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COLD ROTARY FORGING

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WATERVLIET, N.Y. 12189**

TECHNICAL REPORT

AMCMS No. 4930.16.6287.01

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Cold rotary forging of thin wall alloy steel cylinders was investigated. The cold working resulted in a small amount of strain hardening, as measured by an increase in longitudinal yield strength. In most cases, the strain hardening was greater at lower yield strengths regardless of the amount of reduction on the material. The most significant change was a decrease in transverse yield strength after forging. The lower yield strength material showed very little decrease in yield strength after forging, whereas, the

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In addition to the data on mechanical properties, data are also presented on induced residual stresses. The results were inconsistent in that both compressive and tensile residual stresses were observed. However, in general, the stresses were low. The thermal treatments which resolved the strength problem also effectively eliminated the residual stresses.

Since the ultimate aim of the cold working was to produce a finished recoilless rifle tube, the cylinders were forged with an internal rifled configuration. The results showed that it is possible to produce the desired configuration. However, problems must be resolved to meet the tight dimensional tolerance requirements.

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COLD ROTARY FORGING

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September 1975

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ABSTRACT

Cold rotary forging of thin wall alloy steel cylinders was investigated. The cold working resulted in a small amount of strain hardening, as measured by an increase in longitudinal yield strength. In most cases, the strain hardening was greater at lower yield strengths regardless of the amount of reduction on the material. The most significant change was a decrease in transverse yield strength after forging. The lower yield strength material showed very little decrease in yield strength after forging, whereas, the higher yield strength material exhibited a greater decrease in yield strength after forging. This behavior was attributed to the bauschinger effect. It was possible to recover the strength by a thermal treatment at 800°F - 1000°F.

In addition to the data on mechanical properties, data are also presented on induced residual stresses. The results were inconsistent in that both compressive and tensile residual stresses were observed. However, in general, the stresses were low. The thermal treatments which resolved the strength problem also effectively eliminated the residual stresses.

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The authors wish to acknowledge and thank P. Cote, G. Capsimalis, J. Underwood and C. DeLaMater for their work in determining the residual stresses in the forgings and V. Montuori, D. Concordia and F. VanLangen for their work in relating the full size impact data to the sub-size data and Mr. P. Thornton for assistance in relating the full size impact data to the sub-size data and for providing technical and editorial assistance in the preparation of the early drafts of this report. The forgings were produced by Revere Copper and Brass, Inc. on a GFM SX35 machine under contract with Watervliet Arsenal.

INTRODUCTION

"Rotary forging" is a forming process in which the workpiece is rotated as it passes through four symmetrically located hammers (Figure 1). Since the hammers work at a rapid rate, it is possible to cold forge at a rate of 1-1/2 - 3 feet of product per minute. By using a mandrel, it is also possible to produce a tubular forging. A description of the machine and process is given in Reference 1.

The process is widely used throughout the world for producing small arms such as shot gun barrels, machine gun barrels and small caliber tubes. It has been stated that the service life for the small caliber tubes has been extended, and the overall costs reduced through material savings and higher production rates. However, application of this process to large caliber gun tubes requires larger, specifically designed equipment not universally available.

Several programs were initiated to develop rotary forging techniques and procedures for producing thin wall, cold forged, large caliber gun barrels. Emphasis was directed to finish forming the internal rifled configuration, thereby eliminating subsequent machining operations. At the same time, a study was conducted on the effects of this forging process on the mechanical properties and residual stresses of the material being used. A program was devised to forge short cylinders using a variety of processing parameters to evaluate their effect on dimensional accuracy, mechanical properties and residual stress level and direction.

1. Feinschmiedemaschinen Und Ihre Arbeitsweise (Precision Forging Machines and Their Mode of Operation), GFM Publication.

TABLE 1

Mechanical Properties-Preforms

	Transverse				Longitudinal			
Preform	Y.S.$^{(1)}$	RA	$C_v^{(2)}$	$C_v^{(3)}$	Y.S.$^{(1)}$	RA	$C_v^{(2)}$	$C_v^{(3)}$
1	130 ksi	32%	48 ft-lbs	11 ft-lbs.	135 ksi	66%	74 ft-lbs	-
2	108	37	56	12	112	68	93	-
3	154	31	38	8	160	63	57	-
4	131	32	46	10	136	67	75	-
5	154	28	34	8	158	64	56	-
6	107	35	57	12	114	66	92	-
7	130	33	47	10	136	66	77	-
8	111	60	55	11	115	69	99	-
9	108	38	-	-	-	-	-	-
10	116	61	55	11	116	68	93	-
11	156	28	37	8	159	62	58	-
12	113	59	-	-	-	-	55	-
13	131	32	47	10	136	65	75	-
14	145	50	28	7	171	62	41	-
15	145	50	27	8	172	58	41	-
16	166	45	-	-	-	-	-	-

(1) Yield Strength at 0.1% offset
(2) Full-size Charpy bar at -40°F
(3) Sub-size Charpy bar at -40°F

APPROACH TO THE PROBLEM

Sixteen (16) short length hollow cylinders, 5-9/16" O.D. x 4" I.D. x 60" were cold rotary forged. The short cylinders were used to establish the optimum forging parameters to produce full cylinders. Because of the general lack of information on the response of the low alloy steel used in tubes to cold forging, the starting yield strength of the preforms and the forging reduction applied were varied. Since the ultimate aim of the program is to produce a finished tube, the mandrel used was rifled.

After forging, the cylinders were dimensionally inspected, sectioned and evaluated for mechanical properties and residual stresses. Because of an unanticipated loss in transverse yeild strength, a program to develop a thermal treatment to recover the strength, and also to eliminate the residual stresses was undertaken. A series of Temperature (T) - time (t) heating cycles were evaluated.

MATERIALS AND PROCEDURES

Material

Modified electric furnace vacuum degassed 4337 steel with the following composition was used to produce the seamless tubing,with an unknown amount of prior working, used as preforms:

C	Mn	P	S	Si	Ni	Cr	Mo
.36	.74	.007	.009	.30	1.77	.79	.36

Table 1 shows the mechanical properties of the starting cylinders (preforms). Table 2 shows the heat treatments used for

TABLE 2

Heat Treatments-Preform

Heat Treat Cycle	Preform
A - Preheat - 1350°F Austenitize - 1600°F Oil quench from 1550°F Temper - 1000°F - 2 hrs.	14, 15, 16
B - Normalize - 1600°F Austenitize - 1550°F Oil quench Temper - 1150°F - 2 hrs.	1, 4, 7, 13
C - Normalize - 1600°F Austenitize - 1550°F Oil quench Temper - 1250°F - 2 hrs.	2, 6, 8, 9, 10, 12
D - Normalize - 1600°F Austenitize - 1550°F Oil quench Temper - 1050°F - 2 hrs.	3, 5, 11

the various cylinders. It had originally been intended to test material at three nominal yield strength levels, viz., 120, 140 and 160 ksi. However, the results of the heat treatments provided a greater range of yield strengths, and thus, an expanded program. Because it was not possible to obtain a full size Charpy specimen from the thin wall forging, both full size (.394" x .394") and sub-size (.197" x .394") specimens were taken from the preforms in the transverse orientation to develop a correlation. Only full size specimens were tested in the longitudinal orientation.

After determining the yield strength, the short tubes were divided into groups and machined on both I.D. and O.D. The I.D. was constant for all the tubes, whereas the O.D. varied depending on the amount of cross sectional reduction to be imposed. Consideration was also given to the starting surface finishes. In some cases, the inside surface was honed to RMS 32 while others were machined to RMS 125 to RMS 250. In all cases, the O.D. surface finish was the same. Table 3 shows the forging reduction to be applied and the starting surface finish of the preforms.

Final tube preparation prior to cold forging consisted of cleaning both the I.D. and the O.D. with kerosene and Valcolene(a). After cleaning, the I.D. was swabbed with a lubricant called Hamilube X122(b). No lubricant was used on the O.D.

(a) Valcolene, Valeska Co., Div. Kynext Corp., Rome, N.Y.
(b) Harry Miller Corp., Philadelphia, Pa. 19140

TABLE 3

Forging Reduction-Surface Finish

Preform	Forging Reduction	Surface Finish	
		O.D.	I.D.
1	15%	RMS 500	RMS 250
2	20	500	250
3	10	500	125
4	15	500	250
5	15	500	250
6	40	500	250
7	20	500	250
8	20	500	250
9	20	500	250
10	20	500	250
11	20	500	250
12	30	500	250
13	30	500	125
14	30	500	32
15	20	500	32
16	5	500	32

Forging Procedure

Forging Hammers - The forging hammer system consisted of four separate hammers, each made of two parts, viz., base and striking face. The base is normally made from high strength low alloy steel and the striking face of tool steel or carbide inserts. The hammers used in cold forging were made from H13 tool steel and were symmetrical around the tubular workpiece (Figure 1). The hammer face for a tubular workpiece has a curvature slightly larger than the workpiece and may have a single taper or multiple tapers. For this program, the hammer face had multiple tapers (Figure 2). The tapered portion of the hammer face is called the entry angle. The degree of entry angle and the reduction rate control the amount of forging penetration on the workpiece.

Forging Mandrel - The forging mandrel was a precision ground, solid H13 tool steel plug with rifling machined on the O.D. surface (Figure 3) with a surface finish of RMS 4-6. To allow for adjustment of the inside diameter of the workpiece, the mandrel O.D. was tapered with the leading edge smaller. To allow for workpiece springback after forging, the mandrel was smaller than the I.D. required on the forging. Prior to forging, the mandrel was cleaned with kerosene and Valcolene and brushed with lubricant, Hamilube X122.

Cold Forging - After preparation, the tube was loaded into the chuckhead by means of "loading prongs" and was automatically centered. The mandrel was then located through the preform and between the hammers. The preform was then fed between the hammers,

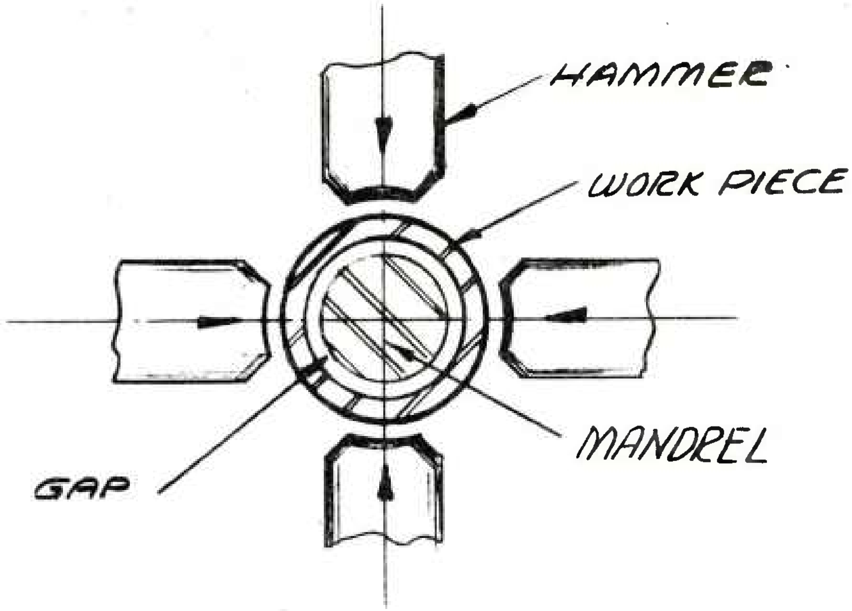

FIG. 1 - Schematic showing relationship of hammers, mandrel and workpiece.

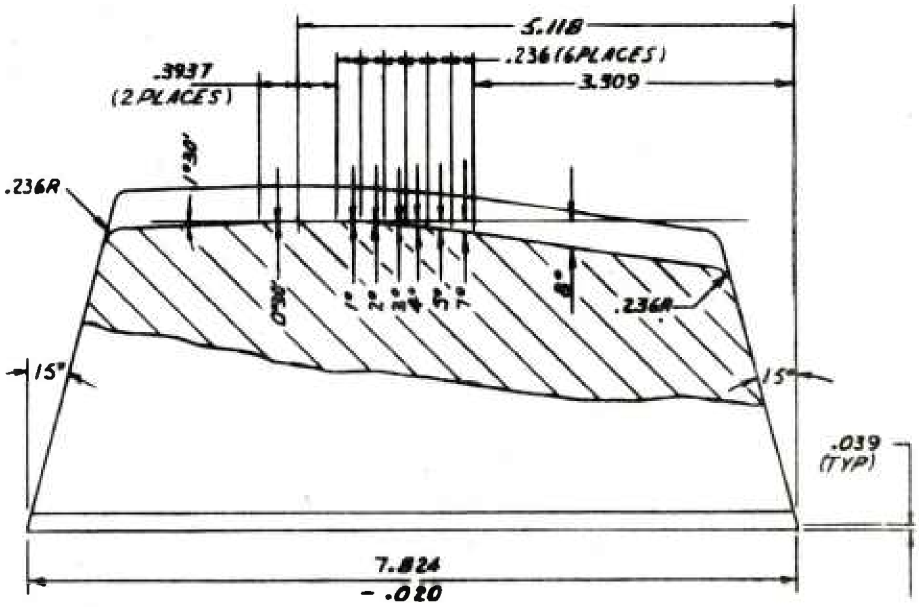

FIG. 2 - Rotary forging hammer - typical for 106mm I.D.

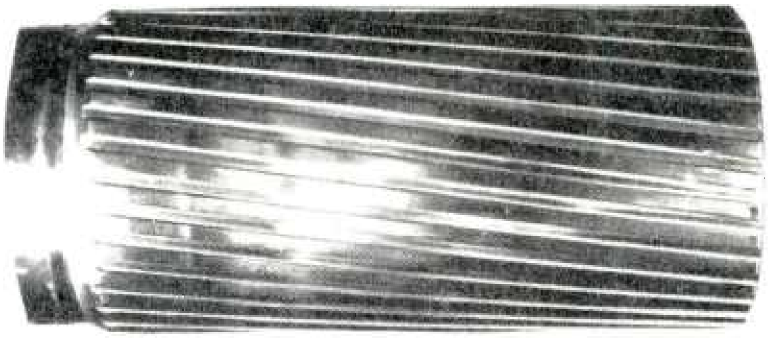

FIG. 3 - Rifled forging mandrel

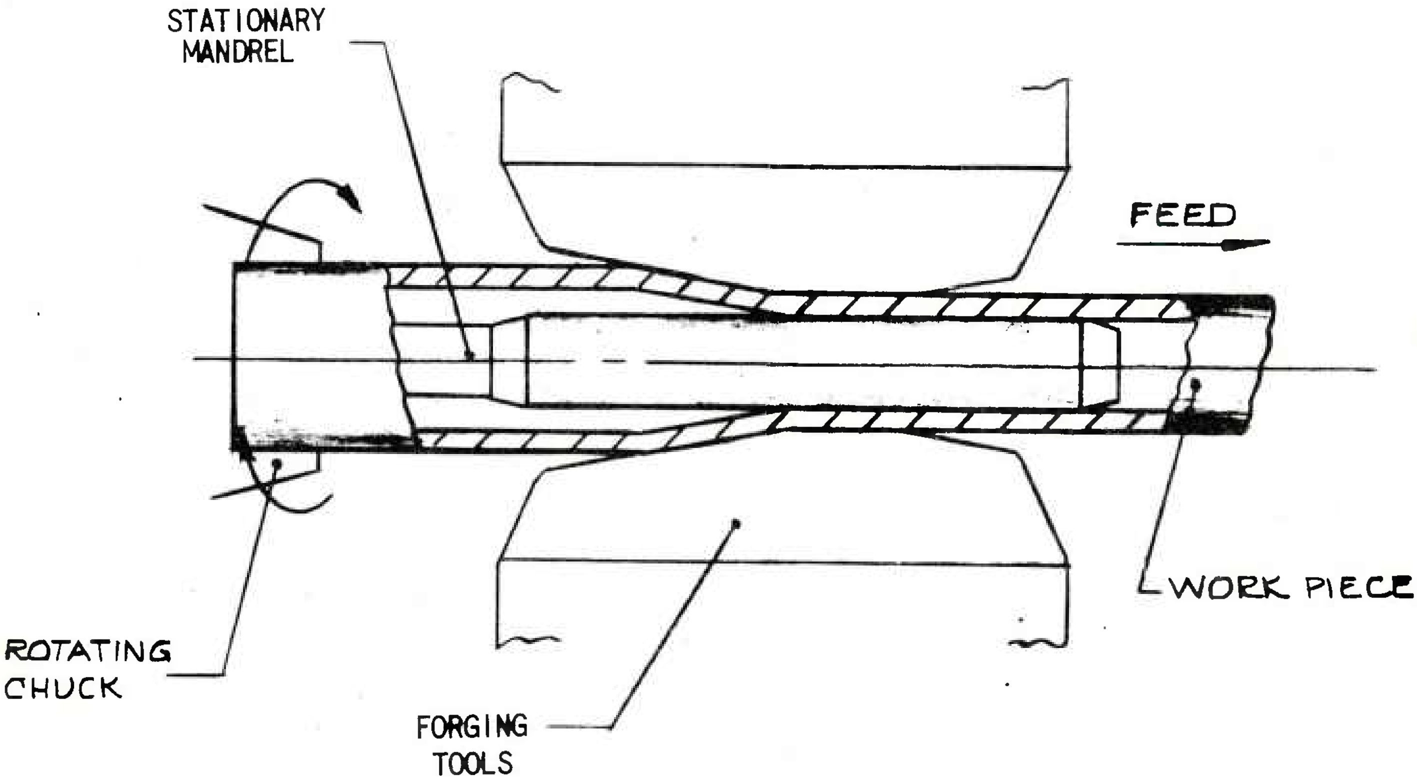

FIG. 4 - Schematic of forging over a mandrel.

over the mandrel and against the counter holder on the exit side of the hammers. With the mandrel and preform in location, water was sprayed to cool both the preform and the hammers during forging. The hammers were fed gradually inward to full depth while rotation and feeding of the preform started. After the hammers reached full depth at the starting end of the preform, it was fed through the hammers for the entire forging length (Figure 4). At the end of the forging cycle, which was programmed, the mandrel and forging were automatically returned to the starting positions. Instantly the loading prongs moved in and clamped around the forging, after which, the chuck jaw released the forging which was then removed from the machine.

Forging Parameters - Various combinations of forging parameters were used. Table 4 compiles the parameters applied.

Evaluation

Dimensional - Several of the cylinders were inspected for conformance to the dimensional requirements of the 106mm recoilless rifle. This included the inspection of the O.D. and I.D., including the twist of the rifling. In addition, the surface finish was evaluated.

Mechanical Properties - To determine the effect of the forging operation, the mechanical property measurements were repeated. However, because of the thin wall of the tubes, only sub-size impact toughness could be measured.

Residual Stresses - Two methods were used to measure residual stresses:

TABLE 4

Forging Parameters

Preform	Hammer Setting (in.)	Chuckhead		Counterholder Pressure (Atm.)	Ring Space Pressure (Atm)	Power (KW)
		Speed (RPM)	Feed (in./min.)			
1	5.27	17	13	35	107	-
2	5.21	17	17	35	-	-
	5.21	17	17	25	101	-
3	5.33	13	13	25	98	120
4	5.27	26	13	25	112	150
5	5.27	17	13	25	112	-
6	5.21	17	17	w/out	o'load	-
	4.97	13	17	25	120	-
	4.97	17	17	25	120	-
	4.97	13	17	25	82	140
7	5.21	17	16	25	110	150
8	5.21	17	17	35	-	-
	5.09	26	17	35	72	-
9	5.21	17	17	35	o'load	-
	4.97	17	17	25	115	-
10	5.21	17	17	w/out	103	-
11	5.21	13	13	25	120	-
12	5.09	17	17	35	-	-
13	5.09	13	13	25	118	-
14	5.20	13	20	35	70	125
	5.20	13	20	35	o'load	-
	5.20	13	20	35	110	190
15	5.32	13	20	35	20	120
16	5.38	13	17	35	82	140

NOTE: Multiple entries signify several passes were required.

(a) Strain gage slitting tests - One inch wide discs were removed from each of the forged tubes and machined approximately 0.1 inches on the O.D. to remove the forging hammer marks. Two resistance strain gages were mounted on the disc, one, on the inside diameter and one, on the radial axis on the outside diameter. Two scribed reference lines were marked on the outside diameter surface opposite the strain gages. Prior to slitting the discs, measurements from the strain gages and the spacing between the scribed lines were recorded. After slitting the discs, the strain gage and line spacing were again recorded and residual stress was calculated. Figure 5 shows a typical test disc specimen after slitting, with the opening exaggerated for clarity. The test determines average or gross stress level.

(b) X-ray - A two-exposure x-ray technique employing both film and diffraction methods was used[2]. In a crystalline material, the d-spacing between atomic planes can be determined with x-rays. When the material is stressed, the d-spacing is changed. If the change is measured in two directions, the stress can be determined by calculation. This method can determine surface stresses and stresses in localized areas. Figure 6 shows the general arrangmemt for testing.

RESULTS AND DISCUSSION

Dimensional Evaluation

Dimensional and surface finish evaluations were made on

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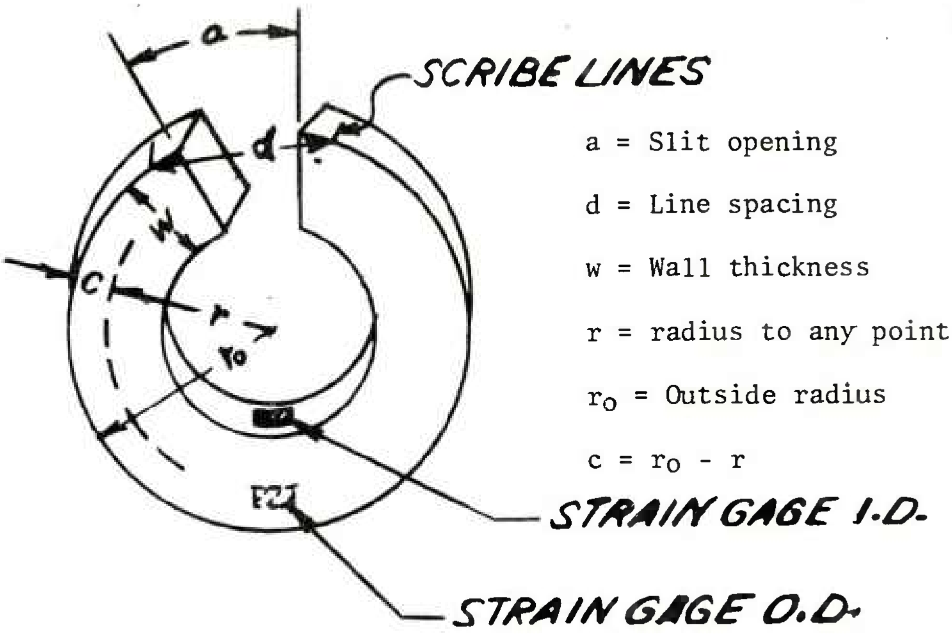
[2] Paul J. Cote and George P. Capsmalis, "Application of X-Ray Stress Measuring Techniques", Watervliet Arsenal Tech. Report WTV 7253, 1972.



a = Slit opening

d = Line spacing

w = Wall thickness

r = radius to any point

r_o = Outside radius

$c = r_o - r$

FIG. 5 - Schematic - Slit disc technique.

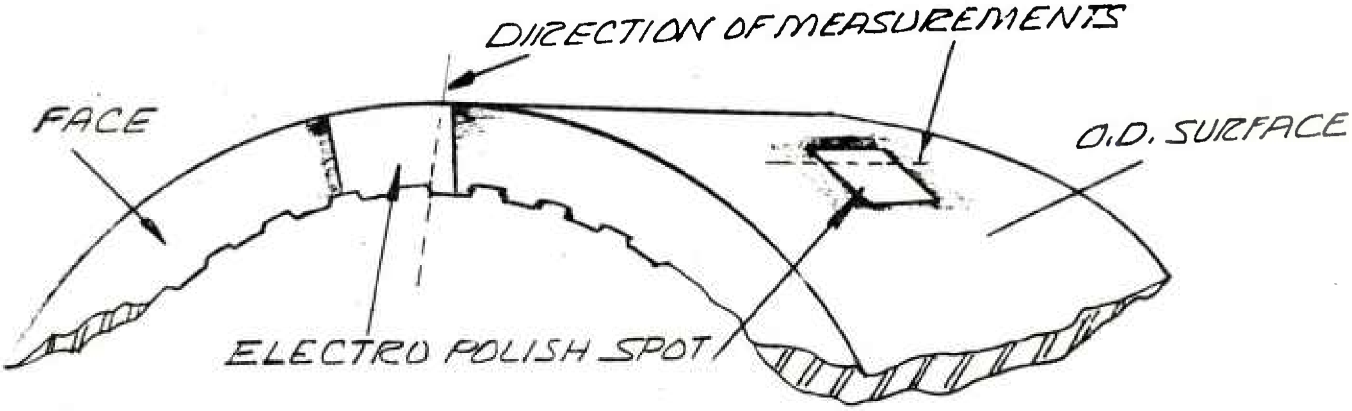


FIG. 6 - Schematic - X-ray diffraction technique.

representative forgings. In all cases, the inside diameter surface finish following cold forging, showed a marked improvement over the surface finishes that were machined prior to forging (Table 5).

Preform 14, which was honed to RMS 32, finished after cold forging to RMS 8 on the inside diameter. A closer examination of the rifling grooves revealed no longitudinal score marks, tears or gouges, which are commonly found in rifling grooves that are produced by the conventional machining methods such as solid rifling broaches and individual rifling cutters. In the absence of these marks, it is presumed that the surface stress concentration may be reduced substantially.

Preforms which were not honed showed a typical surface condition of circumferential grooves (machining marks), very shallow in depth, but visually noticeable with the naked eye. These grooves appeared to have grown in width during forging due to the fact that the workpiece material moves plastically in a longitudinal direction during working.

The starting surface finish on the O.D. for each of the cylinders was RMS 500. Forging produced flat spots around the cylinder in a helical fashion (Figure 7). The flat spots differ in size for each cylinder due to various reductions each tube received. In addition to the effect of varying cross section reduction, rotation speeds and feeds may also affect the size of the flats, as well as the helix condition.

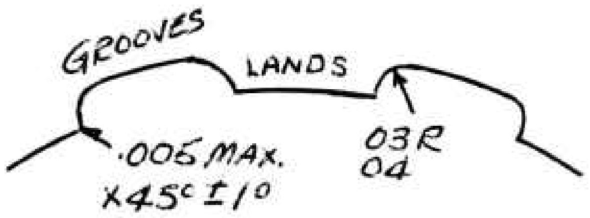
Three (3) of the cylinders were dimensionally inspected for rifling configuration, straightness, concentricity, ovality and general dimensions. The results for the lands and grooves of the forged cylinders are shown in Figure 8 and Table 6. Items which are enclosed

Table 5

Surface Finish - I. D.

Preform	Before Forging	After Forging
1	RMS 250	RMS 125
2	250	63
3	125	-
4	250	125
5	250	63
6	250	32
7	250	63
8	250	-
9	250	32
10	250	63
11	250	125
12	250	125
13	125	63
14	32	8
15	32	-
16	32	16

FIG. 7 - Cold rotary forged cylinder.



		GROOVE WIDTH				LAND WIDTH			
CYL. NO.	REDUCTION %	REQUIRED HIGH	REQUIRED LOW	ACTUAL HIGH	ACTUAL LOW	REQUIRED HIGH	REQUIRED LOW	ACTUAL HIGH	ACTUAL LOW
7	20	.21476	.20676	.2097	.2067	.154	.146	$\boxed{.1558}$	.1503
14*	30			.2175	.2100			.1500	.1470
14*	30			$\boxed{.2185}$	.2125			.1522	$\boxed{.1425}$
11	20			.2122	$\boxed{.2042}$			.1533	.1503

*Different locations in cyl. 14.

☐ Exceeded tolerance requirement

FIG. 8 - Rifling dimensional inspection.

Table 6

Bore Size and Ovality

Forging #14

	Land(2)		Groove(3)	
Location(1)	0°	90°	0°	90°
4"	-.0005	+.0002	+.0001	-.0003
6"	-.0006	+.0003	+.0005	+.0001
8"	-.0007	±.0000	-.0004	-.0006
10"	-.0010	-.0003	±.0000	-.0001
12"	±.0000	+.0007	+.0008	+.0006
14"	-.0010	±.0000	-.0005	-.0010
16"	-.0009	-.0001	-.0005	-.0006
18"	-.0011	-.0007	-.0007	-.0012
20"	-.0014	-.0006	-.0002	-.0002

(1) From starting end of the cold forging operation

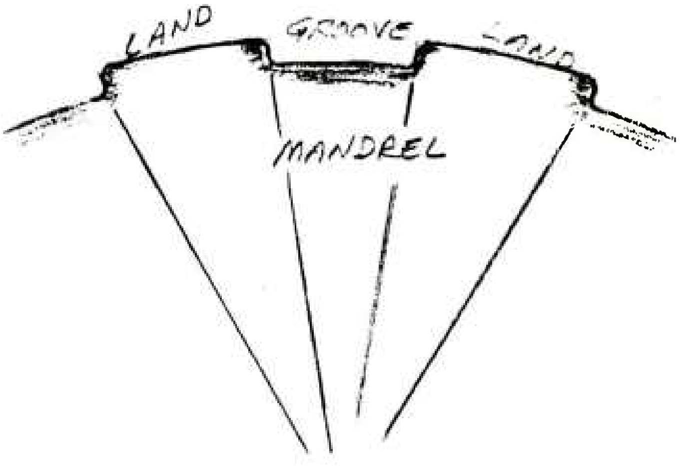
(2) Variation from base diameter of 4.1340"

(3) Variation from base diameter of 4.2080

represent dimensions for lands and grooves which have exceeded the tolerance limits. Figure 9 shows the sizes for the lands and the grooves which were machined on the forging mandrel.

In comparing the forging dimensions (Figure 8) with the mandrel dimensions (Figure 9), the groove width, on the forging mandrel, is larger in size than its counterpart, the land on the forged cylinder, due to spring back. In designing mandrels, it is necessary to consider the elastic limits of both the mandrel material and cylinder material. Some of the variance in dimensions in the forgings inspected may be attributed to the fact that although their yield strengths ranged from 108,000 psi to 156,000 psi, and with a range of elastic limits, all were forged using the same mandrel, with no adjustment for variations of the elastic limits for each preform.

The I.D. measurements shown in Table 6 for Forging #14 represent two readings, 90° apart. The results of these inspections show that the bore is slightly undersize. This situation could be corrected with an adjustment in the mandrel location. The mandrel used has a tapered O.D. which allows for an adjustment in the diameter of the mandrel with respect to the hammers and the preform. The mandrel is positioned under the hammers at the location which will produce, after spring back, the required I.D. The mandrel is fixed in location and free to float radially. The smaller end of the mandrel is the leading edge. Moving the mandrel longitudinally into the hammers increases the bore in the forged cylinder. The results for bore ovality shown in Table 6 are within tolerance limits. The straightness



FORGING MANDREL INSPECTION

Land Width		Groove Width	
High	Low	High	Low
.1975	.1970	.1605	.1525

FIG. 9 - Forging mandrel inspection.

results of Tube #14 (Table 7) are within acceptable limits.

The rifling helix angle on the forging accurately reproduced the helix angle machined on the forging mandrel (Figure 10). However, a deviation from the desired helix of the finished tubes was encountered. Because of the time and cost, it was impossible to redesign and modify the mandrel. However, the dimensional data will be used to produce future mandrels.

The inspection revealed a slight discrepancy in the rifling configuration, particularly in the chamfer on each side of the lands. These chamfers were checked at various locations; all failed to meet drawing requirements. Close examination of these chamfers, using a comparator, showed them to be incomplete on the lands. There are several possible causes for this problem. One possible cause may be excessive reduction. During forging the metal may be forced away from the groove radii. A second possibility is that the feed rate of the material through the hammers may have been too fast, thereby not allowing the metal to flow or remain in the corners before the hammer blow has expended its energy. The inability to fill the rifling may be attributed to the hammer design or to the non-oscillatary chuckhead, and requires further study.

Mechanical Testing

As-Forged - Test data for the cylinders, as-forged, are shown in Table 8. It had been anticipated that an increase in yield strength would be realized from the cold forging. In most cases, a small increase in longitudinal yield strength did occur but in two cases the yield strength

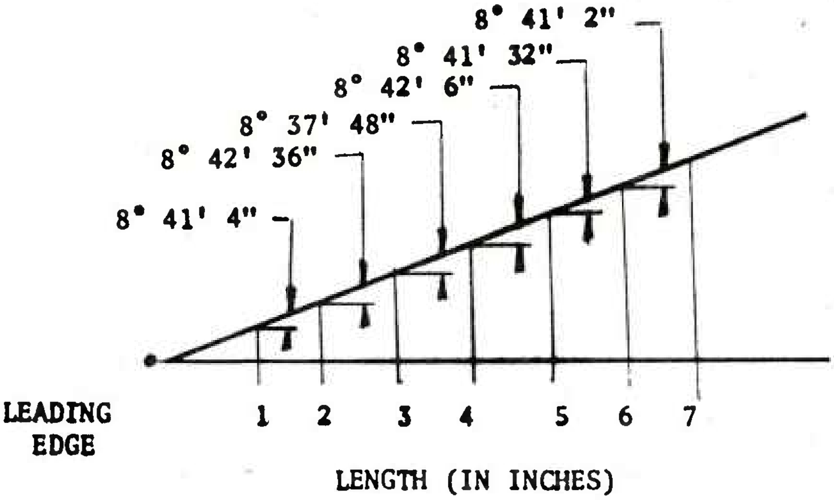
TABLE 7

BORE STRAIGHTNESS

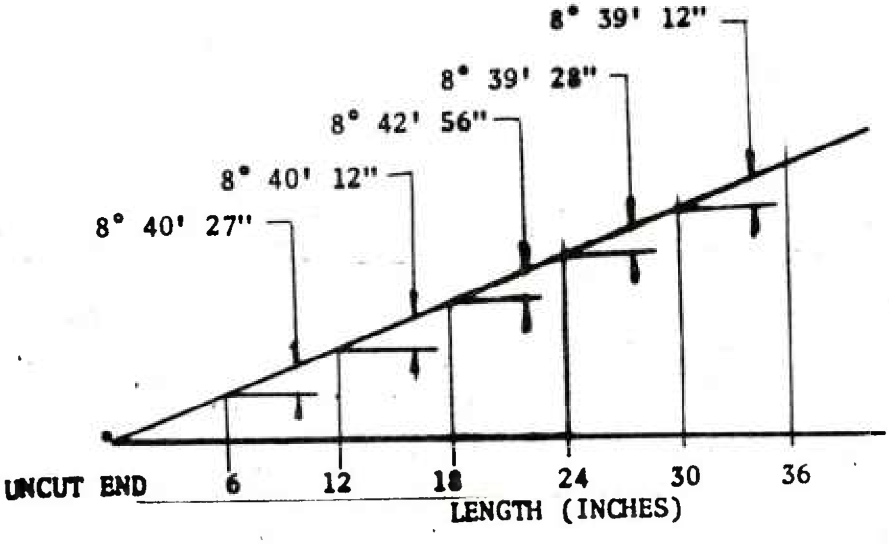
FORGING #14

LOCATION	ERROR (MILS)	LOCATION	ERROR (MILS)
0	-.000	14"	-.016
1"	-.002	15	-.015
2	-.005	16	-.014
3	-.007	17	-.013
4	-.009	18	-.012
5	-.011	19	-.012
6	-.012	20	-.012
7	-.014	21	-.010
8	-.015	22	-.009
9	-.016	23	-.008
10	-.016	24	-.007
11	-.017	25	-.006
12	-.017	26	-.006
13	-.017	27	-.007

NOTE: Locations from the leading edge of cold forging.



Helix Angle for the Rifled Mandrel



Helix Angle Produced by Rifled Mandrel

FIG. 10 - Helix angle of rifling - forging and mandrel.

TABLE 8

Mechanical Properties-As-Forged

	Transverse				Longitudinal			
Forging	Y.S.	RA	$Cv^{(1)}$	$Cv^{(2)}$	Y.S.	RA	$Cv^{(1)}$	$Cv^{(2)}$
1	119 ksi	53%	10 ft-lbs	46 ft-lbs	148 ksi	64%	15 ft-lbs	75 ft-lbs
	103	58	9	40	137	63	14	69
2	115	50	10	46	131	65	16	81
	94	53	9	40	118	65	15	75
3	136	55	9	40	161	58	12	58
	110	52	8	34	157	60	12	58
4	122	53	9	40	150	65	15	75
	108	51	9	40	137	65	14	69
5	142	52	8	34	167	61	12	58
	115	49	7	29	155	64	12	58
6	112	49	10	46	125	58	16	81
	97	50	8	34	121	60	14	69
7	125	53	9	40	145	64	14	69
	103	54	9	40	135	64	15	75
8	109	61	12	58	130	62	16	81
	66	55	11	52	120	63	16	81

TABLE 8 (continued)

Mechanical Properties-As-Forged

Forging	Transverse Y.S.	Transverse RA	Transverse Cv(1)	Transverse Cv(2)	Longitudinal Y.S.	Longitudinal RA	Longitudinal Cv(1)	Longitudinal Cv(2)
9	110 ksi	49%	9 ft-lbs	40 ft-lbs	133 ksi	59%	17 ft-lbs	87 ft-lbs
	93	50	7	29	123	59	14	69
10	107	56	11	52	132	63	16	81
	89	53	10	46	119	68	15	75
11	131	44	7	29	171	62	12	58
	113	44	7	29	154	63	12	58
12	105	51	9	40	127	63	15	75
	84	55	9	40	125	63	15	75
13	129	47	9	40	148	63	14	69
	99	40	8	34	141	62	14	69
14	141	44	-	-	169	57	-	-
	110	46	-	-	161	57	-	-
15	125	49	8	34	167	63	11	52
	99	47	8	34	160	62	11	52
16	114	50	-	-	153	59	-	-
	107	52	-	-	-	-	-	-

1. Sub-size impact data at -40°F.
2. Sub-size data converted to full-size data using Figure 11.

decreased slightly. Generally, it appears that the yield strength of the higher yield strength cylinders, when cold forged, decreased, whereas in the lower yield strength materials, yield strength increased. This increase in longitudinal yield strength, after forging, indicates a slight degree of strain hardening.

In the transverse direction, the yield strength was reduced after cold forging. This apparently is a manifestation of the bauschinger effect, in which the yield strength is lower in compression after having been deformed in tension, and vice versa. During the forging operation, the metal is plastically deformed in compression in the hoop (transverse) and radial directions, but in tension in the longitudinal direction. Thus, transverse tensile testing in the hoop direction involves a re-yielding in a direction opposite to the original deformation, and, therefore, a decrease in strength.

In both orientations, there was generally a wide range in the strength values obtained. For example, forging #5 showed a range of 27 ksi in the transverse orientation, and forging #11 showed a range of 17 ksi in the longitudinal orientation. There is no explanation for this observation. However, it may be an indication of uneven working of the material. The range was generally larger in the transverse orientation than in the longitudinal orientation.

In all the tubes, standard and sub-size Charpy bars were taken prior to forging (Table 1). After forging, only sub-size bars were possible because of the thin wall section. To determine a relationship between the standard and sub-size tests, the data were plotted as shown on Figure 11. This plot indicated that a correlation existed between standard and sub-size Charpy bars. A simple linear regression, using the method of least squares was fit to the data. A relatively high correlation coefficient of .99 was obtained. Using this graph, the sub-size impact results were converted to full-size data. The data are shown in Table 8. In general, in the transverse orientation, a slight decrease in toughness is seen even though the yield strength is lower.

Thermal Treated - To recover the loss in yield strength after rotary forging, a series of thermal treatments were evaluated. These included temperatures of 650°F, 800°F and 1000°F, with soaking times of 2 hours. Limited testing with the 650°F treatment showed an insignificant change in yield strength. Results for the 800°F and 1000°F thermal treatment (Tables 9 and 10) showed an increase in yield strength for each treatment combination as well as an apparent decrease in the range of yield strength. However, the most significant increase was realized at 800°F. In all cases, the transverse yield strength was recovered to slightly above the preform yield strength. The longitudinal yield strength was generally unaffected by the thermal soak except in two cases where a decrease was observed. In general, the toughness showed no effect from the thermal treatment.

Considering the transverse situation, it is most likely that the thermal treatment relieved the condition produced by the bauschinger

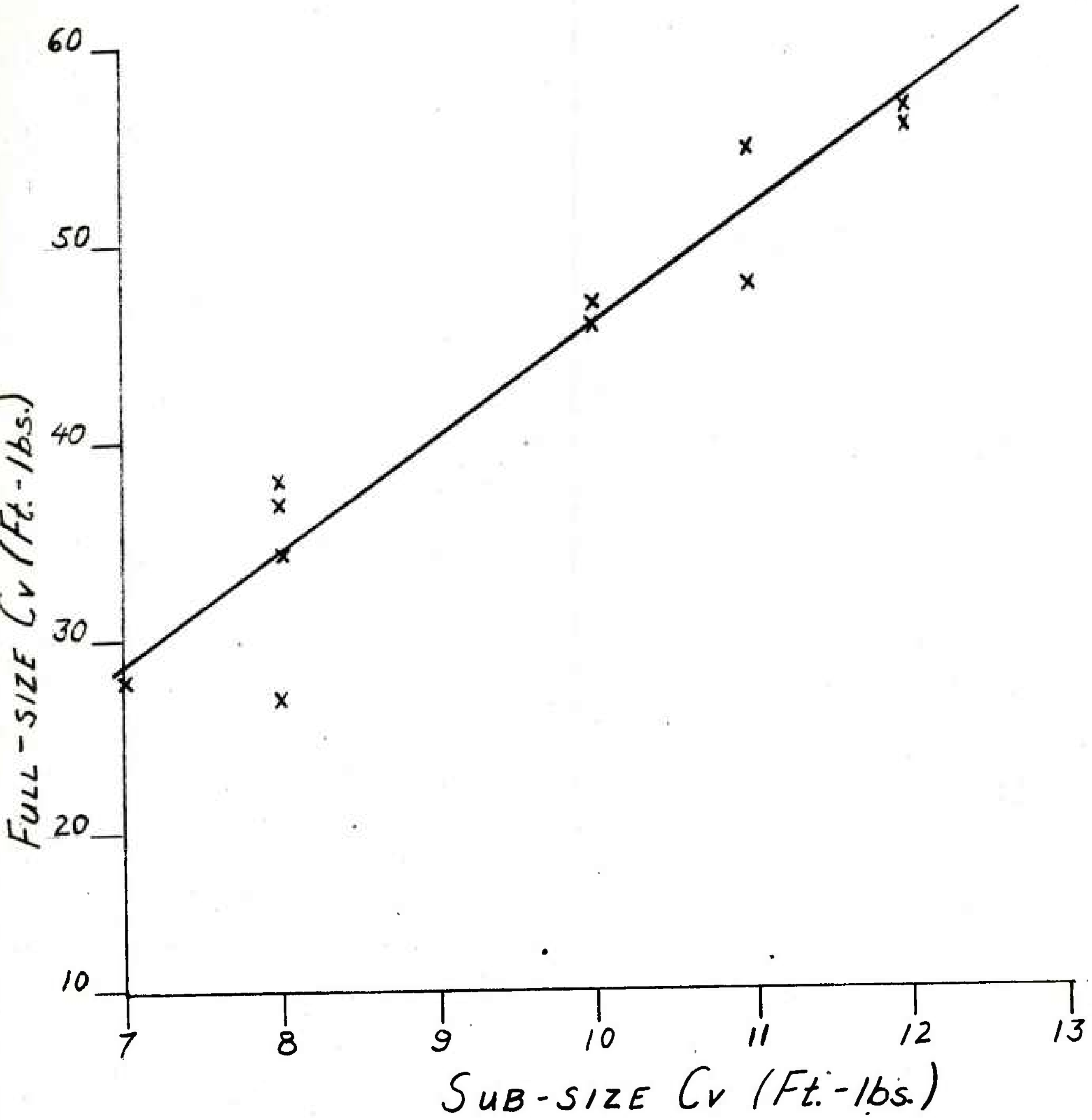


FIG. 11 - Full-size impact toughness vs. sub-size impact toughness.

TABLE 9

Mechanical Properties-Thermal Treated (800°F)

	Transverse				Longitudinal			
Forging	Y.S.	RA	$Cv^{(1)}$	$Cv^{(2)}$	Y.S.	RA	$Cv^{(1)}$	$Cv^{(2)}$
1	141 ksi	53%	10 ft-lbs	46 ft-lbs	146 ksi	65%	15 ft-lbs	75 ft-lbs
	137	54	9	40	144	64	15	75
2	127	55	10	46	131	65	17	87
	122	56	10	46	125	64	16	81
3	152	53	10	46	164	64	12	58
	147	53	8	34	161	64	12	58
4	139	49	9	40	148	65	15	75
	136	52	8	34	143	64	15	75
5	157	50	7	29	167	63	12	58
	155	49	7	29	163	62	12	58
6	138	48	8	34	147	58	17	87
	132	44	6	23	144	61	17	87
7	143	47	9	40	148	65	17	87
	137	53	9	40	141	62	15	75
8	134	47	12	58	128	67	17	87
	113	40	11	52	124	67	16	81

TABLE 9 (continued)

Mechanical Properties-Thermal Treated (800°F)

	Transverse				Longitudinal			
Forging	Y.S.	RA	$C_V^{(1)}$	$C_V^{(2)}$	Y.S.	RA	$C_V^{(1)}$	$C_V^{(2)}$
9	134 ksi	46%	8 ft-lbs	34 ft-lbs	142 ksi	62%	- ft-lbs	-ft-lbs
	114	51	8	34	137	60	-	-
10	128	53	10	46	130	63	17	87
	123	56	10	46	128	65	17	87
11	163	46	7	29	171	61	12	58
	159	47	7	29	162	62	12	58
12	134	50	9	40	138	64	-	-
	131	50	8	34	136	64	-	-
13	148	48	9	40	156	62	14	69
	143	47	8	34	149	63	14	69
14	161	62	9	40	-	-	10	46
	147	50	9	40	-	-	10	46
15	151	53	9	40	166	64	10	46
	148	52	8	34	163	64	9	40
16	161	49	-	-	-	-	-	-
	161	50	-	-	-	-	-	-

1. Sub-size impact data at -40°F.
2. Sub-size data converted to full-size data using Figure 11.

TABLE 10

Mechanical Properties - Thermal Treated (1000°F)

	Transverse				Longitudinal			
Forging	Y.S.	RA	$Cv^{(1)}$	$Cv^{(2)}$	Y.S.	RA	$Cv^{(1)}$	$Cv^{(2)}$
1	140 ksi	55%	-	-	140 ksi	65%	-	-
	138	55	-	-	133	63	-	-
2	120	56	-	-	127	66	-	-
	120	55	-	-	123	64	-	-
3	151	54	-	-	152	65	-	-
	150	52	-	-	153	63	-	-
4	136	52	-	-	143	65	-	-
	135	49	-	-	139	65	-	-
5	154	49	-	-	155	63	-	-
	150	47	-	-	154	63	-	-
6	136	50	-	-	140	65	-	-
	132	49	-	-	140	63	-	-
7	139	51	-	-	140	64	-	-
	138	51	-	-	140	65	-	-
8	115	60	-	-	129	65	-	-
	114	60	-	-	120	67	-	-
9	134	43	-	-	139	64	-	-
	134	50	-	-	133	63	-	-

TABLE 10 (cont'd)

Mechanical Properties - Thermal Treated (1000°F)

	Transverse				Longitudinal			
Forging	Y.S.	RA	Cv(1)	Cv(2)	Y.S.	RA	Cv(1)	Cv(2)
10	123 ksi	51%	-	-	125 ksi	65%	-	-
	123	54	-	-	123	65	-	-
11	158	46	-	-	159	63	-	-
	157	49	-	-	158	61	-	-
12	128	50	-	-	131	61	-	-
	127	53	-	-	128	62	-	-
13	141	46	-	-	147	62	-	-
	141	40	-	-	146	64	-	-
14	158	47	-	-	-	-	-	-
	155	53	-	-	-	-	-	-
15	149	52	-	-	155	63	-	-
	148	49	-	-	154	62	-	-
16	153	53	-	-	-	-	-	-
	152	50	-	-	-	-	-	-

1. Sub-size impact data at -40°F.
2. Sub-size data converted to full-size data using Figure 10.

effect, thereby restoring the material to its original yield strength. It is possible that with longer times or higher temperatures, higher yield strengths may have been obtained. However, it was felt that the T-t combinations utilized were practical and adequate.

Residual Stresses - The slitting technique for residual stress measurement does not determine the specific stress distribution in the test specimen or for the full length tube. However, it does provide a comparative measure of the overall magnitude of any stress present in the disc even though particular values of stress at any given point cannot be determined. Table 11 shows the residual stress determined by the slitting techniques. As shown, two estimates of the residual stress are obtained, viz., one, which is based on the strain gages, and a second, which is based on the change in spacing between the two scribed lines (Figure 5). In most cases, the two techniques provided similar residual stress data. Table 11 indicates that some of the specimens had compressive stresses whereas others had tensile stresses. In all cases, however, the values were relatively low.

The x-ray diffraction test results (Table 12) for discs that were removed adjacent to the discs cited in Table 11, revealed in some cases, residual stresses of the opposite sign to those obtained by slitting. The wide range of stress values observed by x-ray diffraction suggests a highly non-uniform stress distribution throughout the tubes. The results shown for specimens 8 and 15 are opposite in direction and

TABLE 11

Residual Stresses-Slitting Technique

Forging	Condition	Scribed Line		Strain Gage	
		Strain (μin/in)	Stress (ksi)	Strain (μin/in)	Stress (ksi)
1	800° TT	+130	-3.9	+140	-4.2
2	800°	+250	-7.5	+230	-6.9
3	800°	-60	+1.8	-60	+1.8
4	800°	+220	-6.6	+230	-6.9
5	800°	+350	-10.5	+350	-10.5
6	800°	-50	+1.5	-50	+1.5
7	800°	+240	-7.2	+230	-6.9
8	800°	+240	-7.2	-	-
9	800	0	0	-	-
10	800°	+240	-7.2	+290	-8.7
11	800°	+100	-3.0	+70	-2.1
12	800°	+220	-6.6	+220	-6.6

TABLE 11 (continued)

Residual Stresses-Slitting Technique

Forging	Condition	Scribed Line Strain (μ in/in)	Scribed Line Stress (ksi)	Strain Gage Strain (μ in/in)	Strain Gage Stress (ksi)
13	800° TT	0	0	-20	+0.6
14	As-Forged	+406	-12.1	+397	-11.9
14A	650° TT	+280	-8.4	+266	-8.0
14B	800°	+267	-8.0	+259	-7.8
14C	1000°	+111	-3.3	+90	-2.7
15	800°	-360	+11.8	-320	+9.6
16	As-Forged	+192	-5.8	+143	-4.3
16A	650° TT	+231	-6.9	+214	-6.4
16B	800°	+147	-4.4	+118	-3.5
16C	1000°	+111	-3.3	+203	-6.0

TABLE 12

Residual Stress-X-Ray Diffraction

Forging	Condition	Residual Stress	Location
1	800° TT	-3.1	O.D. Surface
2	800°	-13.2	"
3	800°	-6.9	"
4	800°	-2.0	"
5	800°	+10.2	"
6	800°	-8.2	"
7	800°	-	-
8	800°	-23.4	"
9	800°	+18.4	"
10	800°	-11.0	"
11	800°	-5.0	"
12	800°	-2.0	"
13	800°	+9.2	"
14B	800°	-5.0	Face Near O.D.
14B	800°	+5.0	Face Near I.D.
14C	1000°	-6.1	Face Near O.D.
14C	1000°	+5.0	Face Near I.D.
15	800°	+23.5	O.D. Surface
16B	800°	-8.3	"
16B	800°	+9.0	Face Near I.D.
16C	1000°	-9.2	O.D. Surface
16C	1000°	+5.0	Face Near I.D.

higher than the other tubes. These two specimens were sectioned from the only tubes that were cold forged without a mandrel for a back-up

CONCLUSIONS

The work showed that it is possible to cold rotary forge thin wall gun tubes, finishing the inside diameter, including rifling grooves. Although not every dimensional requirement was met, the results indicate that, with further work, the stringent dimensional requirements can be achieved. It should be noted that these tubes were forged on an SX35 machine which did not have an oscillating chuckhead which could have contributed to the dimensional inaccuracies in the rifling.

The test results showed a general trend toward a decrease in transverse yield strength after cold forging. The amount of decrease is dependent on the starting yield strength, i.e., the higher the starting yield strength, the greater the decrease. To recover the losses, a 800°F thermal treatment was incorporated. It is not certain that this is the optimum temperature but it did serve the purpose of establishing a treatment which was both practical and adequate. It is concluded that thermal treatment should be incorporated after cold rotary forging of gun steel, with further studies to determine optimum treatments.

The two methods for measuring the residual stresses of a cold forged tube show the stress distribution to be highly non-uniform in the as-forged and thermal treated conditions. Because of the magnitude of the stresses, no determination can be made as to their effects on tube fatigue life.