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TECHNICAL REPORT ARCCB-TR-92049

APPLICATIONS OF ADVANCED MATERIALS TO CANNON PRODUCTION

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DECEMBER 1992

US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE December 1992	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE APPLICATIONS OF ADVANCED MATERIALS TO CANNON PRODUCTION	5. FUNDING NUMBERS AMCMS No. 728011E620035 PRON No. M76F2023M71A
6. AUTHOR(S) Edward Troiano	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Benet Laboratories, SMCAR-CCB-TL Watervliet, NY 12189-4050	8. PERFORMING ORGANIZATION REPORT NUMBER ARCCB-TR-92049
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Close Combat Armaments Center Picatinny Arsenal, NJ 07806-5000	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report summarizes various techniques that were investigated as possible manufacturing methods to produce advanced alloy gun tubes. Three materials, titanium alloy (Ti 38644), iron base alloy (AF 1410), and aluminum matrix-silicon carbide fiber metal matrix composites (Al-SiC MMC), were studied for possible application to cannon production techniques. Techniques of manufacture included induction coil shrink fitting, cold rotary forging, and manufacture in place. Material property investigations were undertaken in order to determine key critical parameters necessary to design gun tubes with the previously mentioned materials.

14. SUBJECT TERMS Ti 38644, AF 1410, Al-SiC MMC, Induction Coil, Shrink Fitting, Cold Rotary Forging, Stiffeners, Laser Welding, Typing Moments	15. NUMBER OF PAGES 26
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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PROJECT BACKGROUND/OBJECTIVE

Existing guidelines are not well established for manufacturing gun tubes with new advanced alloy jacket materials, such as titanium alloy (Ti 38644), iron base alloy (AF 1410), and aluminum matrix-silicon carbide fiber metal matrix composites (Al-SiC MMC). The ultimate goal in utilizing these advanced materials is to reduce muzzle end weight without sacrificing component life, component reliability and accuracy, or cost. Decreasing muzzle weight also lessens imbalance of the weapon tipping parts. This study concentrated on applying these materials as a jacket to a ten-foot muzzle section of a 120-mm gun tube. The exact solution utilized to manufacture a gun tube with the previously mentioned materials depends on the material used. Methods investigated included press fitting, shrink fitting, and manufacturing in place, i.e., winding a composite jacket directly on the muzzle end of the gun. Additional information on advanced materials can be found in References 1 through 5.

Since the alloys used in this study were relatively new, there was only a limited amount of available textbook data. Therefore, some extensive investigation of high temperature tensile properties was undertaken. For example, Ti 38644 and AF 1410 were studied by thermally simulating firing cycles from room temperature through 800°F.

MATERIALS INVESTIGATED

Ti 38644 (ref 1) was produced and procured from Reactive Metals, Inc., Niles, Ohio. This material was chosen because it is 38 percent lighter than steel, and it is capable of developing 160 Ksi yield strength at room temperature. The combination of strength and weight makes Ti 38644 an attractive choice for the application.

AF 1410 was produced by Universal-Cyclops, Titusville, Pennsylvania, and procured through National Forge, Inc., Irvine, Pennsylvania. AF 1410 is an extremely high strength, high toughness ferrous-based alloy that exhibits exceptionally good properties even under the most severe temperature extremes. Although the material possesses a *density similar to that of gun steel*, it was felt that its high strength could be utilized to create a thinner walled, and therefore, a lighter weight gun tube.

Al-SiC MMC (ref 2) was investigated under contract with AVCO Specialty Materials, Lowell, Massachusetts. Various lay-ups of fiber orientation and interlayer materials were investigated for an optimum configuration. Metal matrix composites offer good strength to weight ratios and tailorable properties.

PROBLEM AREAS

The use of each of these materials posed problems that needed to be addressed. The exact solution utilized to manufacture a gun tube from each of these materials was highly dependent on the material. Certain conditions, such as heat treatment and consolidation techniques for the composite, needed to be established.

Concerns were expressed when suggesting the use of titanium alloys as jacket material. For example, titanium possesses approximately half the flexural modulus of steel. How, then, could the droop of the tube be minimized? The solution was to laser weld stiffeners (see Figure 1) to the external surface of the tube. The stiffeners would add only a minimal amount of weight, while adding considerably to the stiffness of the tube. Although the practice of welding material to the surface of a gun tube is not typically condoned, it did provide a possible solution to the problem. If laser welding could not be used, the concept of stiffeners would still be a viable solution. The stiffeners can be produced by extruding them directly on the titanium jacket and shrink fitting as explained in the next section.

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Another problem with Ti 38644 is its complex time and temperature heat treatment profiles and its incompatibility with gun steel. Gun steel is typically tempered in the 1000° to 1100°F range, while the titanium alloy is an age-hardened material, typically aged at 900°F for 11 hours. This aging treatment would have a detrimental effect on the steel properties if the two were heat treated together after manufacturing. Therefore, the two materials need to be heat treated separately to their respective optimum levels. Such a complexity adds to the problem of machining because the materials need to be fully hardened prior to machining.

A negative feature when considering AF 1410 is that the density of the material is approximately the same as the gun steel it will be replacing. Since the goal is to attain a lighter weight tube, why then would one replace the gun steel with a material of the same density? Since the strength and toughness of AF 1410 are superior to that of gun steel, the possibility exists for a thinner-walled tube, and hence, a lighter weight tube. However, due to program cutbacks initiated at this stage of the project, the jacketed AF 1410 tube was never manufactured.

Many areas of concern were expressed when considering MMC. For example, how would an MMC jacket be fabricated on a steel liner? Two possible methods were investigated, shrink fitting and fabricating in place. Unfortunately, both of these methods pose problems. Shrink fitting is difficult to accomplish because of the minimal coefficient of thermal expansion (CTE) of SiC. Since the CTE is minimal, the material must be heated to a higher temperature in order to attain the needed expansion. However, at higher temperatures, the aluminum will have a tendency to flow more easily, making thermal fabrication difficult. The second method of fabricating the jacket on the steel liner also poses problems. MMC must be consolidated after fabricating in order to reduce voids. Typically, consolidation techniques are done under high pressure and high temperature. As previously mentioned, the CTE of the Al-SiC MMC is magnitudes of times smaller than the steel portions. When the material is heated (during consolidation), the steel and MMC jacket expand, and the steel is actually forced into the MMC jacket. At this elevated temperature, there is intimate contact at the interface between the two materials. On cooldown the steel returns to its original dimensions, and all voids, etc. that were removed from the MMC during consolidation accumulate at the interface. This is an undesirable condition, since there is no contact at the interface after cooldown, and therefore, the load-carrying capability of the tube is greatly reduced.

APPROACH

Method of Manufacturing with Ti 38644

Traditionally, jacketed tubes have been produced by placing the jacket on a liner in order to provide thick-walled sections and favorable residual stresses. The objectives of this project, as previously stated, are to address tube weight as well as tipping moment considerations. In the past, gun tubes have been shrunk fit together by heating the jacket in a conventional oven until a desired temperature is reached. This temperature provides enough radial dilation of the jacket material to slide it over the liner. Once this temperature is reached, the jacket is wrapped in insulating material and transported to the liner, where they are shrunk together. During the time when the jacket is removed from the oven until the actual shrink fitting takes place, a considerable amount of heat is lost from the jacket. This loss of heat causes the radial expansion of the jacket to decrease, and increases the potential for the jacket to "bind up" on the liner during manufacturing.

In order to minimize the possibility of "bind up," an induction coil shrink fit tower was designed (see Figure 2). The apparatus utilizes induction heating as opposed to conventional oven heating. Also, the heated jacket remains in place, that is, it does not need to be transported to the liner. As opposed to the hot jacket being transported to the colder liner, the colder liner is transported to the hot jacket. This minimizes any thermal losses caused as a result of transportation, and maintains the desired amount of radial dilation needed for manufacturing. A uniform soak temperature was obtained by cycling the current on and off during heating. The cyclic heating of the titanium jacket took approximately 4 hours (at 325 amps) to reach a temperature of 750°F. This temperature provided sufficient radial dilation of the jacket to easily slide over the liner. The method and details of the shrink fitting process are outlined in Appendix A.

Cold rotary forging the titanium jacket onto the steel liner was the second method of manufacturing with Ti 38644 investigated. The text fixture in Figure 3 was designed so a full-size prototype could be forged. Since the CTEs (the time/temperature profiles) of steel and titanium are not compatible, cold rotary forging of the test fixture was accomplished at room temperature, as seen in Figure 4. During forging, a water bath was applied to the workpiece to minimize any thermal effects caused by working. A 30 percent reduction in area was accomplished in a single pass on an SPF 55 GFM rotary forge. Property measurements were evaluated in the pre- and post-forged conditions, and are discussed below. Evaluation of the steel/titanium interface after cold rotary forging indicated that this method of manufacturing could not be used because only random contact was made at the interface. As mentioned earlier, if intimate contact is not made at the steel/titanium interface, the load-carrying capability of the composite tube is greatly reduced.

Previously, the concept of a stiffened tube was evaluated as a possible solution to the question of flexural stability. Under contract with EBTEC, Agawam, Massachusetts, several short tube segments were fabricated with stiffeners welded to them. During this contract, specific guidelines were to be established for laser welding stiffeners to tube sections. The development of processing parameters was to commence with the production of a full-length (105-mm M68) all steel, proof-of-principle, LASER (Long Axially Stiffened Experimental Rifle) gun tube, Figure 1. A 105-mm tube was selected because of economic reasons and because EBTECs proposed workstation would have difficulty accepting the size and weight of a 120-mm tube. Specification LCB 8-85 was submitted and went out for quotation to procure a 5 kW, CO_2 pulsed laser. The laser would be capable of welding, heat treating, cutting, and drilling. The specification received four prospective bidders. However, due to ManTech Program cutbacks, a majority of the funding needed to purchase the laser was retracted and the procurement action terminated.

Method of Manufacturing with Al-SiC MMC

Two methods of manufacturing with Al-SiC MMC were investigated. The first method involved press fitting the MMC jacket onto the liner, followed by mechanical autofrettage. The contractor supplied a jacket that was three thousandths of an inch larger in inside diameter than the steel liner it was going to be pressed onto. Although the jacket was larger at the contacting interface than the liner, frictional effect and the fact that the jacket was not perfectly straight, dictated that it would need to be pressed rather than simply slid onto the liner. The liner and jacket were then aligned, and a hydraulic press was used in an attempt to press the two together. A lead-based lubricant was applied to the steel in order to minimize friction at the interface. Upon manufacturing, the Al-SiC jacket was pressed several inches before binding on the steel liner. Further attempts to continue pressing resulted in severe deformation of the Al-SiC jacket. This test proved that press fitting would not be feasible at least under these conditions.

Manufacturing the Al-SiC in place (on a liner) was also investigated on fifteen small-scale prototype specimens. In this method, the Al-SiC jacket was actually wound on the steel liner, and consolidation of the Al-SiC took place while the jacket was on the steel liner. As stated previously, a gap was created at the jacket/liner interface during consolidation. It was felt that autofrettage after consolidation would aid in minimizing or eliminating this gap. Although this did help to minimize the gap, it did not eliminate it. Two full-scale prototype tubes were manufactured and fired at Aberdeen Proving Ground, Maryland. Because of the difficulties encountered in manufacturing the fifteen small-scale prototypes (ref 2), both tubes were wrapped with only hoop windings and no consolidation technique was utilized. The fifteen small-scale prototypes were manufactured with various lay-ups of hoop and axial plies, as well as different plasma-sprayed interlayer materials. These provided an array of manufacturing options that were evaluated for application to the full-scale model.

Property Measurement of Ti 38644

Under contract with Rensselaer Polytechnic Institute (RPI), Troy, New York, Ti 38644 was exposed to elevated temperature tensile testing by a Gleeble Model 1500. The Gleeble machine was originally designed at RPI to investigate the thermal effects caused by welding, however, it simulates the effects of thermal cycling quite well. The results of high temperature tensile testing are outlined in Table 1 and are presented graphically in Figures 5 through 7. Both longitudinal and transverse samples were investigated. The data suggest that the material exhibits adequate strengths up to the maximum working temperature of 800°F. Charpy v-notch (CVN) specimens were also tested in this phase of the project. Samples were tested at -40°F from the transverse and longitudinal directions. Results of the transverse and longitudinal CVN testing indicated values ranging from 8.5 to 10.5 ft-lbs. As mentioned above, the titanium alloy was cold forged to investigate rotary forging as a possible method of manufacturing. Properties were measured to compare the pre-cold forged condition with the post-cold forged condition (ref 4). The ultimate tensile strength, yield strength, reduction in area, and CVN are outlined in Table 2 and shown graphically in Figures 8 through 11.

Property Measurement of AF 1410

AF 1410 was also studied under contract with RPI. The contract included investigation of tensile properties at elevated temperatures, age-hardening response, and microstructure (ref 5). Test results indicate that specimen orientation has little or no effect on the ultimate tensile strength, yield strength, and true fracture stress; however, it does have a significant effect on the percent reduction in area and the true fracture strain. The temperature dependency of Young's modulus was also investigated for the transverse and longitudinal directions. Young's modulus was shown to be dependent on the specimen orientation (longitudinal higher than transverse) and test temperature. Results of high temperature tensile testing of AF 1410 can be seen in Table 3, as well as Figures 12 through 14. Age-hardening testing indicates that optimum aging response takes place after 6 hours when held between 800°F and 1000°F.

CONCLUSIONS

This study has concentrated on investigating three materials, Ti 38644, AF 1410, and Al-SiC MMC, for future use in cannons and cannon components. Several important conclusions can be drawn from this program as follows:

- We have successfully demonstrated that induction coil shrink fitting can be utilized to manufacture jacketed cannon tubes.

- Although the impact strength of Ti 38644 is lower than desired, it can be used with a reasonable degree of confidence as a jacket material.

- Cold rotary forging of Ti 38644 is possible on the SPF 55 GFM rotary forge at Watervliet Arsenal. This method of manufacturing is a viable way of producing a titanium jacket to near net shape. If rotary forging is considered for producing titanium jackets, additional work is needed to assess the possibility of hot rotary forging, followed by heat treatment.

- AF 1410 possesses extremely high strength and ductility and is ideally suited not only for jacketed tubes but also for a mono-block design. This material should be given special consideration in the future if a more advanced material than gun steel is desired for gun tubes.

- Al-SiC MMC should also be considered as a candidate for a mono-block design. Its special features, such as high strength and low weight, make it extremely desirable for use in gun tubes. Although this material has many good features, no successful method of manufacture has been demonstrated. If this obstacle can be overcome, Al-SiC MMC should also be given special consideration in advanced gun tube designs.

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Table 1. Results of High Temperature Tensile Testing of Ti 38644

Orientation	Temperature (°F)	Ultimate Tensile Strength (Ksi)	0.1% Yield Strength (Ksi)	% Reduction in Area
Transverse	77	161	134	14.3
Transverse	400	160	132	11.6
Transverse	600	158	127	9.8
Transverse	600	157	123	11.6
Transverse	800	141	96	27.8
Transverse	800	144	111	29.4
Longitudinal	77	180	157	10.8
Longitudinal	200	167	140	21.4
Longitudinal	200	166	152	17.2
Longitudinal	400	171	142	25.3
Longitudinal	400	155	131	13.5
Longitudinal	600	144	114	13.5
Longitudinal	600	144	138	
Longitudinal	800	162	130	23.7
Longitudinal	800	140	106	26.0

Table 2. Comparison of Pre- and Post-Forging Mechanical Properties of Ti 38644

Orientation	Ultimate Tensile Strength (Ksi)	0.1% Yield Strength (Ksi)	% Reduction in Area	CVN (ft-lbs)
Pre-Forged Room Temperature Properties of Ti 38644				
Longitudinal	179	161	14	9.0
Longitudinal	178	159	13	8.5
Longitudinal	180	162	12	8.5
Longitudinal	177	159	12	9.0
Longitudinal	183	168	8	
Longitudinal	182	168	10	
Transverse	181	164	5	9.5
Transverse	179	162	6	11.0
Transverse	185	168	6	10.5
Transverse	184	165	5	10.0
Transverse	179	168	7	
Transverse	182	169	6	
Post-Forged Room Temperature Properties of Ti 38644				
Longitudinal	186	171	13	5.0
Longitudinal	193	177	13	5.0
Longitudinal	200	191	13	4.5
Longitudinal	191	180	10	5.5
Longitudinal	195	182	9	
Longitudinal	198	186	9	
Transverse	201	168	4	4.0
Transverse	188	152	10	4.0
Transverse	175	140	15	4.5
Transverse	179	145	13	4.0
Transverse	178	146	6	
Transverse	189	155	11	

Table 3. Results of High Temperature Tensile Testing of AF 1410

Orientation	Temperature (°F)	Ultimate Tensile Strength (Ksi)	0.1% Yield Strength (Ksi)	% Reduction in Area
Transverse	77	256	205	66.4
Transverse	77	251	207	66.9
Transverse	77	253	210	66.8
Transverse	200	240	188	67.2
Transverse	200	235	194	67.0
Transverse	400	229	179	67.9
Transverse	400	220	181	67.4
Transverse	600	210	164	68.3
Transverse	600	208	160	67.7
Transverse	800	198	138	68.8
Transverse	800	201	144	67.7
Longitudinal	77	246		71.6
Longitudinal	77	244	194	70.6
Longitudinal	77	264	208	71.4
Longitudinal	200	232	181	71.8
Longitudinal	200	232	196	71.7
Longitudinal	400	220	191	72.8
Longitudinal	400	222	192	73.0
Longitudinal	600	208	164	73.1
Longitudinal	600	210	166	72.9
Longitudinal	800	196		72.9
Longitudinal	800	192	134	73.0

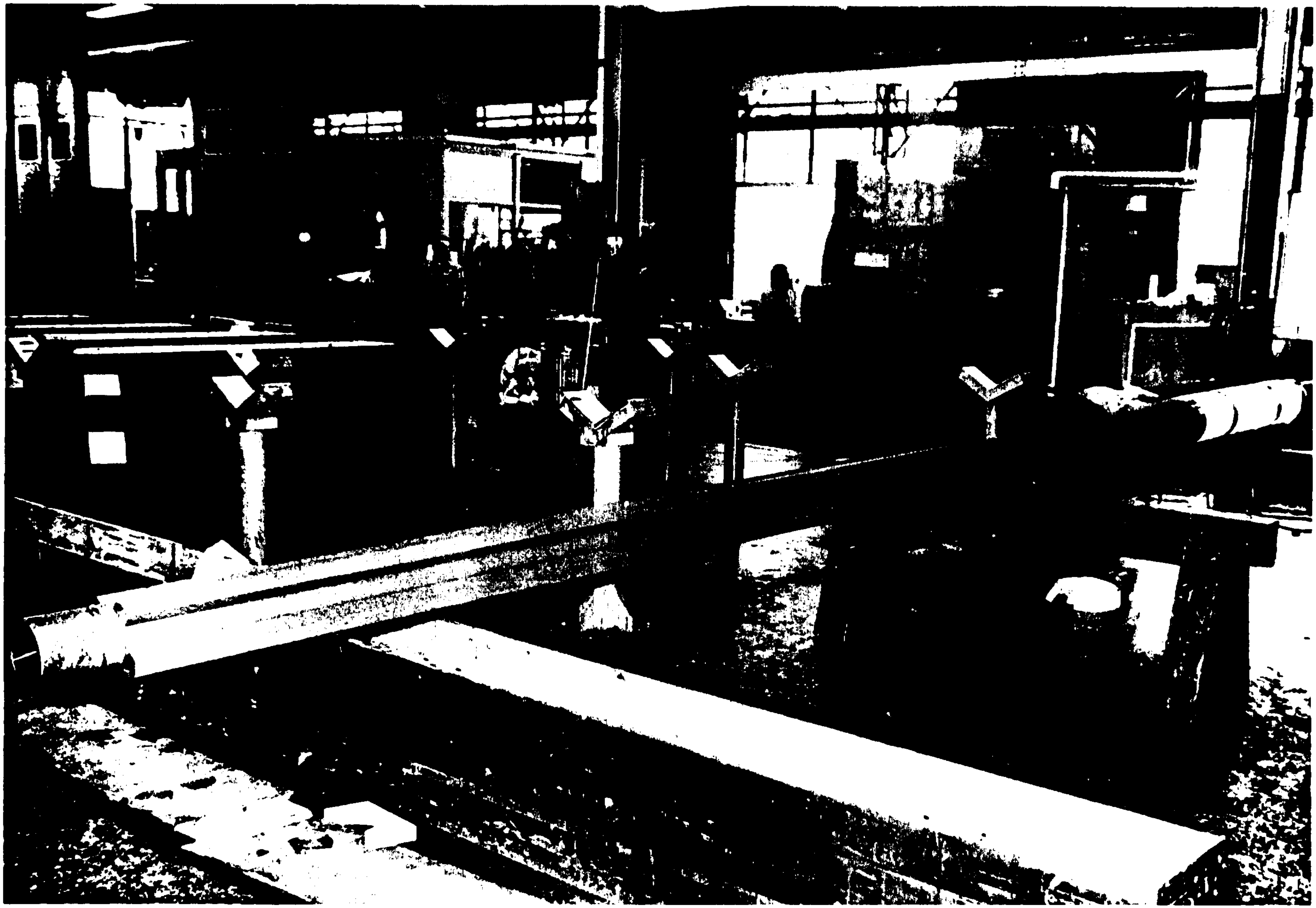

Figure 1. Laser 105 proof-of-principle gun tube with stiffeners.

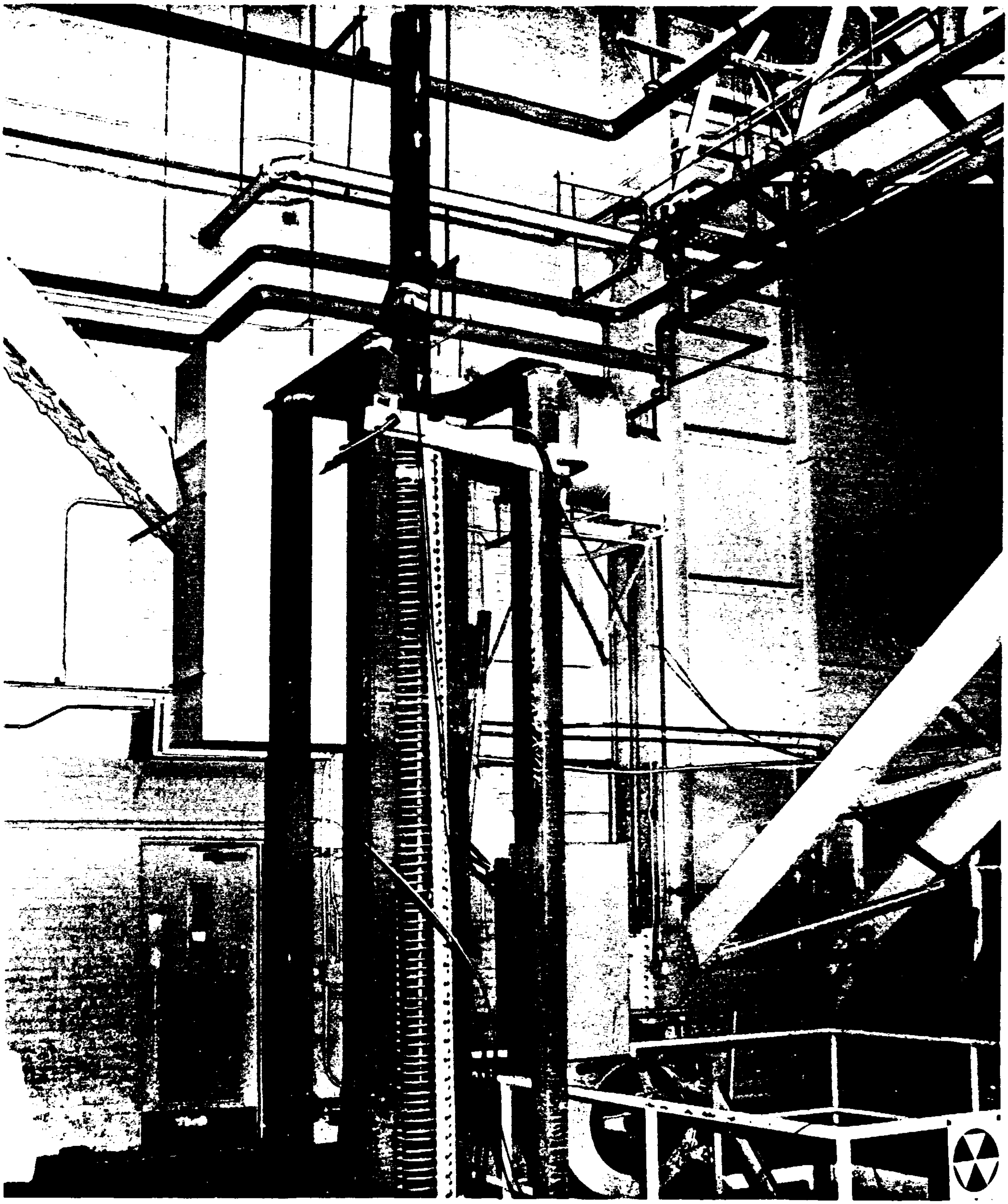

Figure 2. Induction coil shrink fit tower.

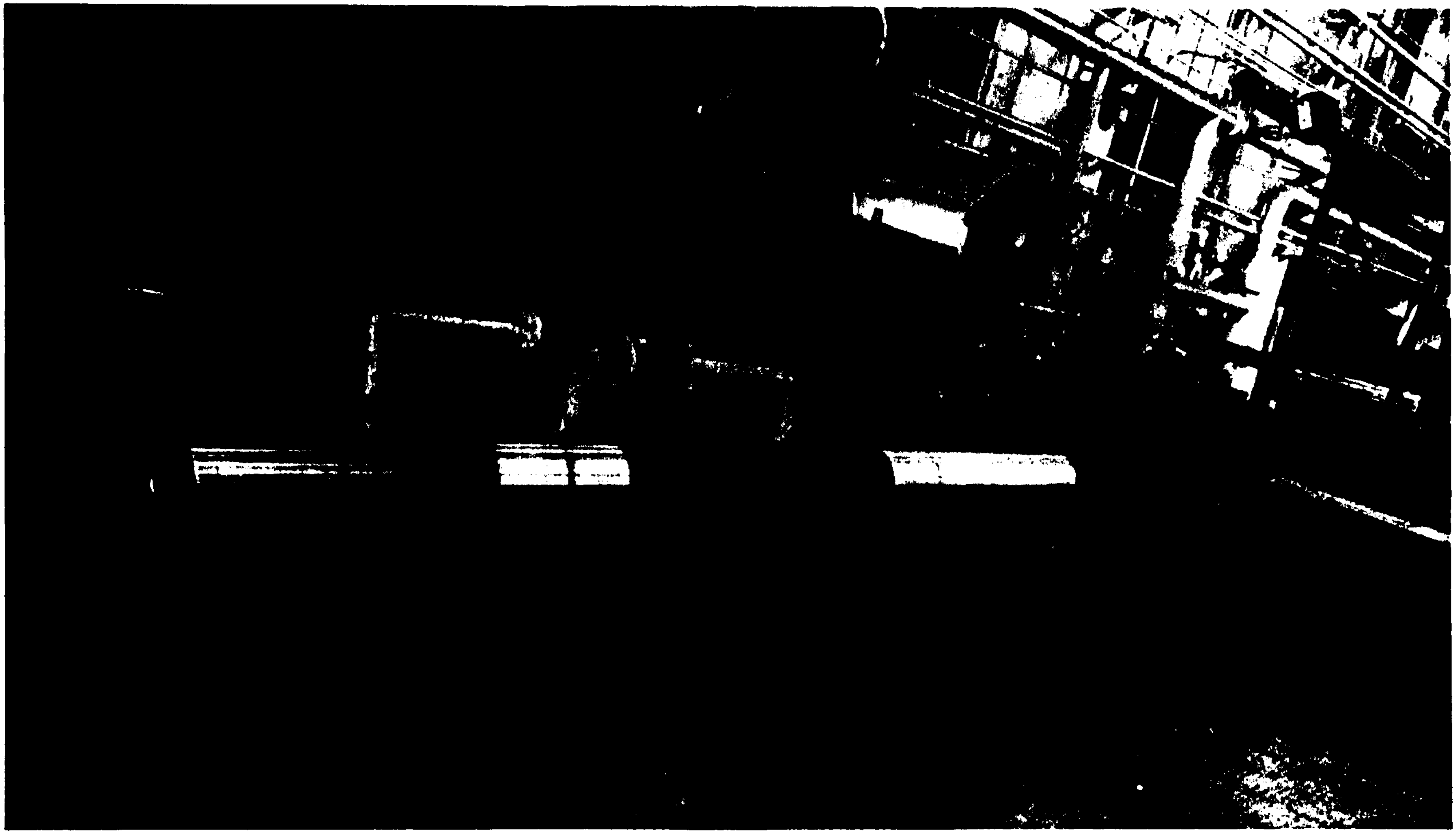

Figure 3. Prototype test fixture used to cold rotary forge Ti 38644.

Figure 4. Forging Ti 38644 with water quench bath being applied.

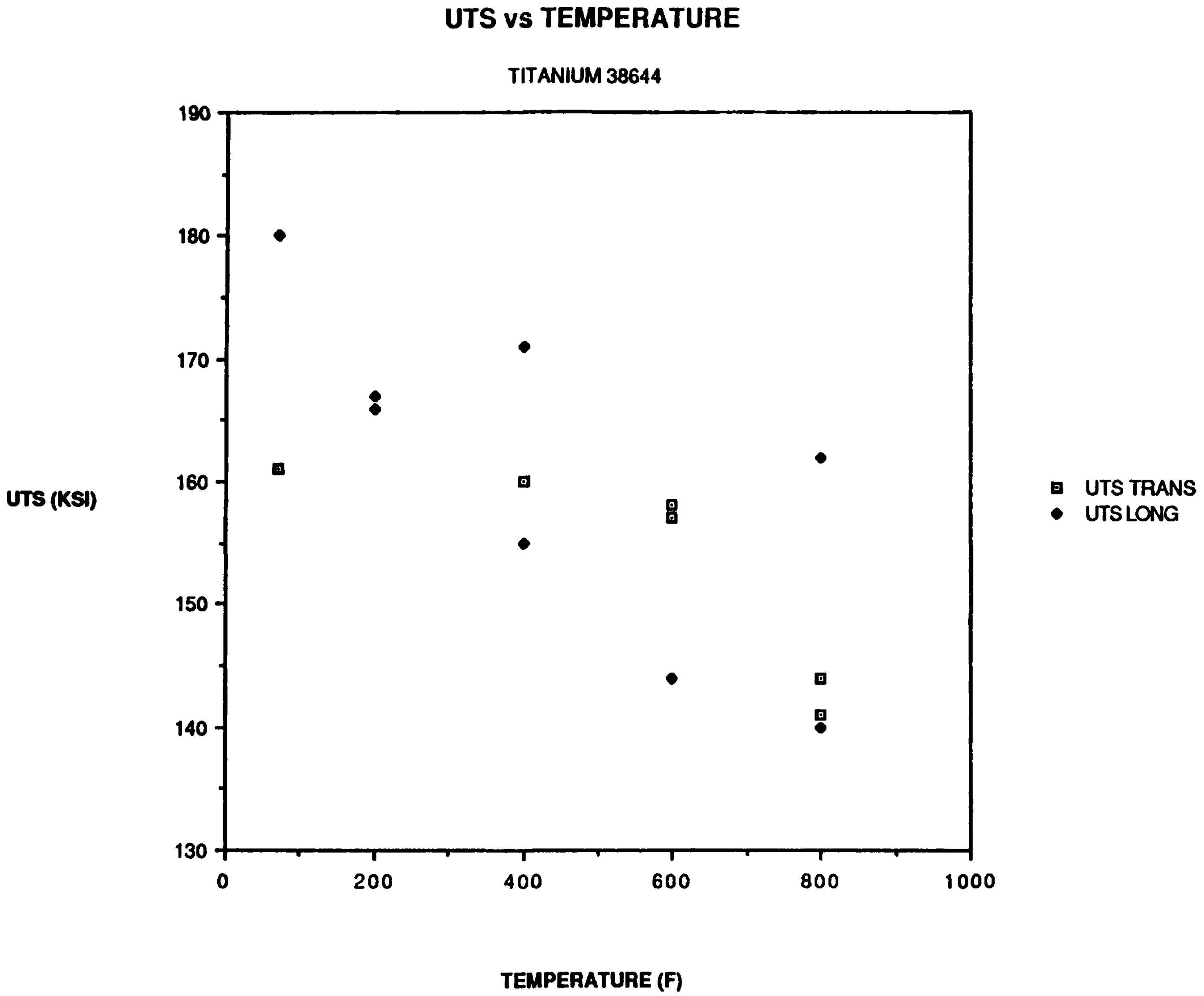

Figure 5. Ultimate tensile strength versus temperature for Ti 38644.

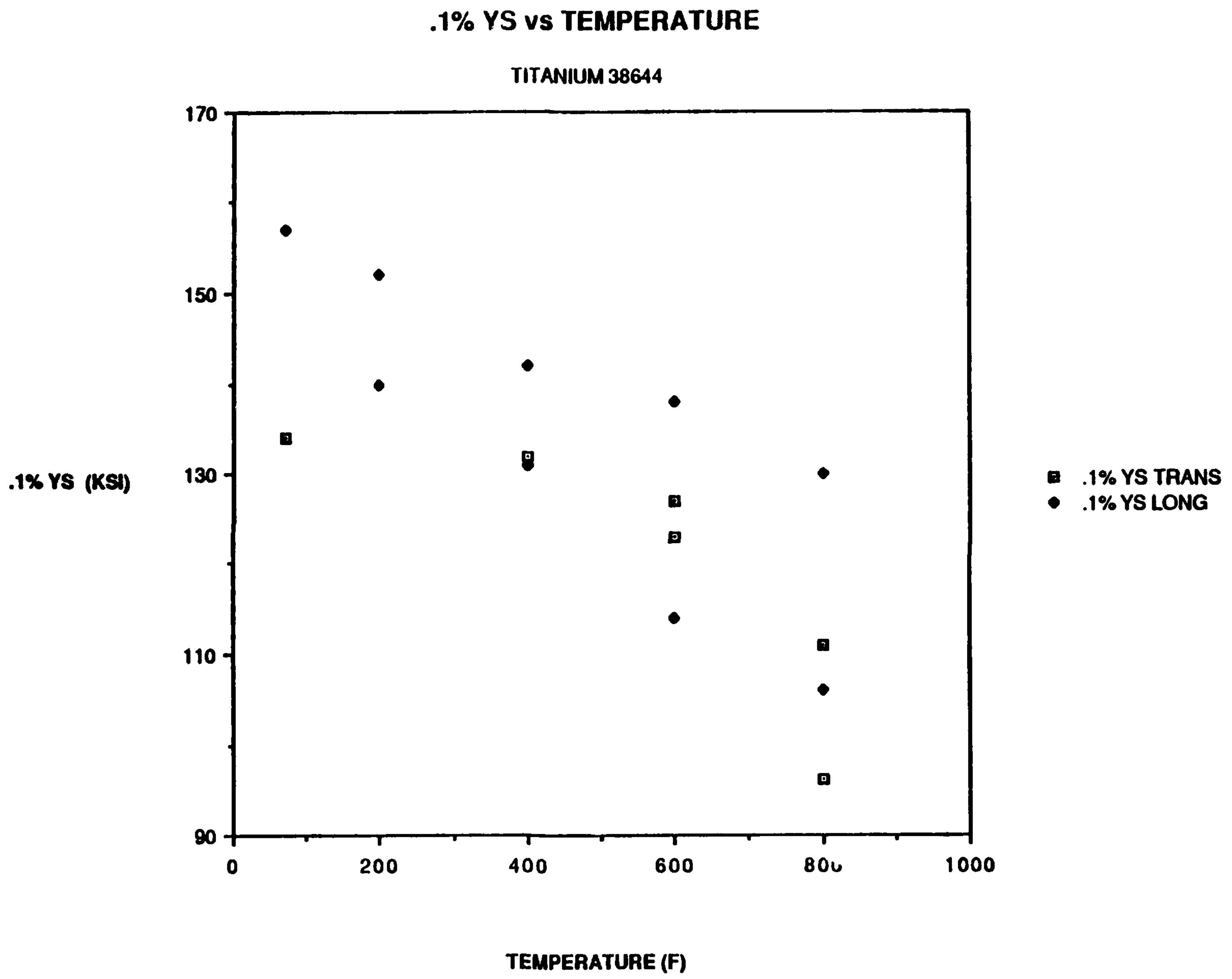

Figure 6. 0.1 percent yield strength versus temperature for Ti 38644.

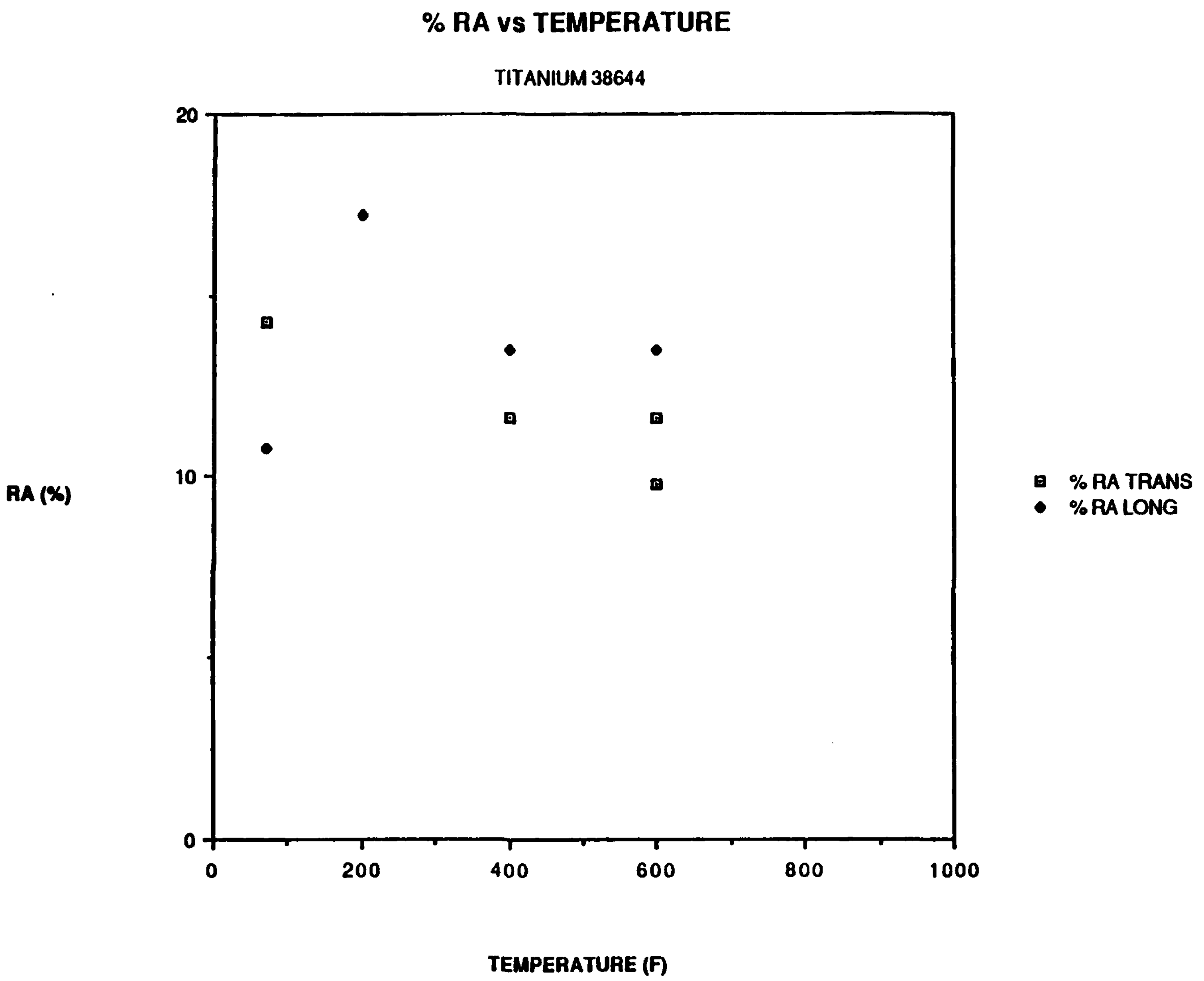

Figure 7. Percent reduction in area versus temperature for Ti 38644.

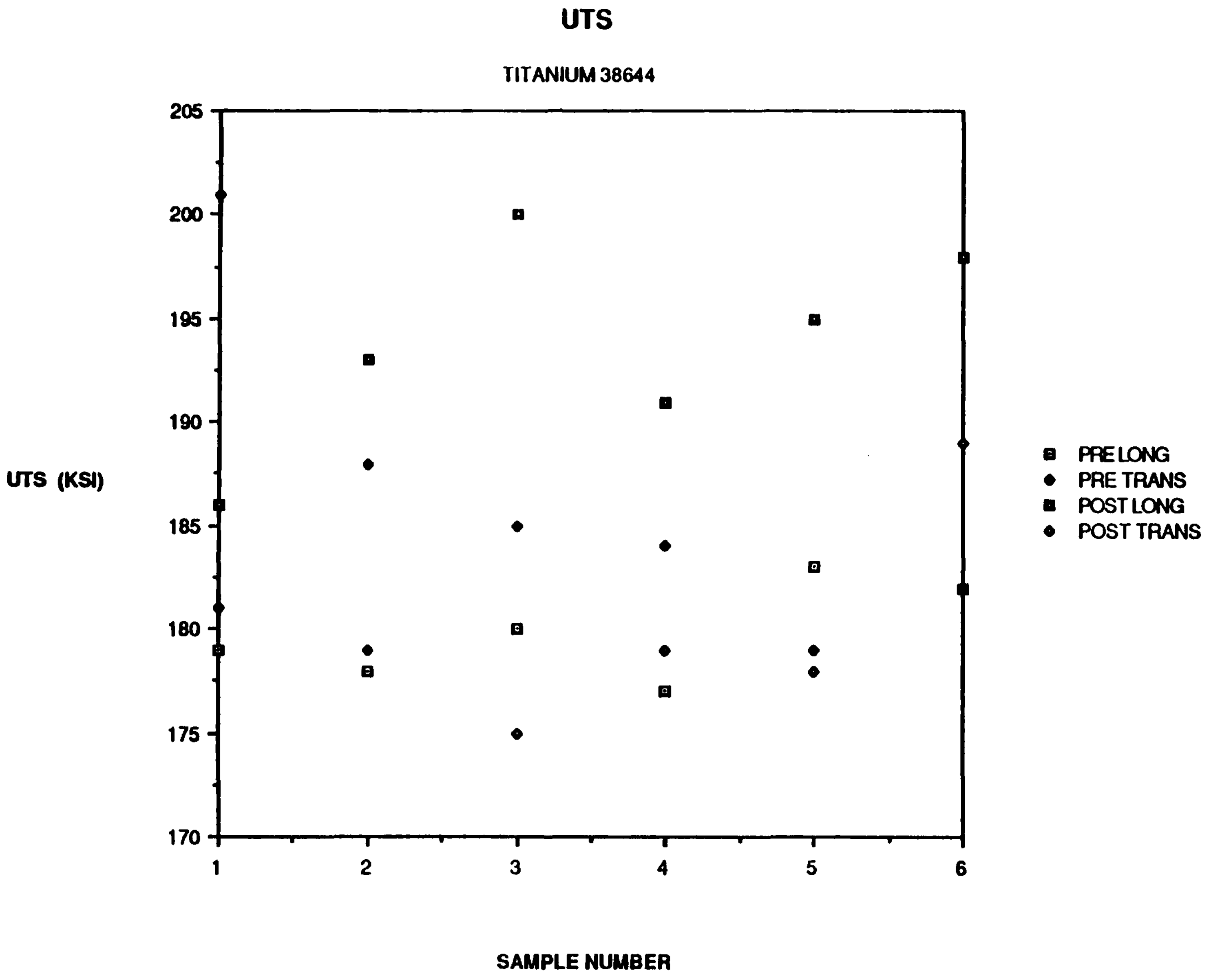

Figure 8. Ultimate tensile strength of pre- and post-forged conditions for Ti 38644.

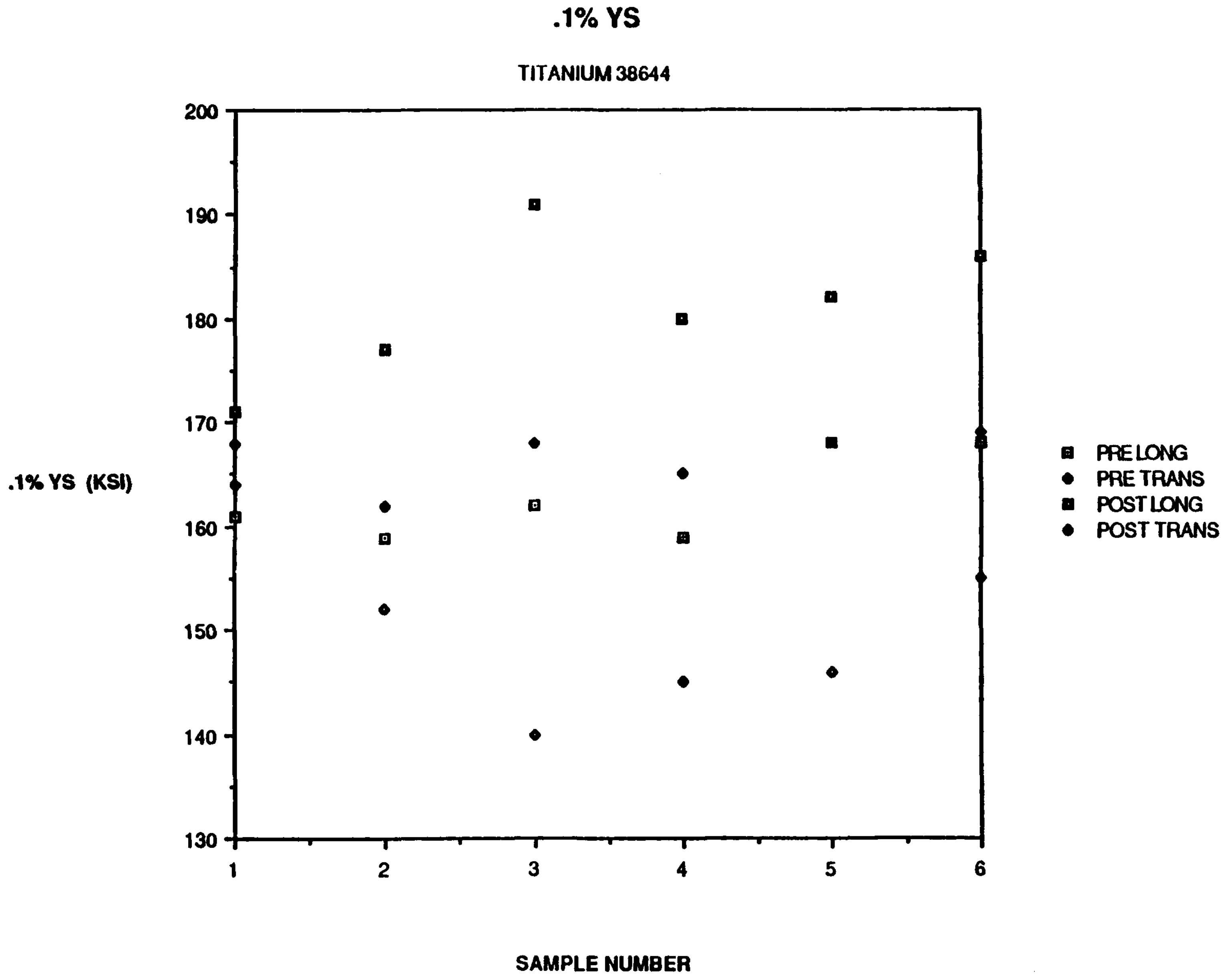

Figure 9. 0.1 percent yield strength of pre- and post-forged conditions for Ti 38644.

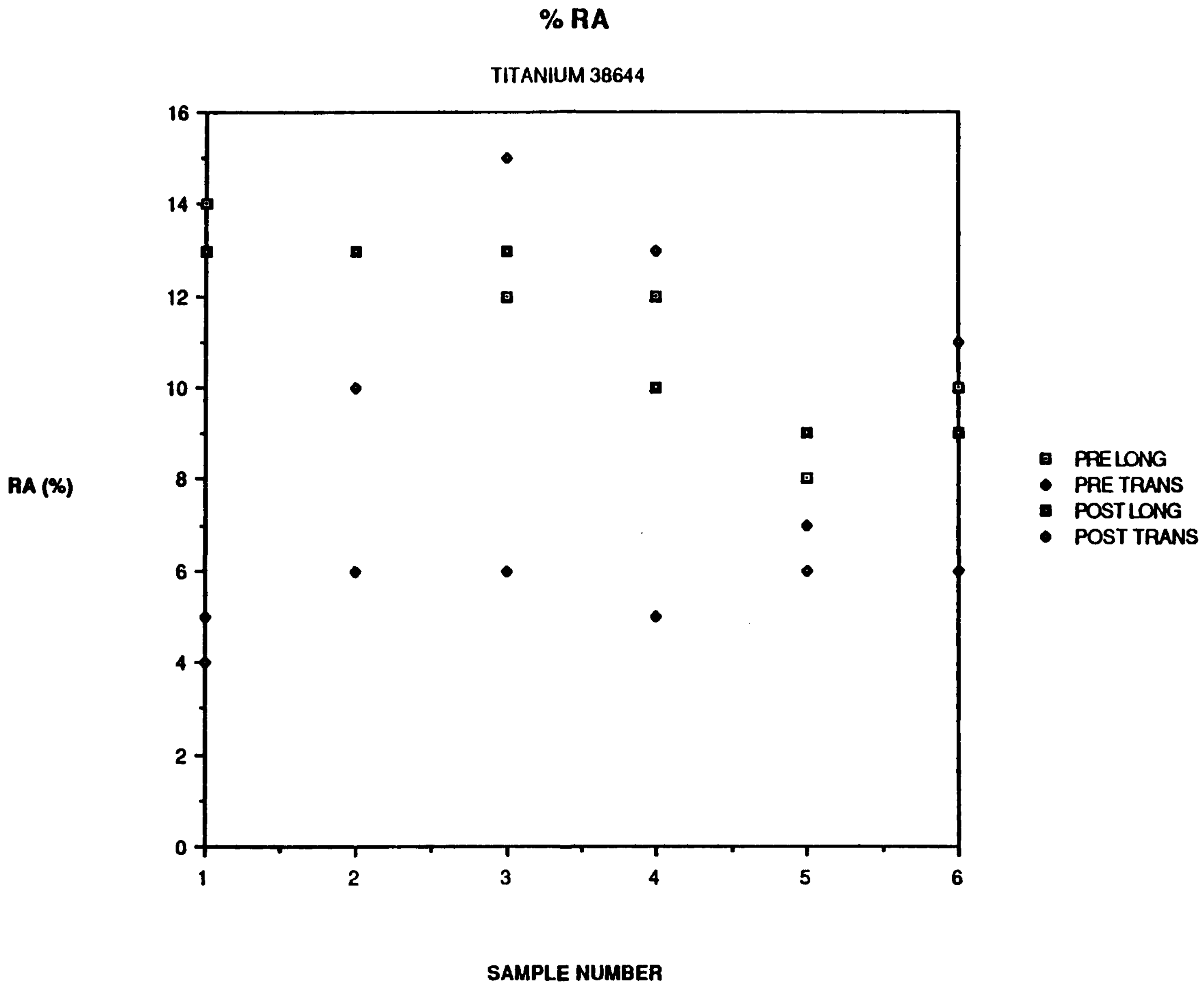

Figure 10. Percent reduction in area of pre- and post-forged conditions for Ti 38644.

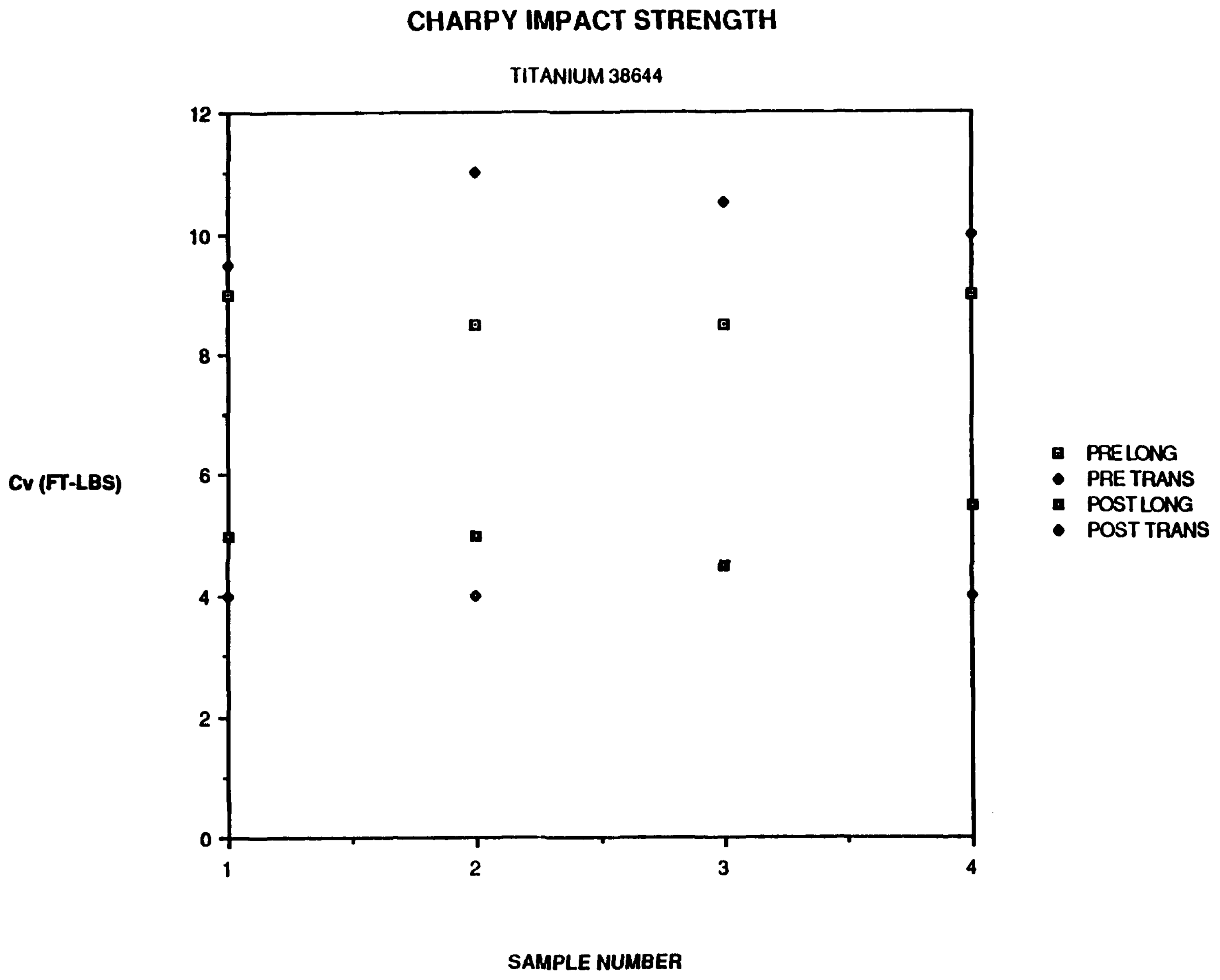

Figure 11. Charpy v-notch of pre- and post-forged conditions for Ti 38644.

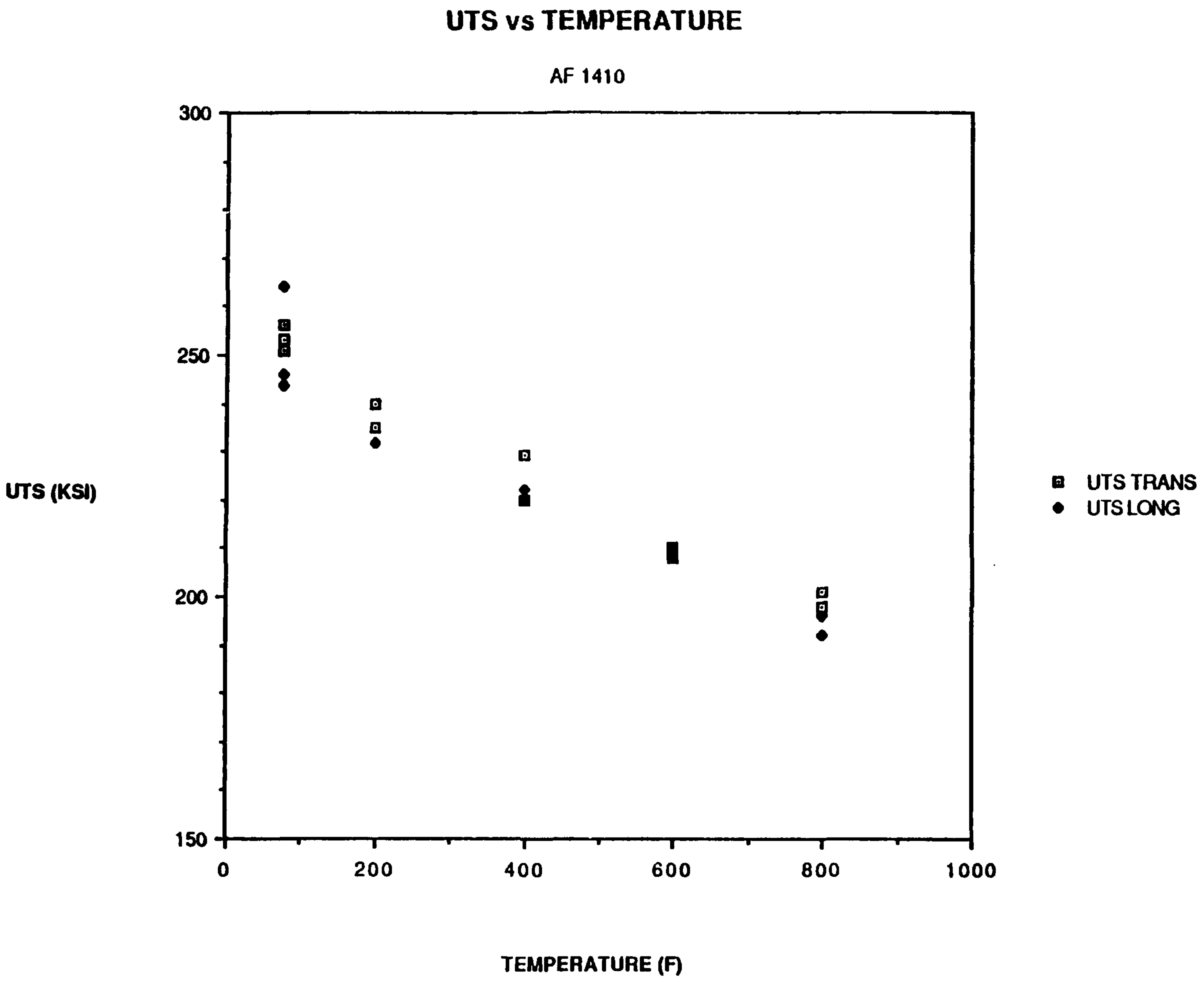

Figure 12. Ultimate tensile strength versus temperature for AF 1410.

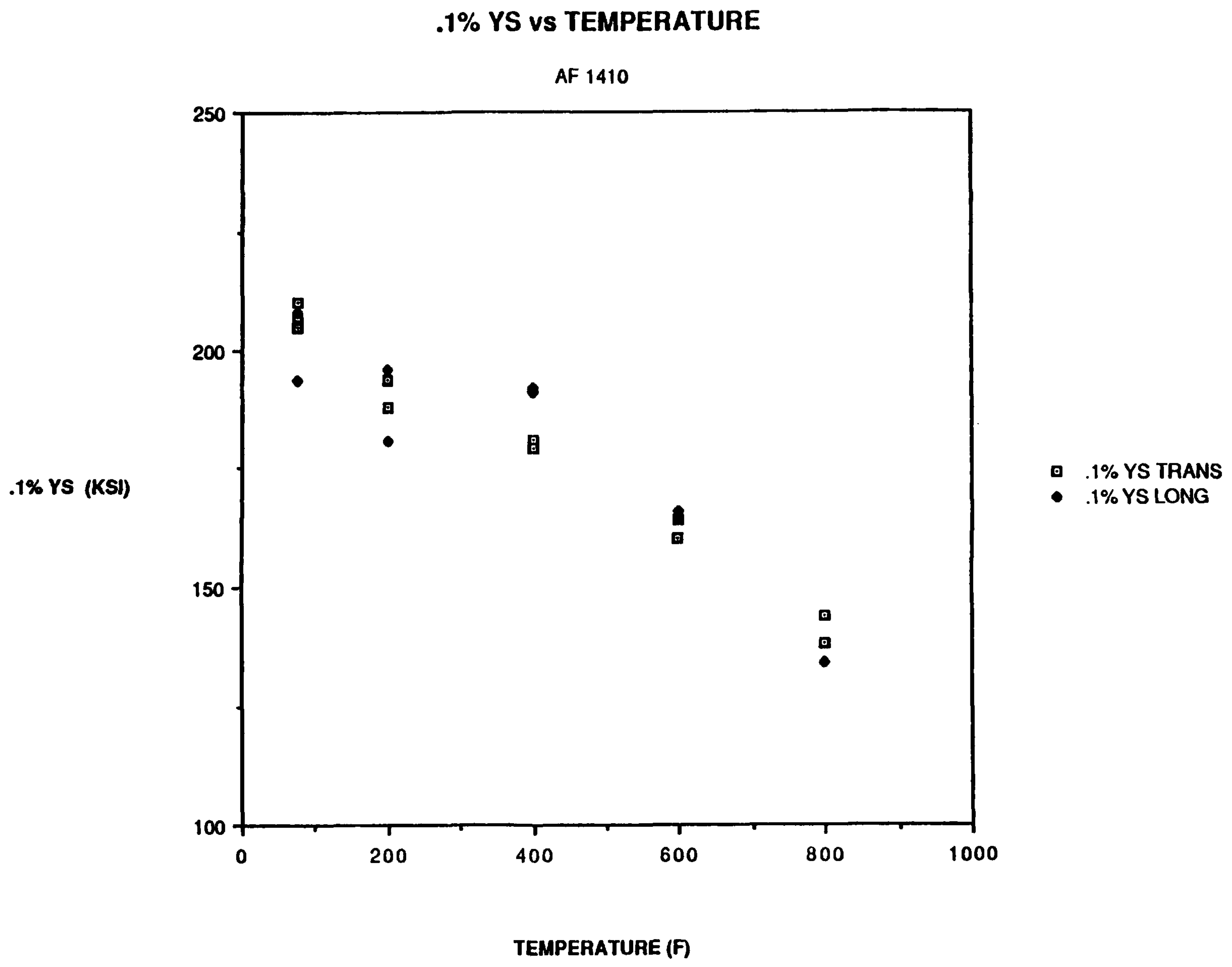

Figure 13. 0.1 percent yield strength versus temperature for AF 1410.

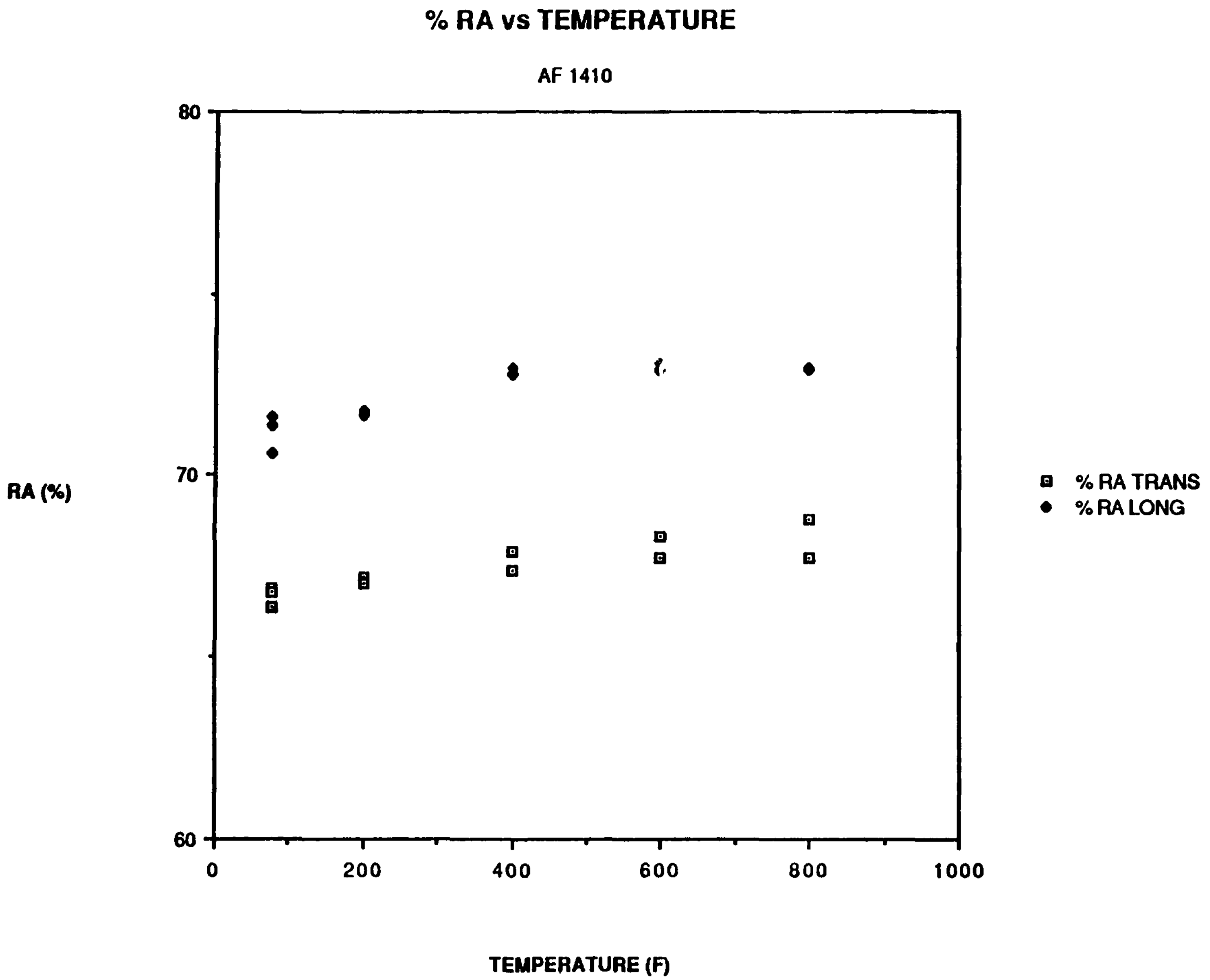

Figure 14. Percent reduction in area versus temperature for AF 1410.

APPENDIX A
TITANIUM SLEEVE SHRINK FIT

1. Raise titanium sleeve WTV-D31612 using a swiveled lifting device, lower and thread into plate WTV-D30672.
2. Lower induction coil WTV-F31363 into position around titanium sleeve and make necessary hookups.
3. Insert insulation blanket between induction coil and titanium sleeve.
4. Place circular water quenching device on top of induction coil for later use.
5. Raise carrier assembly WTV-31365 using a swiveled lifting device, lower and thread into plate WTV-30673 (hold with crane until Part 6 is finished).
6. Place stabilizers WTV-31367 into position by sliding them into contact with carrier and bolting down.
7. Turn power to induction coil and heat titanium sleeve to 750°F.
8. When 750°F is achieved, turn off power to induction coil.
9. Raise liner WTV-F31610 using swiveled lifting device, align on carrier assembly until muzzle end is approximately one inch above stabilizers.
10. Loosen bolts holding stabilizers and slide back as far as possible.
11. Lower liner into titanium sleeve until steel jacket WTV-31611 comes into contact with titanium sleeve.
12. Immediately water quench steel/titanium interface with previously mentioned water quenching device.
13. Quench until steel/titanium interface reaches 100°F.
14. Unthread titanium and steel liner as one piece and remove from induction coil.

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