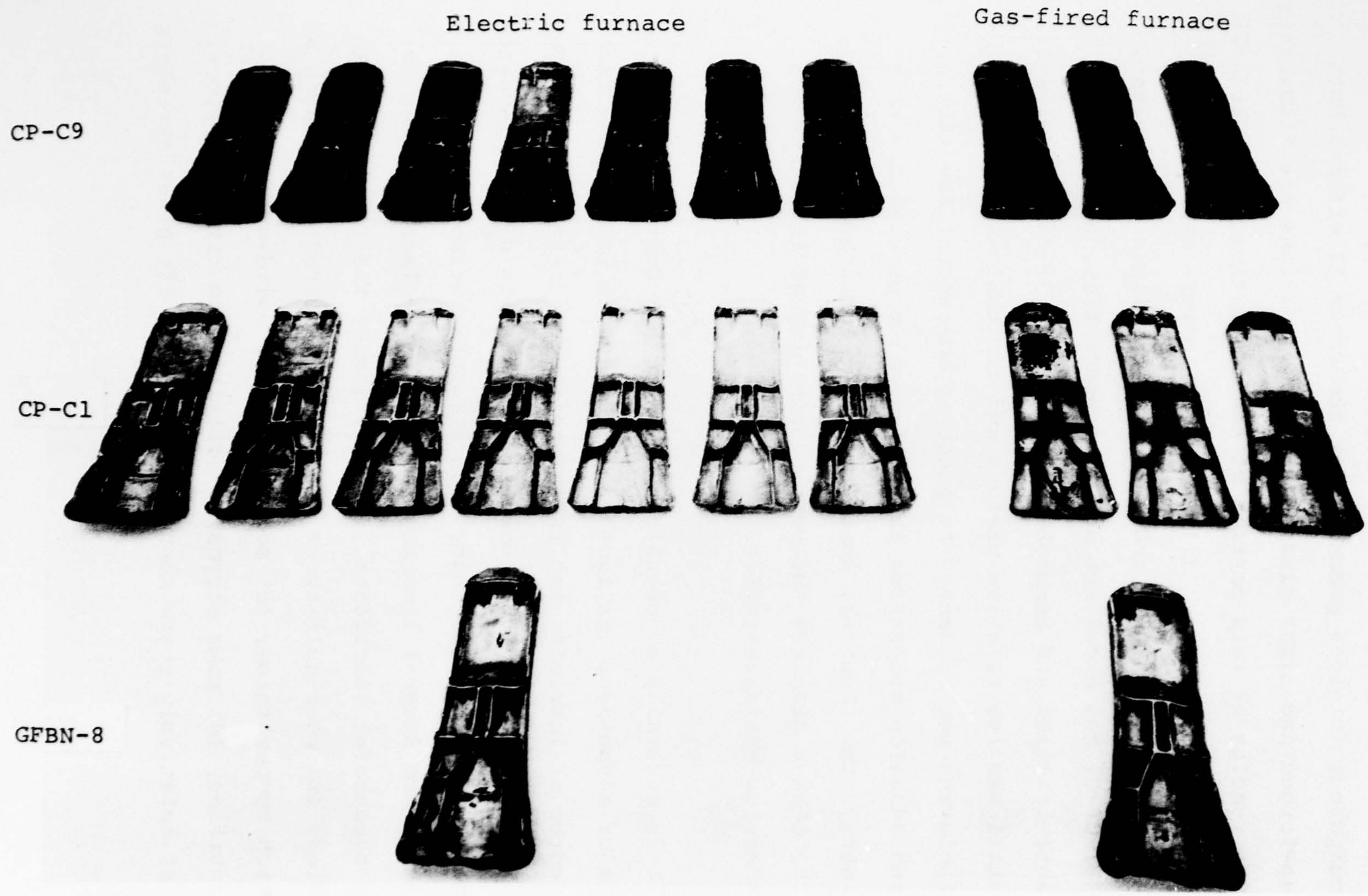


Figure 41a Complete set of twenty-two structural component forgings produced by isothermal forging at 1750F for Phase II effort.

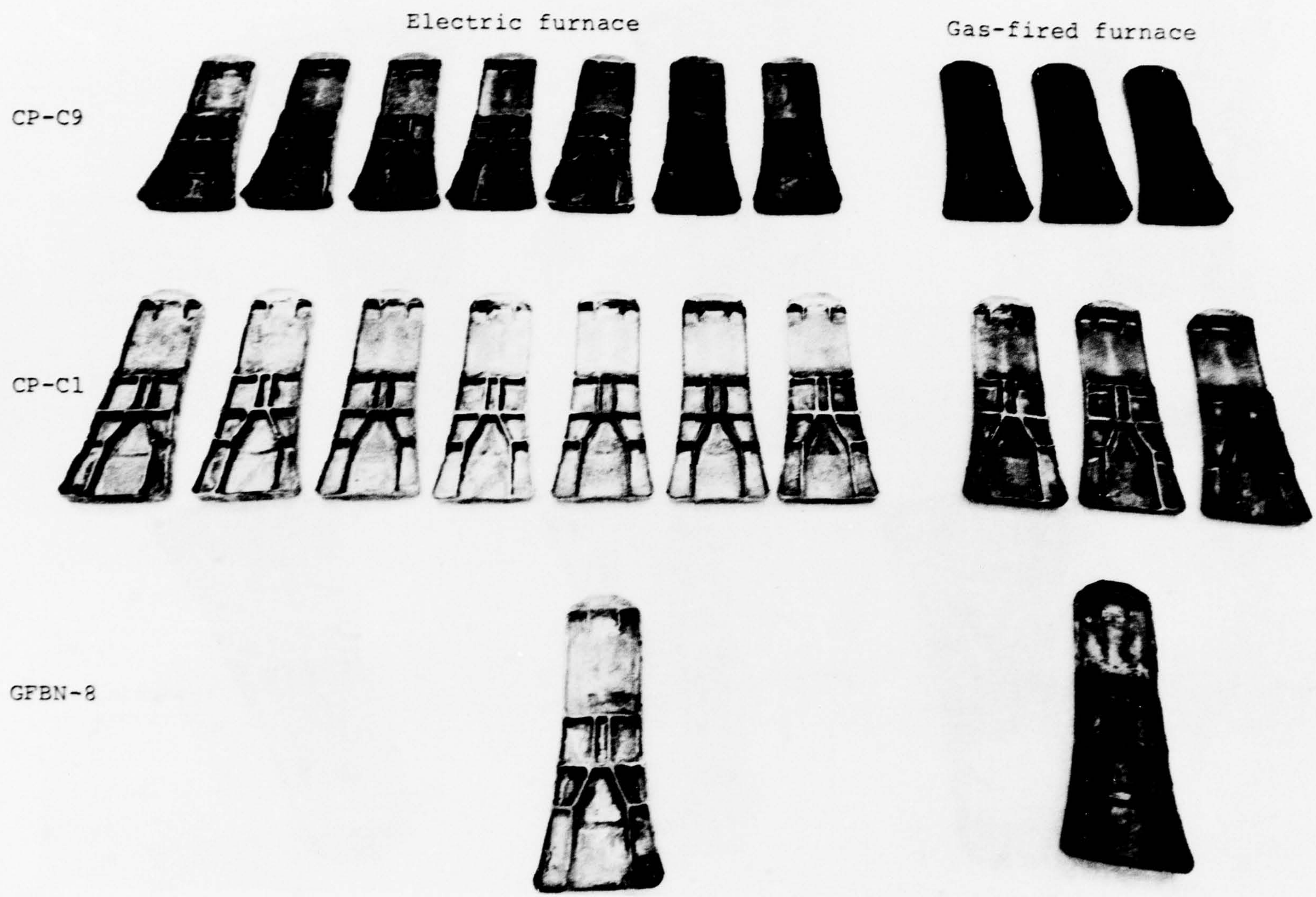


Figure 41b   Complete set of twenty-two structural component forgings produced by isothermal forging at 1600F for Phase II effort.

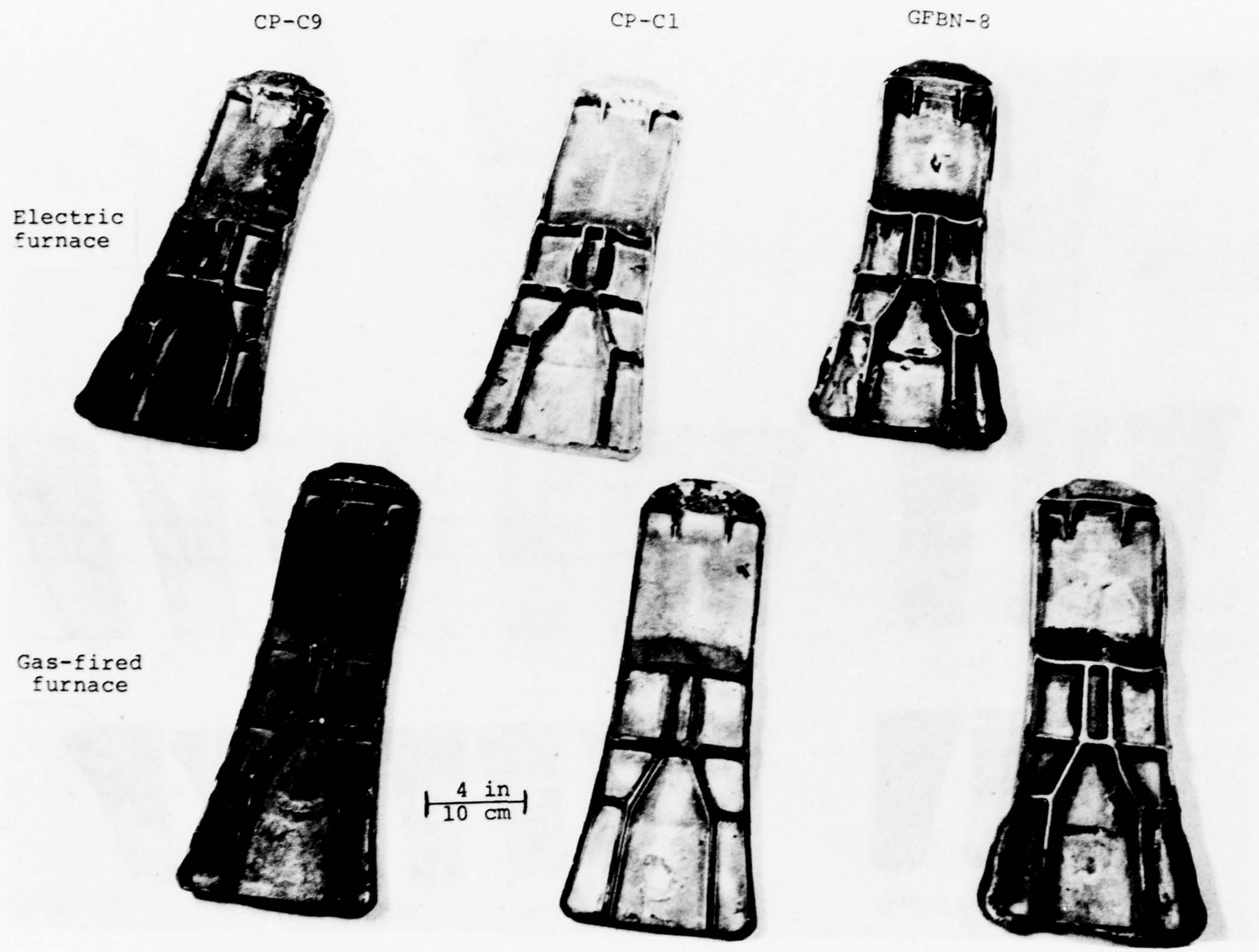


Figure 42a Closeup top view of structural component forgings produced by isothermal forging at 1750F for Phase II effort.

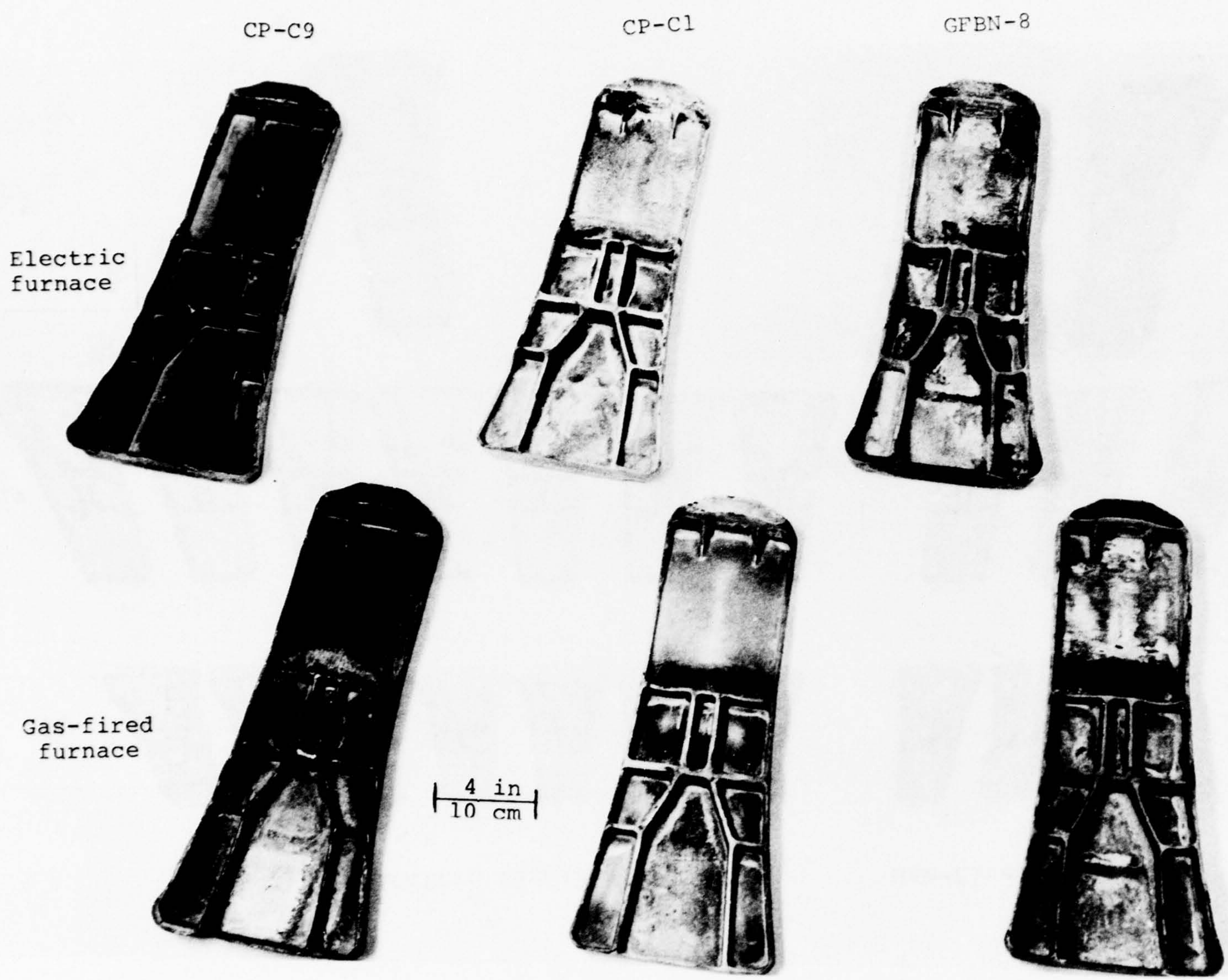


Figure 42b Closeup view of structural component forgings produced by isothermal forging at 1600F for Phase II effort.

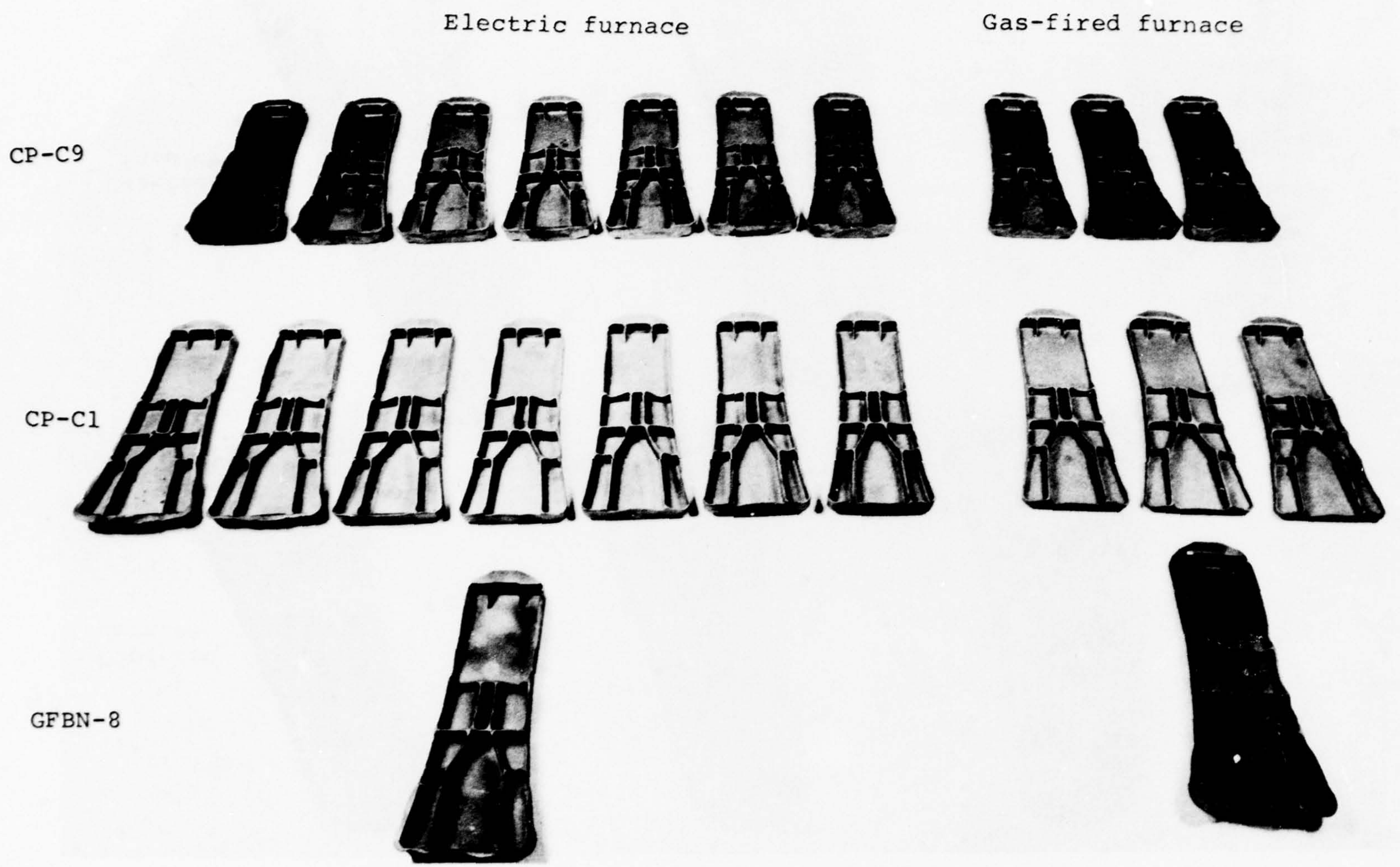


Figure 43a Complete set of twenty-two structural component forgings produced by isothermal forging at 1750F for Phase II effort; blast-cleaned condition.

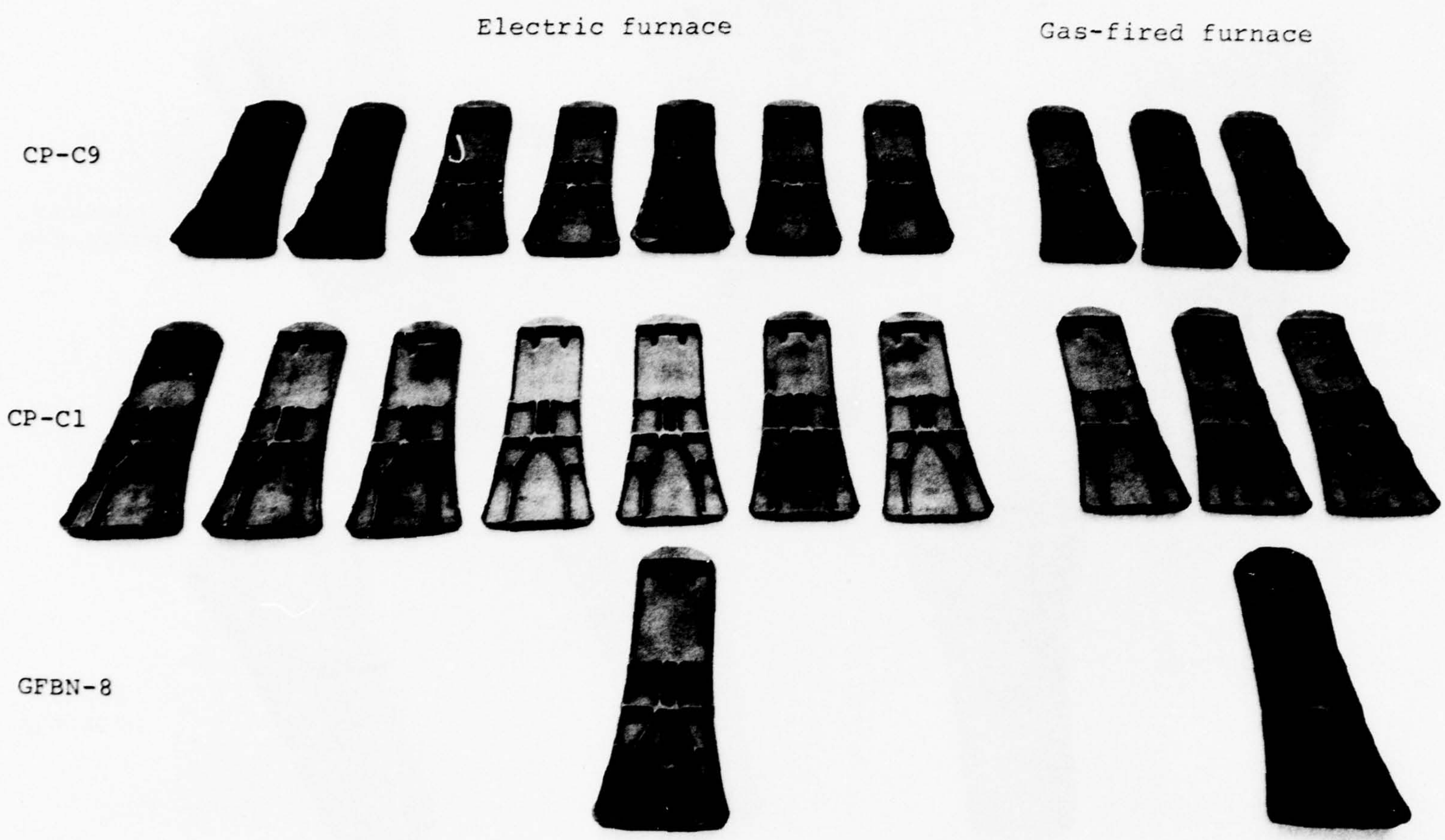


Figure 43b Complete set of twenty-two structural component forgings produced by isothermal forging at 1600F for Phase II effort; blast-cleaned condition.

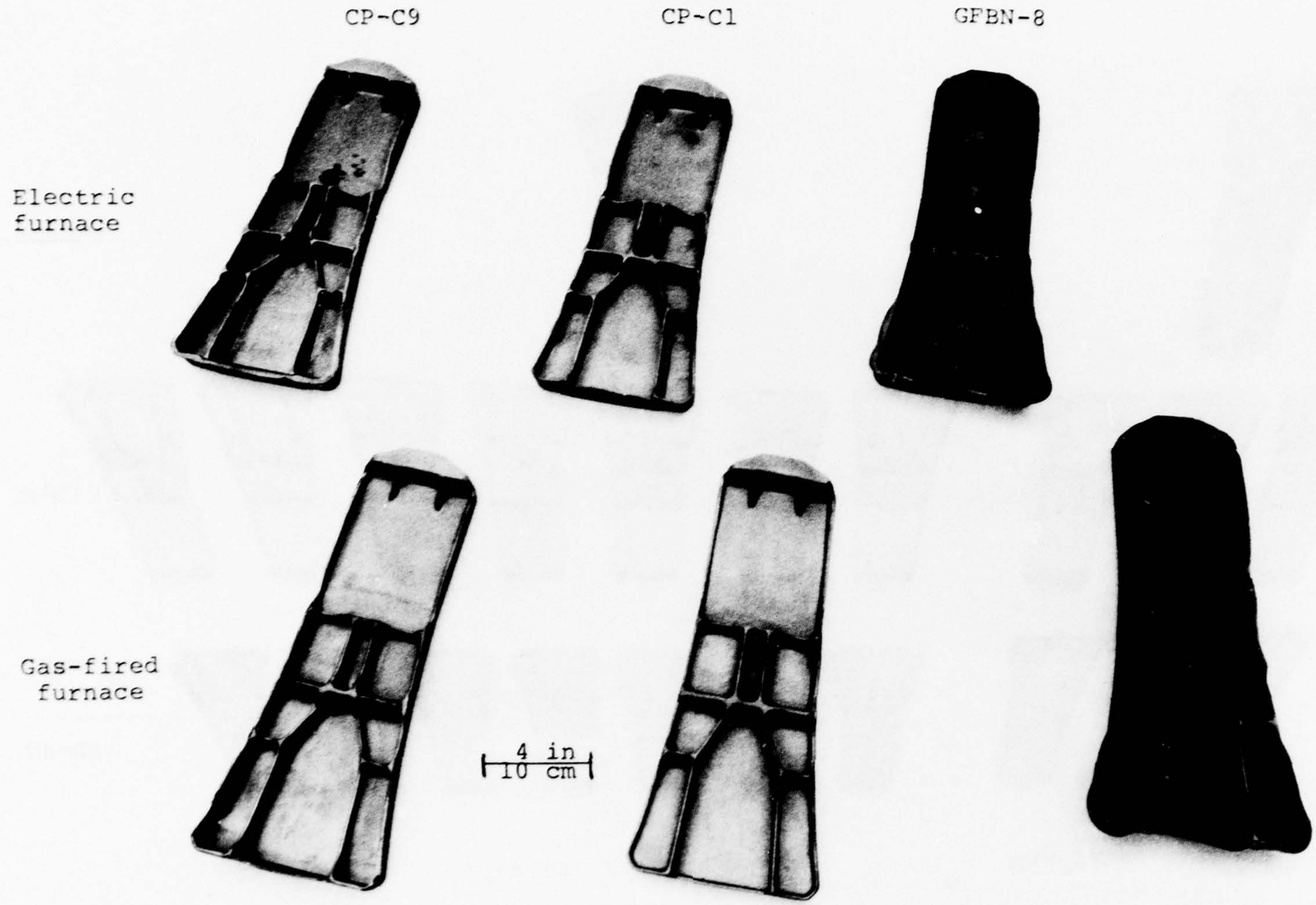


Figure 44a Closeup top view of structural component forgings produced by isothermal forging at 1750F for Phase II effort; blast-cleaned condition.

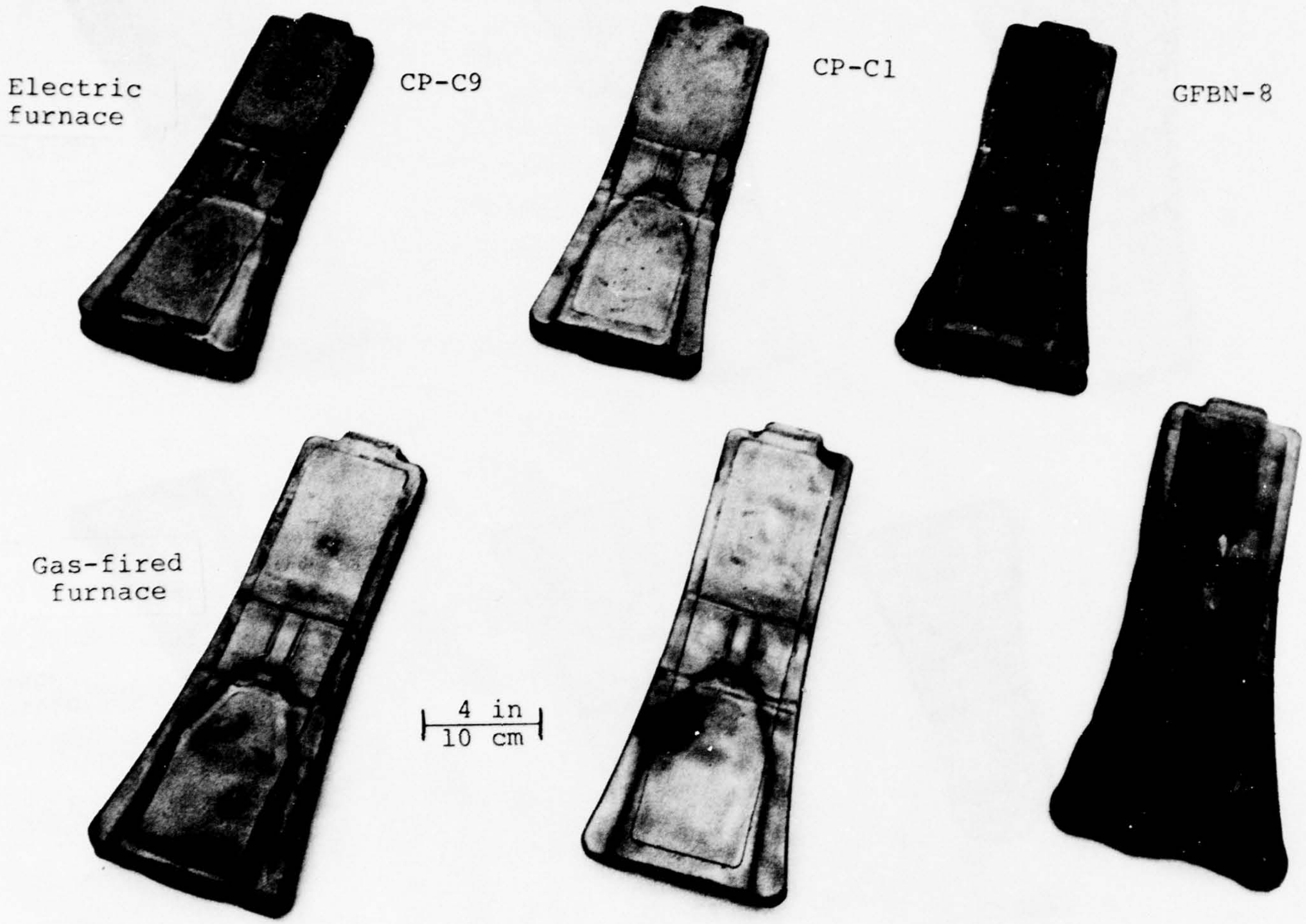


Figure 44b Closeup bottom view of structural component forgings produced by isothermal forging at 1750F for Phase II effort; blast-cleaned condition.

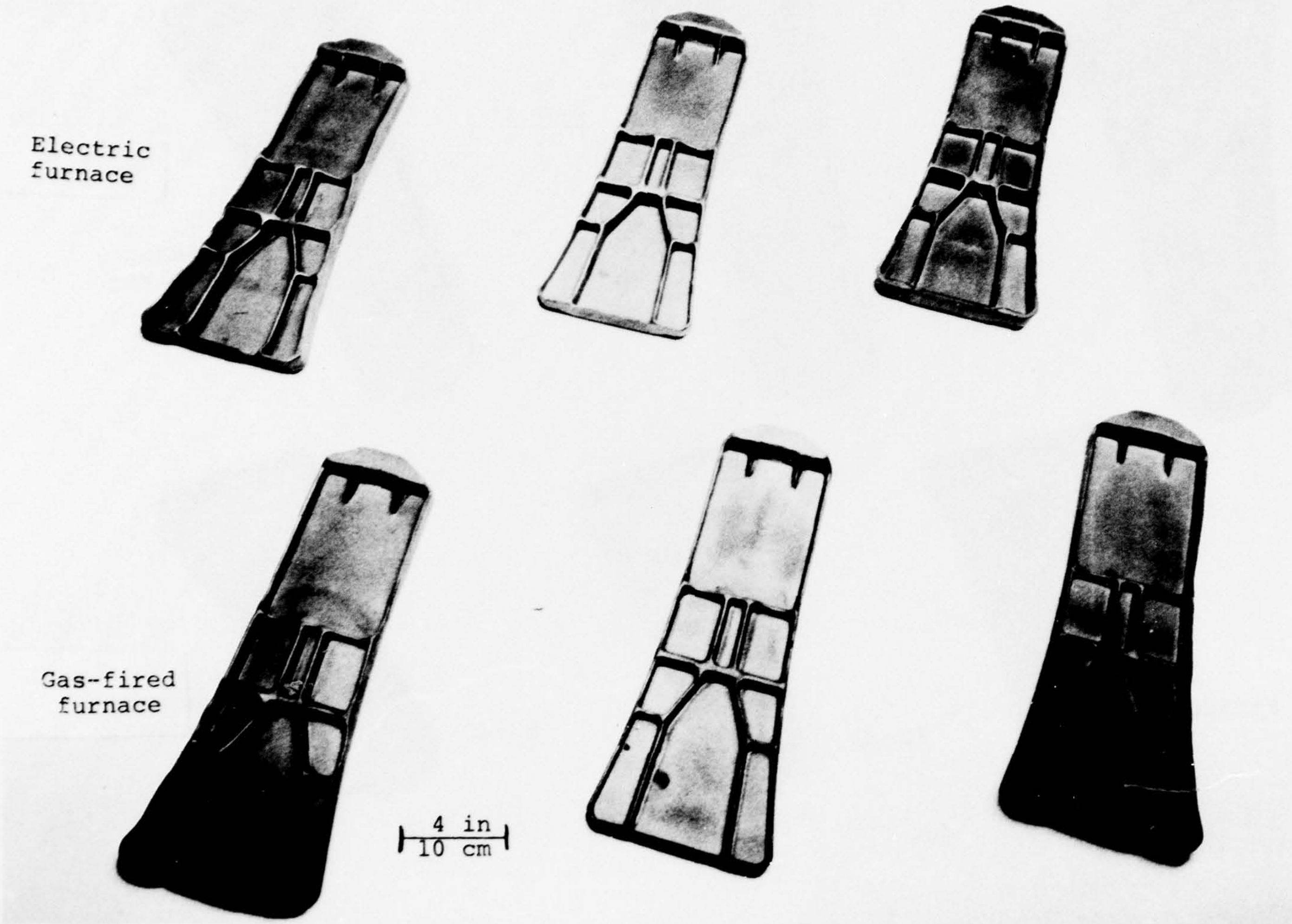


Figure 45a Closeup top view of structural component forgings produced by isothermal forging at 1600F for Phase II effort; blast-cleaned condition.

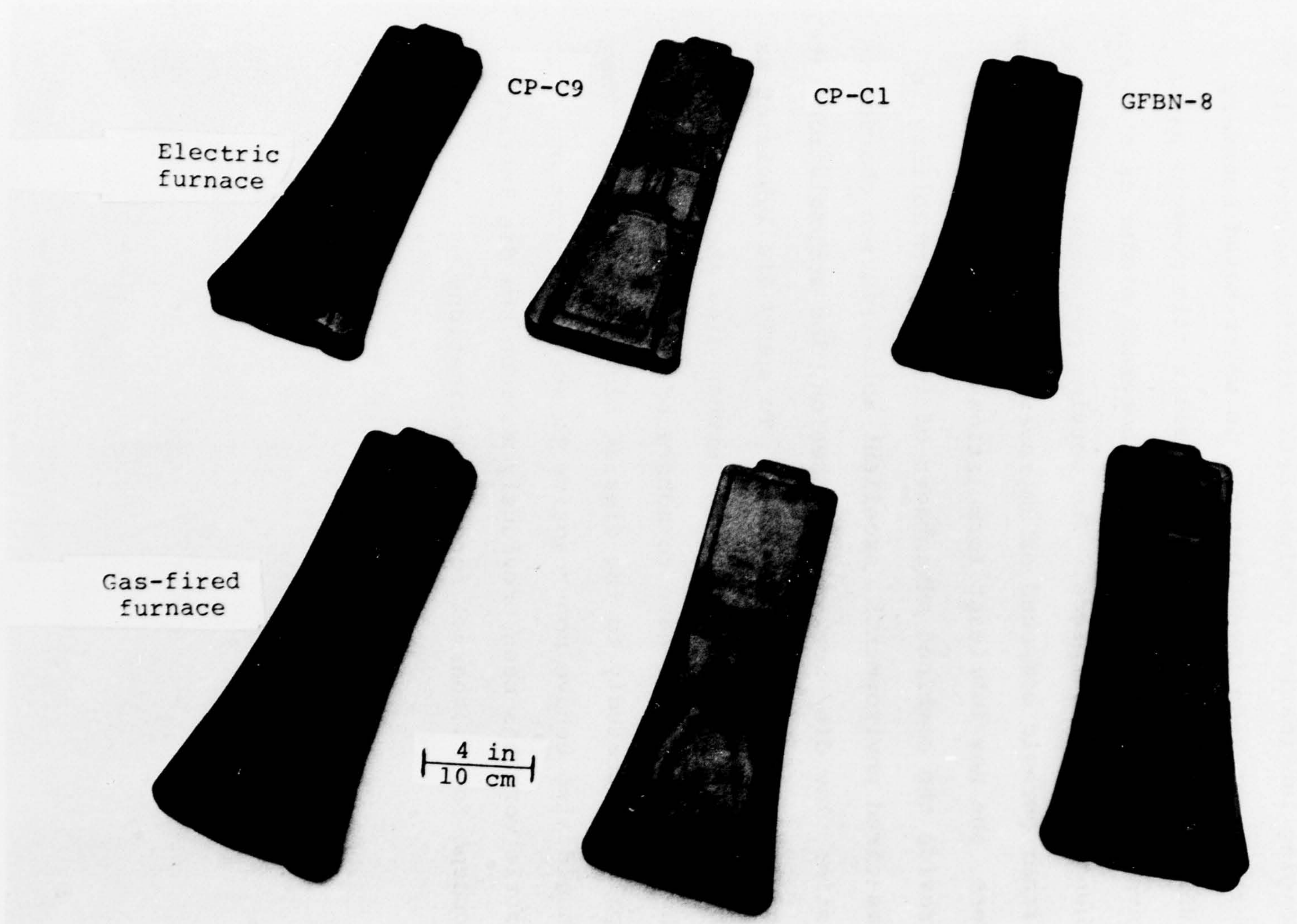


Figure 45b Closeup bottom view of structural component forgings produced by isothermal forging at 1600F for Phase II effort; blast-cleaned condition.

There are two possible approaches for improved isothermal forging lubrication of alpha-beta titanium alloys: (1) To further continue investigations in water-based boundary lubricants containing dispersed solid film powders as an interface separation agent and inorganic binder as a wetting agent for the workpiece. The wetting component may be either ceramic compound or improved glass-type compositions. Here, the new lubricant formulations should be able to provide the combined advantages of improved stability in gas-fired environments, excellent anti-friction characteristics, low die/ work-piece adhesion, low accumulation rate, and less corrosive action. (2) To apply die lubricant as an efficient parting-compound between dies and workpiece. The die lubricants have to adhere effectively and can be applied repeatedly to the dies at high temperatures. They should also behave non-reactive to workpiece coating. Little work has been previously made on the die lubricant concept for isothermal forging applications.

C. Structural Examination

Three forgings were sectioned for both macro and microstructural examinations; a sketch showing the locations of macro slices and microstructure examinations is given in Figure 46. The sectioned forgings were selected from one of the best forgings from Ti-6Al-4V alloy parts and from each of alpha-beta forged and beta-forged Ti-10V-2Fe-3Al alloy.

Figures 47a and 47b illustrate the macro and microstructures of the as-forged Ti-6Al-4V alloy. It is seen that the forging had a highly distorted macroetch pattern with a structure characterized by the alpha-beta finish. The microstructure of the forging contains approximately $25\sim35\%$ globular alpha in a matrix of transformed alpha plus beta, characteristic of forging at temperature moderately high in the alpha-beta field with an air cool.

The structures for alpha-beta and beta forged Ti-10V-2Fe-3Al alloy are given in Figures 48 and 49, respectively. Here the macrostructure of the alpha-beta forgings is characterized by a highly directional flow pattern in the zones leading from thin web to thin ribs (Figures 48a and 48b). However, the beta-forged condition shows a recrystallization of hot-worked structure with a much lesser degree of grain flow in the zones leading from web to ribs (Figures 49a and 49b). The microstructure of both alpha-beta and beta

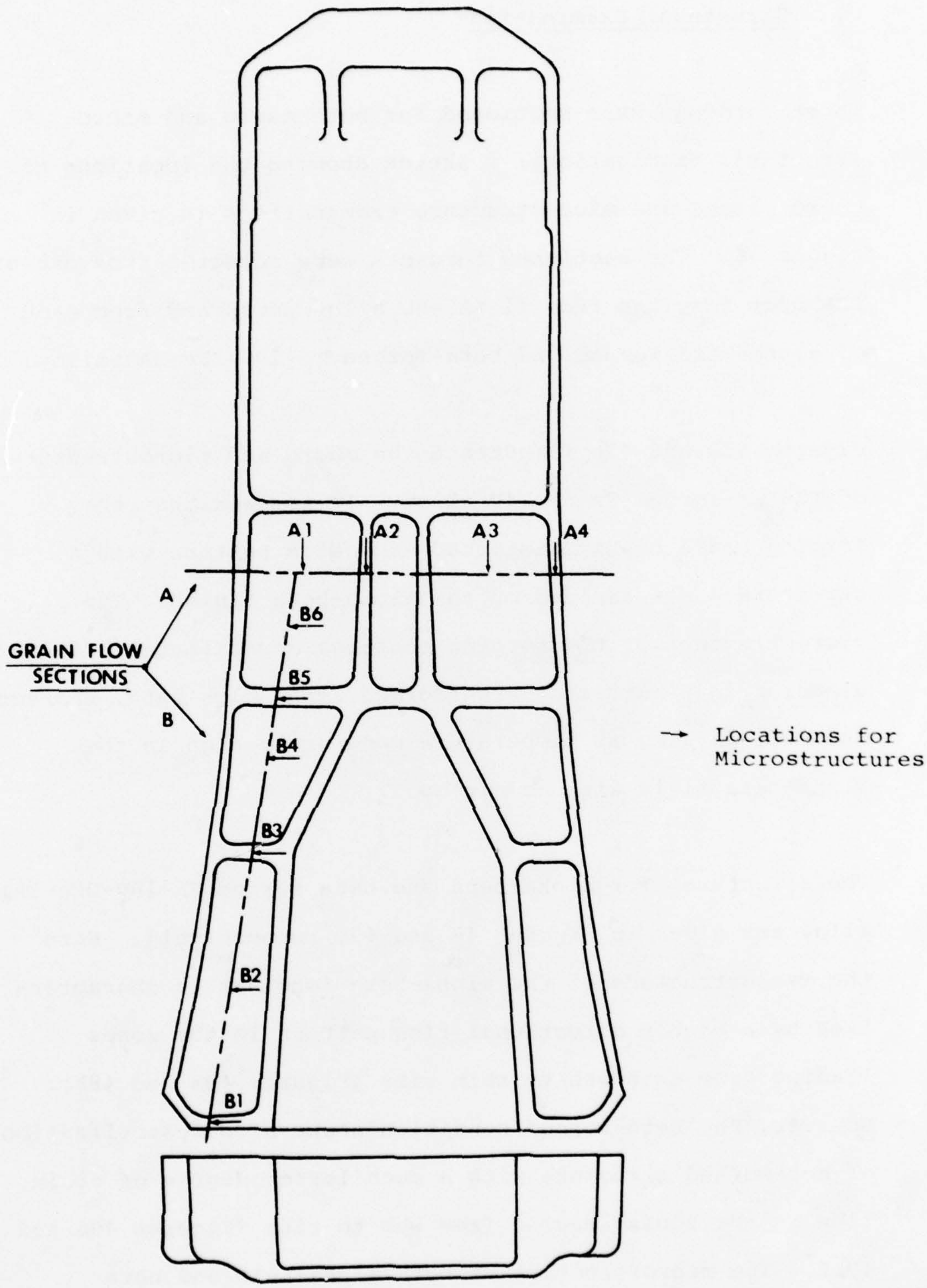


Figure 46 A sketch of F-15 Bulkhead-Centerbody forging showing locations for structural examinations

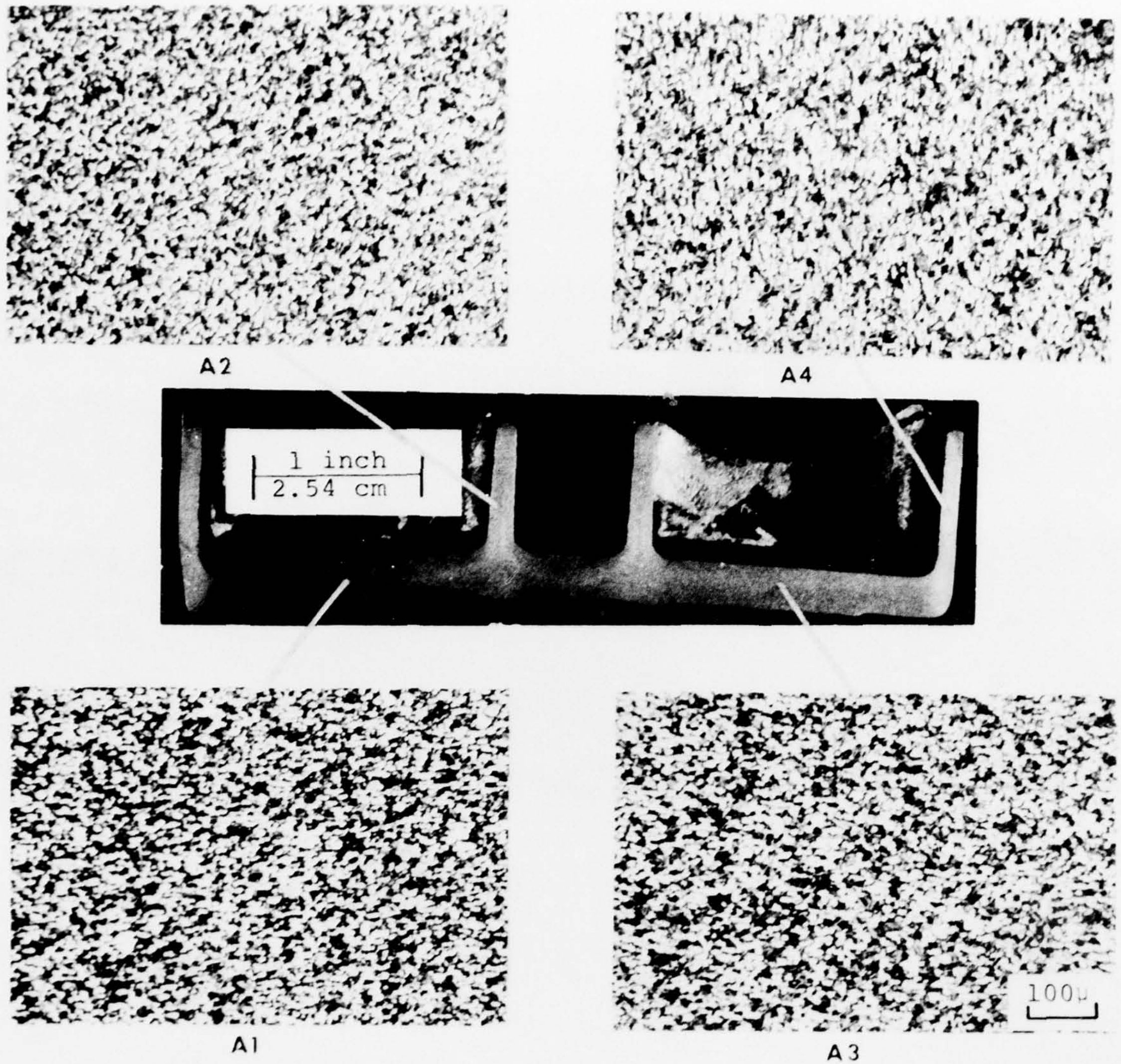


Figure 47a Transverse section - macro and microstructures for an isothermally forged Ti-6Al-4V alloy F-15 Bulkhead-Centerbody forging; as alpha-beta forged condition (1750F/air cool).

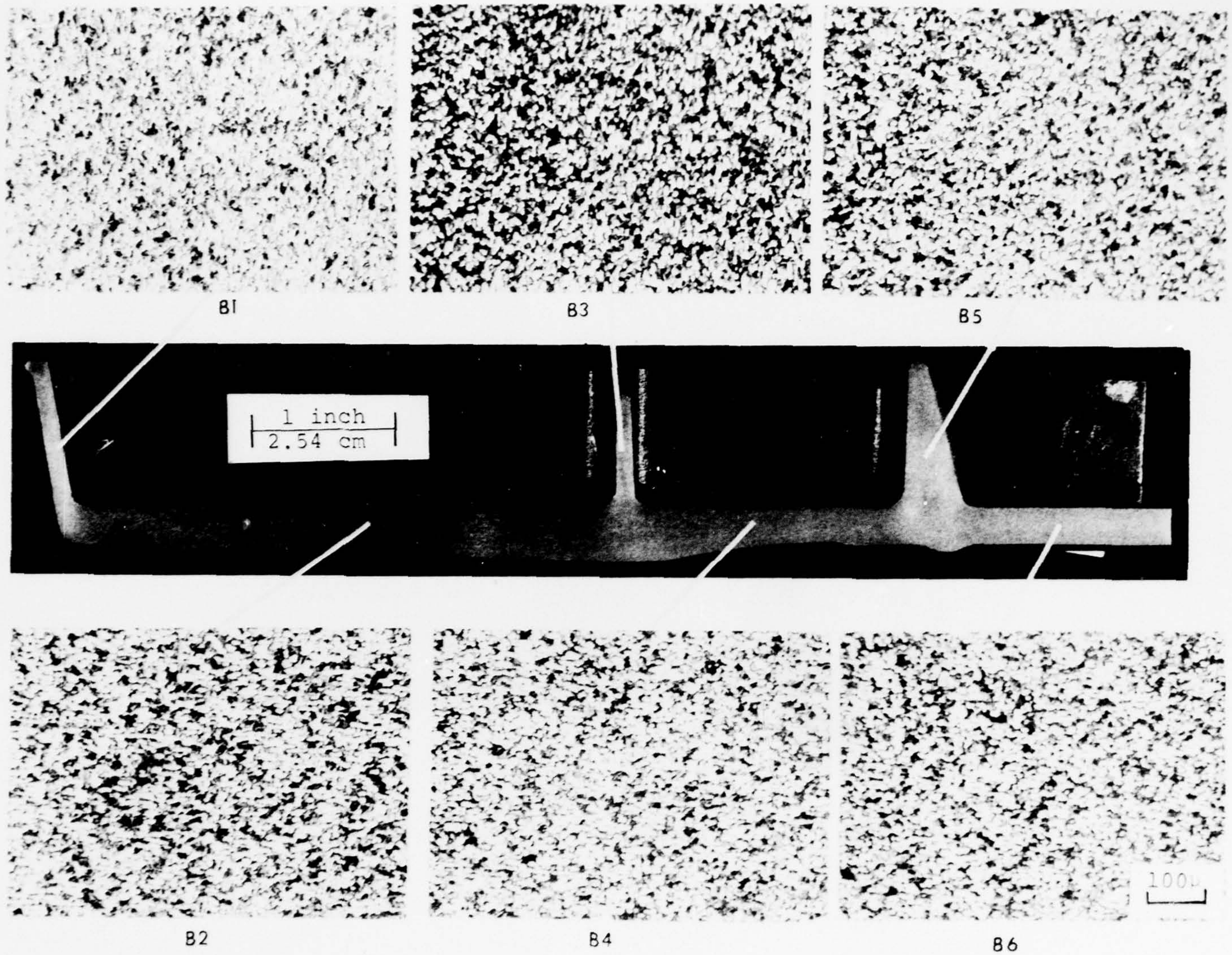


Figure 47b Longitudinal section - macro and microstructures for an isothermally forged Ti-6Al-4V alloy F-15 Bulkhead-Centerbody forging; as alpha-beta forged condition (1750F/air cool).

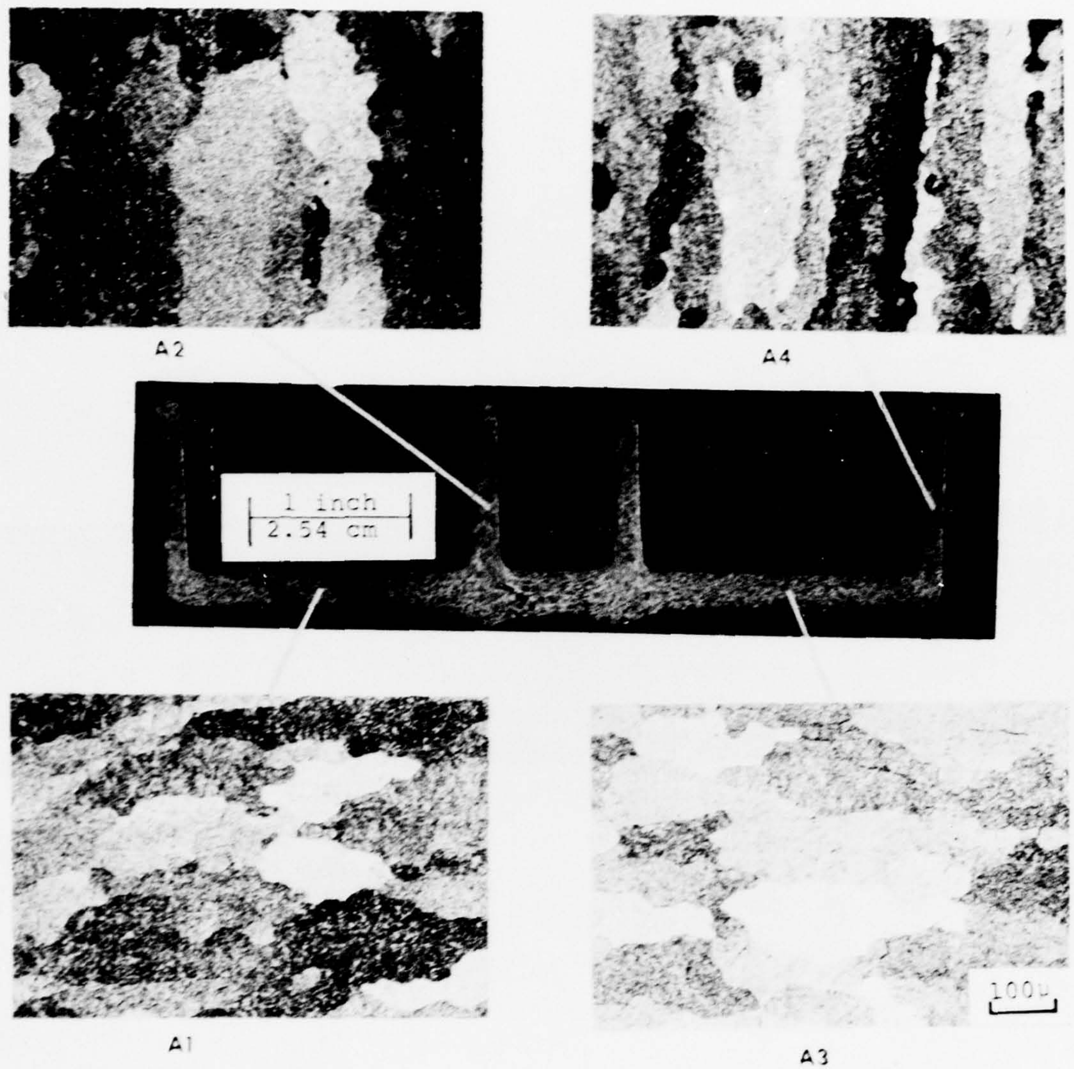


Figure 48a   Transverse section - macro and microstructures for an isothermally forged Ti-10V-2Fe-3Al alloy F-15 Bulkhead-Centerbody forging; as alpha-beta forged condition (1400F/air cool).

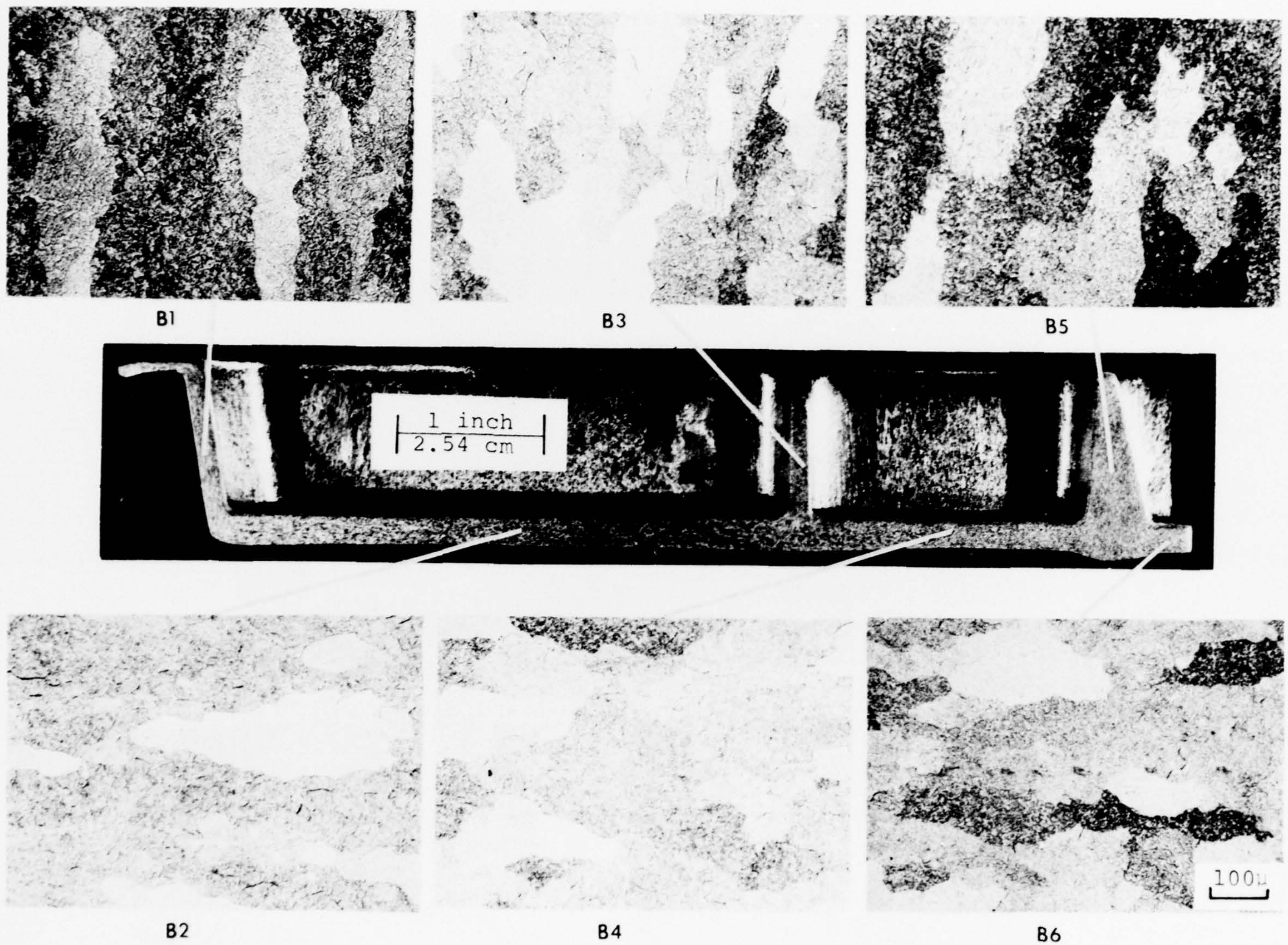


Figure 48b Longitudinal section - macro and microstructures for an isothermally forged Ti-10V-2Fe-3Al alloy F-15 Bulkhead-Centerbody forging; as alpha-beta forged condition (1400F/air cool).

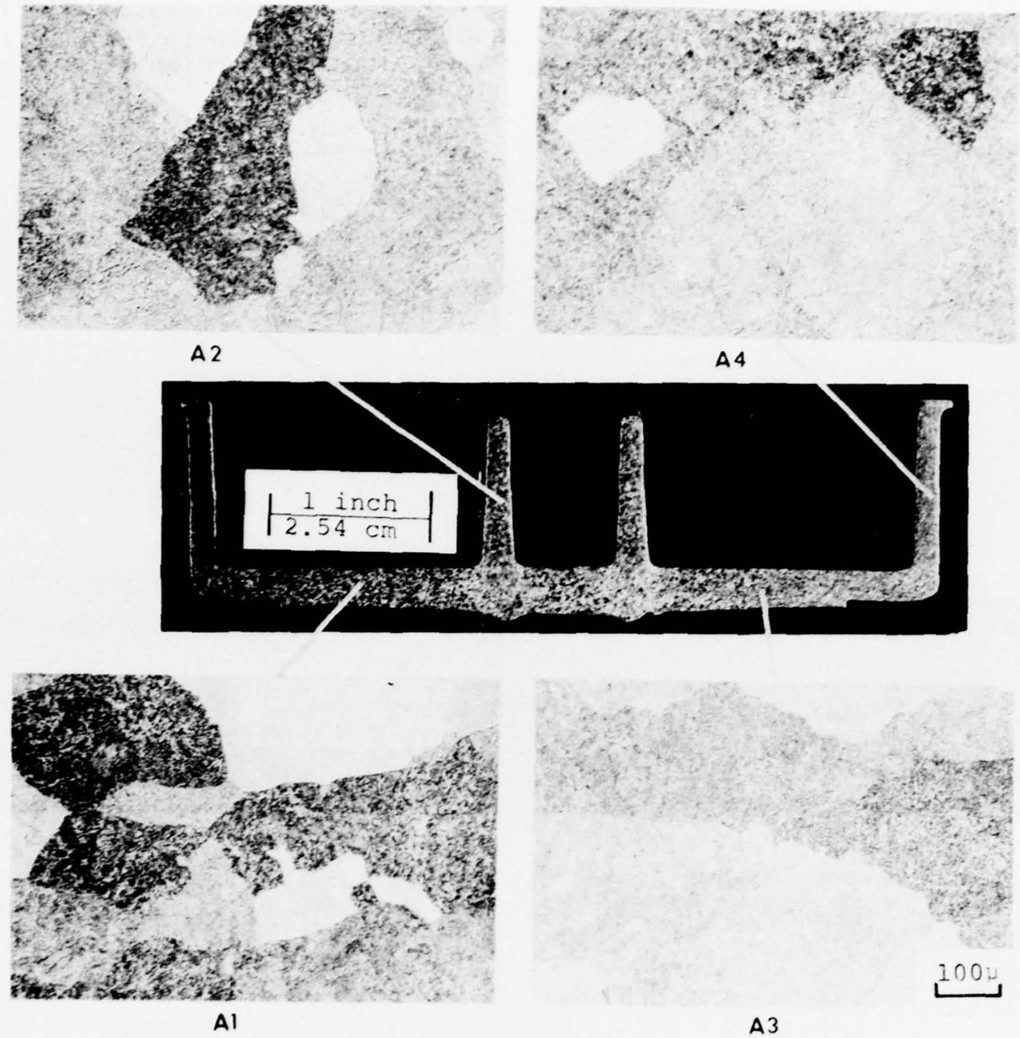


Figure 49a   Transverse section - macro and microstructures for an isothermally forged Ti-10V-2Fe-3Al alloy F-15 Bulkhead-Centerbody forging; as beta-forged condition (1550F/air cool).

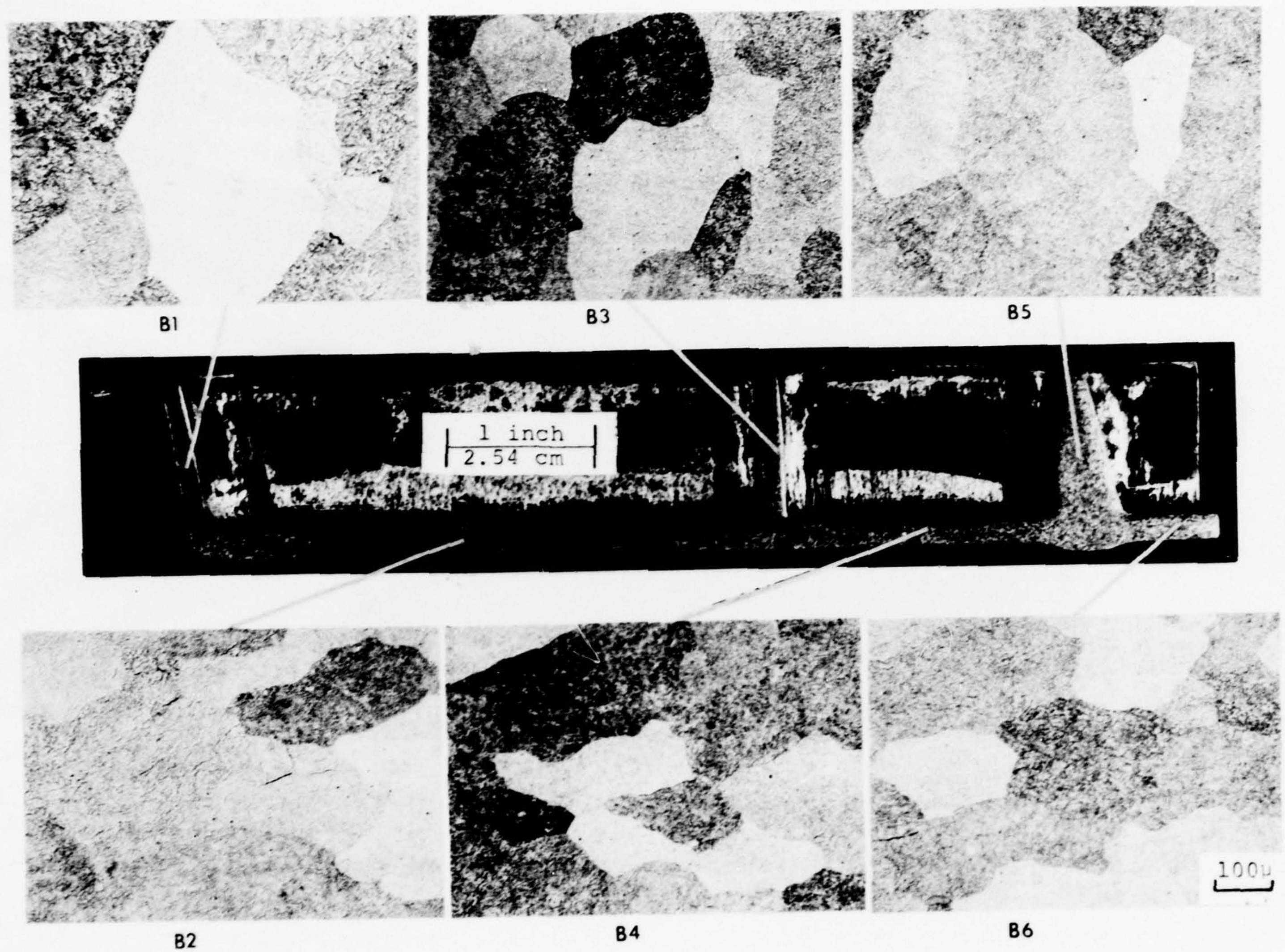


Figure 49b Longitudinal section - macro and microstructures for an isothermally forged Ti-10V-2Fe-3Al alloy F-15 Bulkhead-Centerbody forging; as beta-forged condition (1550F/air cool).

forged Ti-10V-2Fe-3Al alloy consists of fine alpha in a matrix of large beta grains; characteristic of beta titanium alloy forgings. However, the microstructure of beta forged condition is characterized by a finer and lesser transformed alpha needles in a matrix of less distorted and larger beta grains, as compared with alpha-beta forged condition.

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