

AD-755 408

ENGINEERING DATA ON NEW AEROSPACE
STRUCTURAL MATERIALS

O. L. Deel, et al

Battelle Columbus Laboratories

Prepared for:

Air Force Materials Laboratory

September 1972

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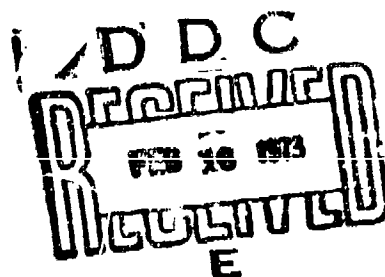
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O. L. DEEL and H. MINDLIN

Battelle
Columbus Laboratories

TECHNICAL REPORT AFML-TR-72-196
VOLUME II

SEPTEMBER 1972



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Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and index, and citation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Battelle Columbus Laboratories 505 King Avenue, Columbus, Ohio 43201		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP NA	
3. REPORT TITLE Engineering Data on New Aerospace Structural Materials			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Summary Report, April 1971 to July 1972			
5. AUTHOR(S) (Last name, first name, initial) Deel, O. L., and Mindlin, H.			
6. REPORT DATE September 1972		7a. TOTAL NO. OF PAGES 168	7b. NO. OF REFS 0
8a. CONTRACT OR GRANT NO. F33615-71-C-1261		9. ORIGINATOR'S REPORT NUMBER(S) AFML-TR-72-196 Vol. II	
8b. PROJECT NO. 7381			
8c. TASK NO. 736106		10. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. AVAILABILITY/LIMITATION NOTICES Approved for public release; distribution unlimited			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Air Force Materials Laboratory Wright-Patterson Air Force Base, Ohio	
13. ABSTRACT The major objectives of this research program were to evaluate newly developed materials of interest to the Air Force for potential weapons system usage, and then to provide "data sheet" type presentation of engineering data for these materials. The effort covered in this report has concentrated on 15-5 PH (H1025) forged bar, HP 9Ni-4Co-0.20C forged bar, PH 13-8 Mo (H1060) forged bar, 7049-T76 extrusions, Ti-6Al-2Sn-4Zr-6Mo sheet, Inconel 702 sheet (Aged), and Inconel 706 forged bar (creep-rupture heat treatment). The properties investigated include tension, compression, shear, bend, impact, fracture toughness, fatigue, creep and stress rupture, and stress-corrosion at selected temperatures.			

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Mechanical Properties						
Chemical Composition						
Corrosion Resistance						
Physical Properties						
Stainless Steel						
Alloy Steel						
Aluminum Alloy						
Nickel Base Alloy						
Titanium Alloy						
15-5 PH						
PH 13-8 Mo						
9Ni-4Co-0.20C						
7049						
Ti-6-2-4-6						
Inconel 702						
Inconel 706						

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Security Classification

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AEROSPACE STRUCTURAL MATERIALS

O. L. Deel and H. Mindlin

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FOREWORD

This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, under Contract F33615-71-C-1261. This contract was performed under Project No. 7381, "Materials Applications", Task No. 738106, "Engineering and Design Data". The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, by Mr. Clayton Harmsworth (AFML/LAE), technical manager.

This final report covers work conducted from April, 1971, to July, 1972. This report was submitted by the authors on August 4, 1972.

This technical report has been reviewed and is approved.

A. Olevitch

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Chief, Materials Engineering Branch
Materials Support Division
Air Force Materials Laboratory

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INTRODUCTION

The selection of structural materials to most effectively satisfy new environmental requirements and increased design load requirements for advanced Air Force weapons systems is of vital importance. A major difficulty that design engineers encounter, particularly for newly developed materials, materials processing, and product forms, is a lack of sufficient engineering data information to effectively evaluate the relative potential of these developments for a particular application.

In recognition of this need, the Air Force has sponsored several programs at Battelle's Columbus Laboratories to provide comparative engineering data for newly developed materials. The materials included in these evaluation programs were carefully selected to insure that they were either available or could become quickly available on request and that they would represent potentially attractive alloy projections for weapons system usage. The results of these programs have been published in four technical reports, AFML-TR-67-413, AFML-TR-68-211, AFML-TR-70-252, and AFML-TR-71-449.

This technical report is a result of the continuing effort to relieve the above situation and to stimulate interest in the use of newly developed alloys, or new processing techniques for older alloys, for advanced structures.

The materials evaluated under this program are as follows:

- (1) 15-5 PH (H1025) stainless steel forged bar
- (2) HP 9Ni-4Co-0.20C steel forged bar
- (3) PH 13-8 Mo (H1000) stainless steel forged bar
- (4) 7049-T76 aluminum extrusion
- (5) 6Al-2Sn-4Zr-6Mo titanium sheet
- (6) Inconel Alloy 702 sheet (Aged)
- (7) Inconel Alloy 706 forged bar (Creep-rupture heat treatment).

The temper or heat-treat conditions selected for evaluation are described in each alloy section.

The program approach was, as on previous contracts, to search the published literature and to contact metal producers and aerospace companies for any pertinent data. If very little pertinent information was available, a complete material evaluation was conducted. Upon completion of each material evaluation, a "data sheet" was issued to make the data immediately available to potential users rather than defer publication to the end of the contract term and the summary technical report. These data sheets are reproduced in Appendix III.

Detailed information concerning the properties of interest, test techniques, and specimen types are contained in Appendices I and II of this report.

MATERIALS INFORMATION AND TEST RESULTS

15-5 PH Stainless Steel

Material Description

15-5 PH is a precipitation-hardening stainless steel that offers a combination of high strength and hardness, excellent corrosion resistance, plus good transverse toughness and good forgeability. It is produced by consumable vacuum arc remelting and is virtually "ferrite free".

Fabrication practices for 15-5 PH are generally the same as those established for 17-4 PH. Most techniques are similar to those recommended for the regular grades of stainless steel. Hardening heat treatments require temperatures of only 900 F to 1150 F, depending on the properties desired. Because of the comparatively low hardening temperatures, scaling and distortion difficulties are essentially eliminated.

15-5 PH is available in the form of sheet, strip, plate, bar, and wire. Typical applications include forgings, pump and valve parts for high pressure systems, aircraft components, and hollow bar parts for hydraulic actuators and controls.

The chemical composition of the forging used for this evaluation is as follows:

<u>Chemical Composition</u>	<u>Percent</u>
Carbon	.037
Manganese	.31
Phosphorus	.018
Sulfur	.010
Silicon	.30
Chromium	15.14
Nickel	4.58
Copper	3.32
Columbium	.24
Tantalum	.01
Iron	Balance

The material tested was obtained from Armco Heat 4W0370 in the form of 2-1/8 inch x 5-3/4 inch x 8 foot forged bar.

Processing and Heat Treating

The specimen layout for 15-5 PH is shown in Figure 1. Specimens were machined in the as-received Condition A followed by heat treatment for 4 hours at 1025 F to Condition H1025.

Test Results

Tension. Results of tests in both the longitudinal and transverse directions at room temperature, 400 F, 700 F, and 900 F are given in Table I. Typical tensile stress-strain curves at temperature are shown in Figures 2 and 3. Effect-of-temperature curves are shown in Figure 6.

Compression. Results of tests in the longitudinal and transverse directions are given in Table II for room temperature, 400 F, 700 F, and 900 F. Typical stress-strain and tangent-modulus curves at temperature are shown in Figures 4 and 5. Effect-of-temperature curves are shown in Figure 7.

Shear. Results of pin shear tests in the longitudinal and transverse directions at room temperature are given in Table III.

Impact. Results of room temperature Charpy tests in the longitudinal and transverse direction are given in Table IV.

Fracture Toughness. Six slow-bend type tests were conducted at room temperature. Results are presented in Table V. Since the size ratio, $2.5(K_Q/TYS)^2$, was greater than both the specimen thickness and width in all tests, the K_Q value is not a valid K_{Ic} value by existing ASTM criteria.

Fatigue. Axial-load tests were conducted at room temperature, 400 F, and 700 F for both unnotched and notched transverse specimens. Test results are given in Tables VI and VII and presented as S-N curves in Figures 8 and 9.

Creep and Stress Rupture. Tests were performed at 700 F, 900 F, and 1100 F. Results are presented in tabular form in Table VIII and as log-stress versus log-time curves in Figure 10.

Stress Corrosion. Specimens were tested as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 6.7×10^{-6} in/in/F for 70 F to 900 F.

Density. The density value is 0.283 lb/in³.

TABLE 1. TENSILE TEST RESULTS FOR
15-5 PH (H1025) FORGED BAR

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, psi x 10 ⁶
<u>Longitudinal at Room Temperature</u>					
1L-1	164.0	163.0	15.0	62.4	30.5
1L-2	165.0	164.0	15.5	63.6	30.8
1L-3	164.0	163.0	15.5	62.2	30.6
<u>Transverse at Room Temperature</u>					
1T-1	164.0	162.0	12.5	50.0	28.7
1T-2	165.0	162.0	13.0	52.7	28.6
1T-3	163.0	161.0	13.5	50.9	29.2
<u>Longitudinal at 400 F</u>					
1L-4	147.0	141.0	12.5	50.0	27.3
1L-5	147.0	140.0	12.5	49.8	27.8
1L-6	147.0	140.0	11.5	48.8	28.1
<u>Transverse at 400 F</u>					
1T-4	147.0	141.0	10.5	43.3	27.9
1T-5	146.0	139.0	10.5	42.0	27.2
1T-6	147.0	141.0	11.5	43.7	29.5
<u>Longitudinal at 700 F</u>					
1L-7	137.0	128.0	10.0	43.5	26.5
1L-8	136.0	127.0	10.0	46.4	27.0
1L-9	139.0	130.0	11.0	46.2	27.4
<u>Transverse at 700 F</u>					
1T-7	136.0	126.0	9.0	38.8	24.0
1T-8	136.0	128.0	9.0	37.8	25.2
1T-9	136.0	127.0	9.5	39.2	26.2
<u>Longitudinal at 900 F</u>					
1L-10	120.0	112.0	15.0	60.8	21.9
1L-11	120.0	111.0	15.0	58.3	21.3
1L-12	119.0	110.0	14.0	58.2	23.4
<u>Transverse at 900 F</u>					
1T-10	118.0	108.0	14.0	51.0	23.7
1T-11	118.0	110.0	13.5	50.2	23.0
1T-12	120.0	112.0	13.0	53.2	22.9

TABLE II. COMPRESSION TEST RESULTS FOR
15-5 PH (H1025) FORGED BAR

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, psi x 10 ⁶
<u>Longitudinal at Room Temperature</u>		
2L-1	168.0	29.8
2L-2	165.0	31.0
2L-3	173.0	29.9
<u>Transverse at Room Temperature</u>		
2T-1	165.0	29.8
2T-2	166.0	30.1
2T-3	165.0	30.9
<u>Longitudinal at 400 F</u>		
2L-4	145.0	29.1
2L-5	145.0	28.3
2L-6	144.0	28.9
<u>Transverse at 400 F</u>		
2T-4	145.0	28.2
2T-5	143.0	29.3
2T-6	144.0	29.2
<u>Longitudinal at 700 F</u>		
2L-7	133.0	27.9
2L-8	129.0	27.7
2L-9	128.0	27.4
<u>Transverse at 700 F</u>		
2T-7	130.0	27.8
2T-8	130.0	28.6
2T-9	130.0	27.8
<u>Longitudinal at 900 F</u>		
2L-10	113.0	24.6
2L-11	111.0	24.4
2L-12	111.0	24.2
<u>Transverse at 900 F</u>		
2T-10	111.0	25.3
2T-11	111.0	23.9
2T-12	111.0	24.2

TABLE III. SHEAR TEST RESULTS FOR
15-5 PH (H1025) FORGED BAR

Specimen Number		Ultimate Shear Strength, ksi
	<u>Longitudinal</u>	
4L-1		106.0
4L-2		106.0
4L-3		105.0
4L-4		105.0
	<u>Transverse</u>	
4T-1		105.0
4T-2		104.0
4T-3		104.0
4T-4		106.0

TABLE IV. IMPACT TEST RESULTS FOR 15-5 PH
(H1025) FORGED BAR

Specimen Number	Energy, ft/lbs
<u>Longitudinal</u>	
10L-1	81.0
10L-2	81.0
10L-3	80.0
10L-4	78.0
10L-5	82.5
10L-6	81.5
<u>Transverse</u>	
10T-1	37.0
10T-2	38.5
10T-3	38.5
10T-4	43.0
10T-5	44.0
10T-6	43.0

TABLE V. FRACTURE TOUGHNESS TEST RESULTS FOR 15-5 PH (H1025) FORGED BAR
(LONGITUDINAL)

Specimen Number	W, inches	a, inch	T, inch	P, pound	Span, inches	$f(\frac{a}{W})$	$K_Q^{(a)}$
1L	1.501	.873	.749	11,800	6	3.5	181.49
4L	1.500	.886	.749	12,600	6	3.6	200.6
2L	1.500	.883	.748	12,050	6	3.6	190.6
6L	1.501	.891	.749	12,450	6	3.7	200.2
3L	1.500	.852	.748	11,900	6	3.3	174.5
5L	1.500	.882	.749	12,600	6	3.6	198.6

(a) Candidate fracture toughness values, K_Q , are invalid as K_{IC} values since a , T ,
 $< 2.5 \left(\frac{K_Q}{TYS} \right)$.

TABLE VI. AXIAL LOAD FATIGUE TEST RESULTS FOR
UNNOTCHED 15-5 PH (H1025) FORGED BAR
(TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-5	170	18,720
5-3	165	42,200
5-2	160	120,700
5-4	155	111,200
5-1	150	4,156,200
5-6	14	275,300
5-7	140	7,934,500
5-8	135	4,167,900
5-9	130	10,010,900 ^(a)
<u>400 F</u>		
5-20	160	14,900
5-19	150	31,600
5-18	140	47,000
5-23	130	49,800
5-22	130	113,500
5-24	120	944,900
5-25	120	10,208,100 ^(a)
<u>700 F</u>		
5-10	140	(b)
5-14	135	37,700
5-13	130	32,700
5-16	125	66,600
5-11	120	59,400
5-17	115	50,400
5-12	110	10,123,000 ^(a)

(a) Did not fail.

(b) Failed in first cycle.

TABLE VII. AXIAL LOAD FATIGUE TEST RESULTS FOR
NOTCHED ($K_t=3.0$) 15-5 PH (H1025) FORGED BAR
(TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-31	130	9,260
5-32	120	14,650
5-33	110	16,010
5-34	90	45,120
5-35	80	80,250
5-36	70	128,930
5-37	60	191,100
5-38	50	10,965,000
<u>400 F</u>		
5-43	110	14,100
5-49	90	39,100
5-40	80	55,200
5-41	70	100,000
5-52	65	147,200
5-42	60	7,121,200
5-53	60	16,121,300 ^(a)
<u>700 F</u>		
5-59	100	11,000
5-57	90	16,500
5-56	80	47,700
5-55	70	44,400
5-60	70	815,200
5-53	65	2,547,900
5-54	60	5,548,700
5-61	55	17,060,300

(a) Did not fail.

TABLE VIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF 15-5 PH (H1025) FORGED BAR
(TRANSVERSE)

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 in. percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
31	134.5	700	--	--	--	--	--	On loading	9.2	--	--
32	130	"	0.01	0.03	0.35	2.0	12	1.150	37.3	10.8	0.08
33	125	"	0.10	0.4	7.0	30	98	0.857	410.9	12.3	0.013
38	105	"	8.0	60	475(b)	1300(b)	--	0.539	312.5(a)	0.943	0.0006
39	95	"	65	325	2225(b)	--	--	0.481	503.5(a)	0.723	0.00015
310	100	900	--	0.7	0.2	0.45	1.0	0.750	1.6	13.8	1.7
314	85	"	0.15	0.65	6.5	39	89	0.450	139.7	11.5	0.013
34	70	"	2	22	280	530	705	0.338	861.6(a)	16.1	0.0008
311	60	"	4.4	75	550	1200(b)	--	0.385	578.6(a)	0.915	0.00063
313	50	"	20	350	960(b)	--	--	0.265	772.4(a)	0.631	0.00027
36	50	1100	0.05	0.17	0.75	1.9	3.7	0.267	6.6	20.0	0.44
35	30	"	1.0	4.5	20	51	90	0.357	167.5	38.5	0.015
37	20	"	3.2	17	92	217	370	0.150	725.4(a)	32.3	0.0036
312	10	"	60	180	680	1635(b)	--	0.077	671.8(a)	0.573	0.00053

(a) Test discontinued.

(b) Estimate.

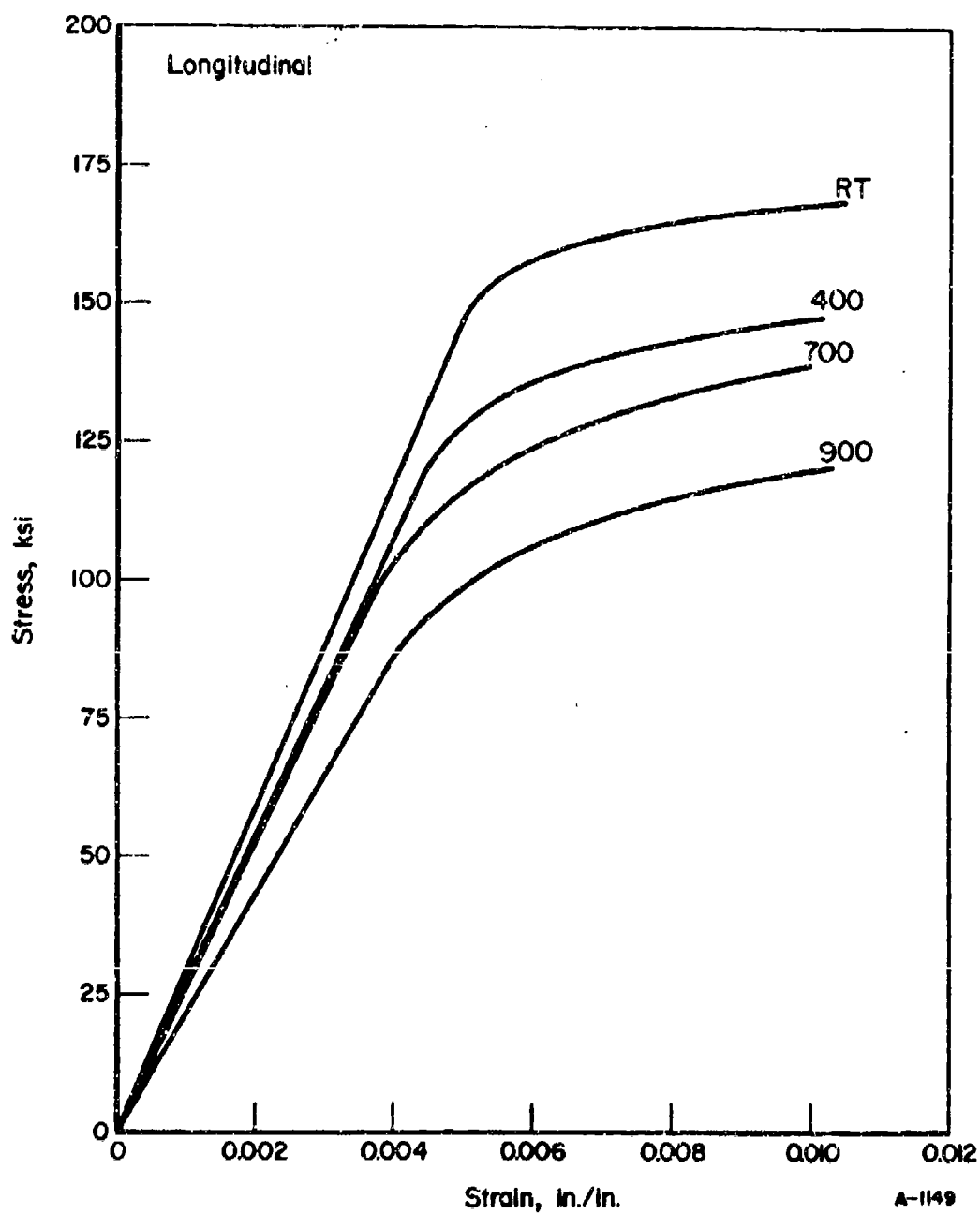


FIGURE 2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
15-5 PH (H1025) FORGED BAR (LONGITUDINAL)

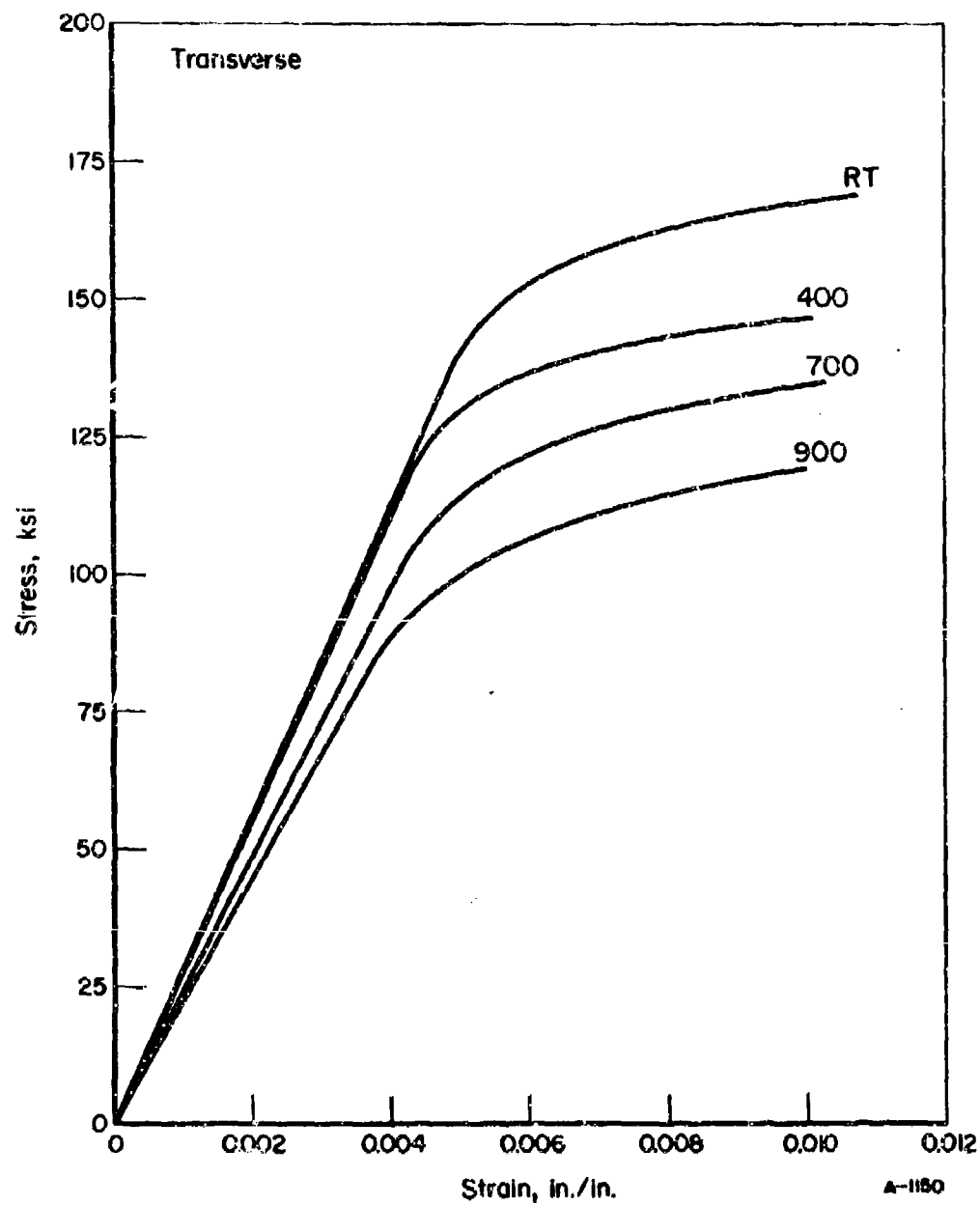


FIGURE 3. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
15-5 PH (H1025) FORGED BAR (TRANSVERSE)

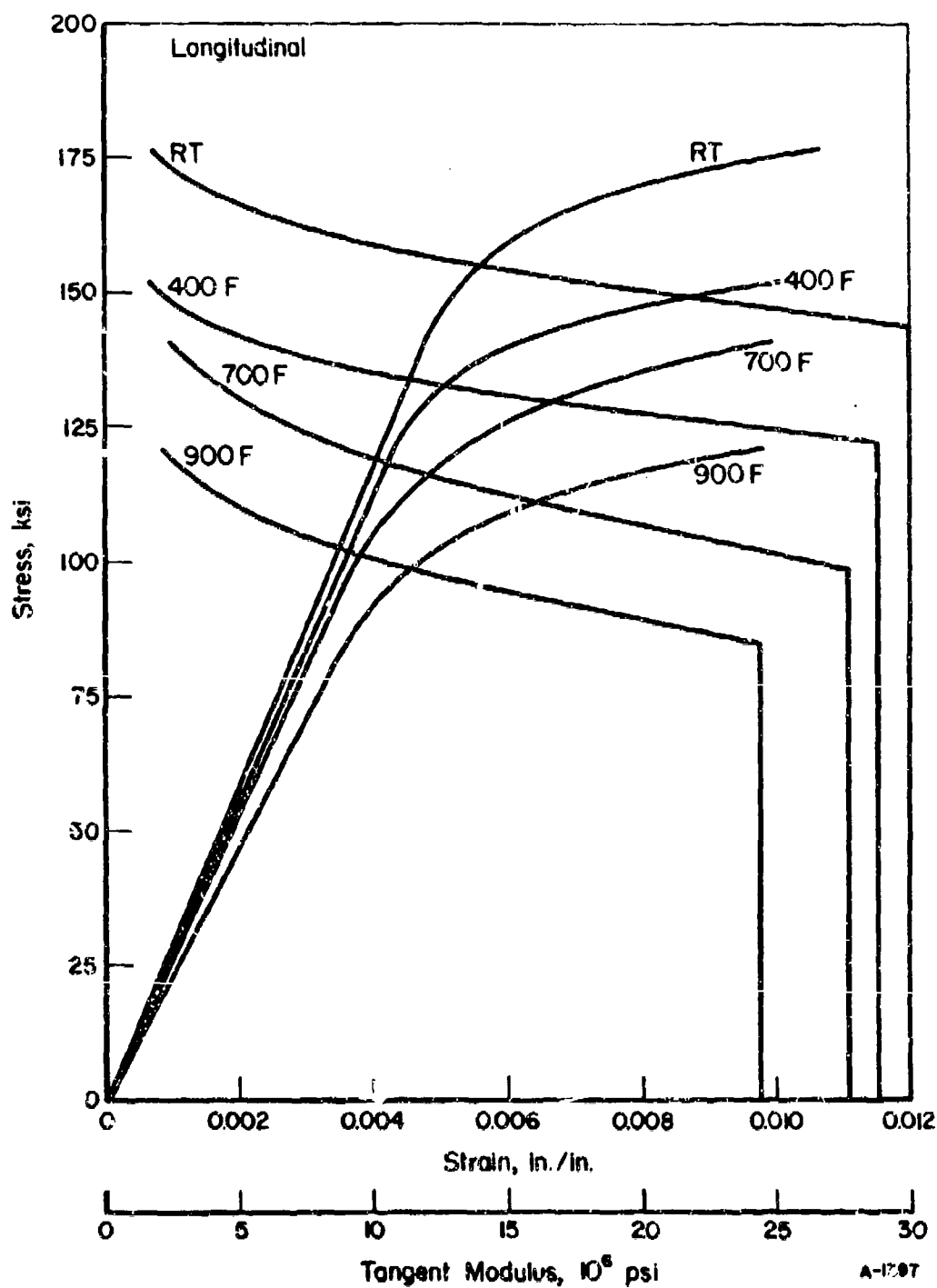


FIGURE 4. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 15-5 PH (H1025) FORGED BAR (LONGITUDINAL)

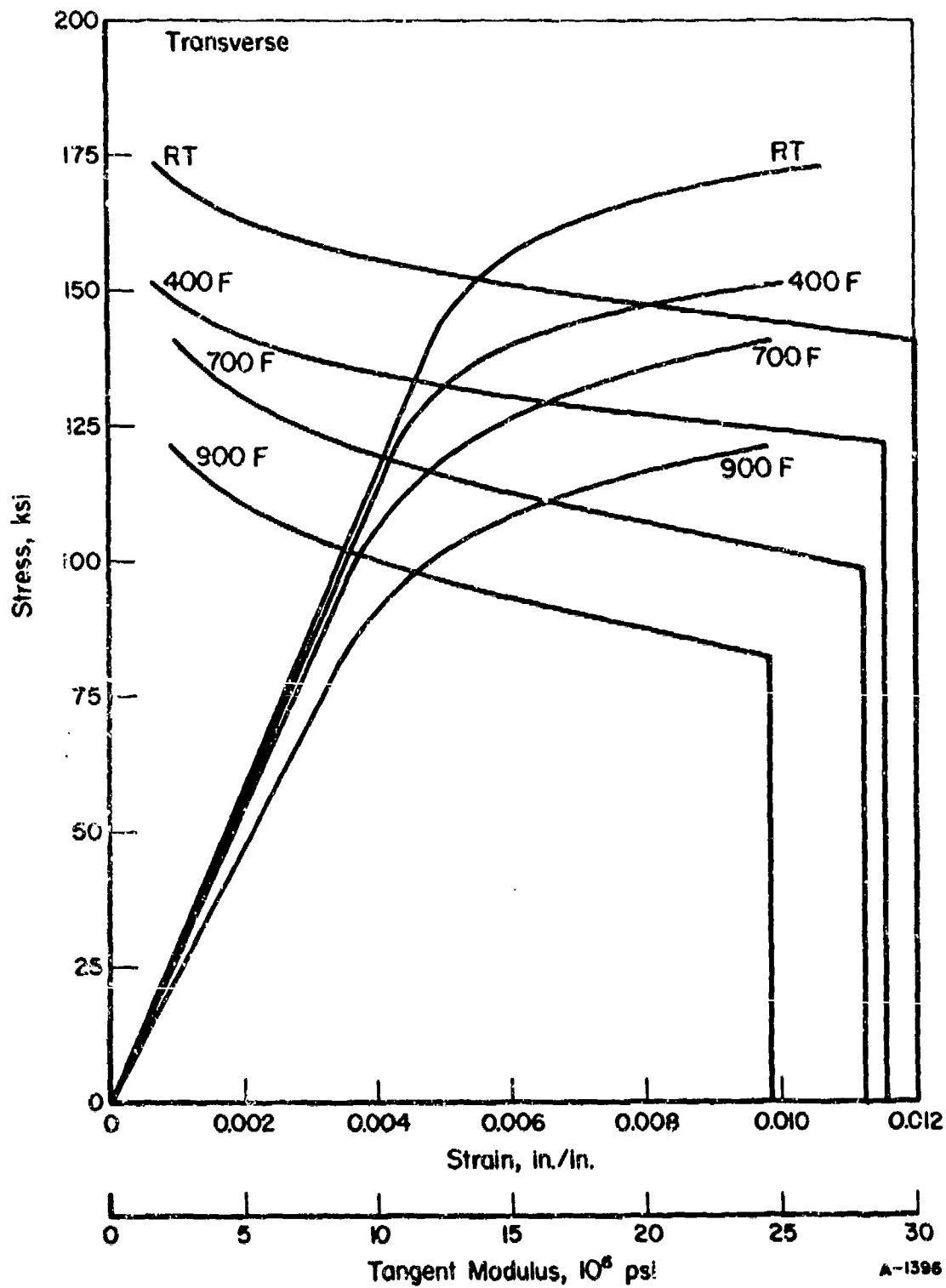


FIGURE 5. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 15-5 PH (H1025) FORGED BAR (TRANSVERSE)

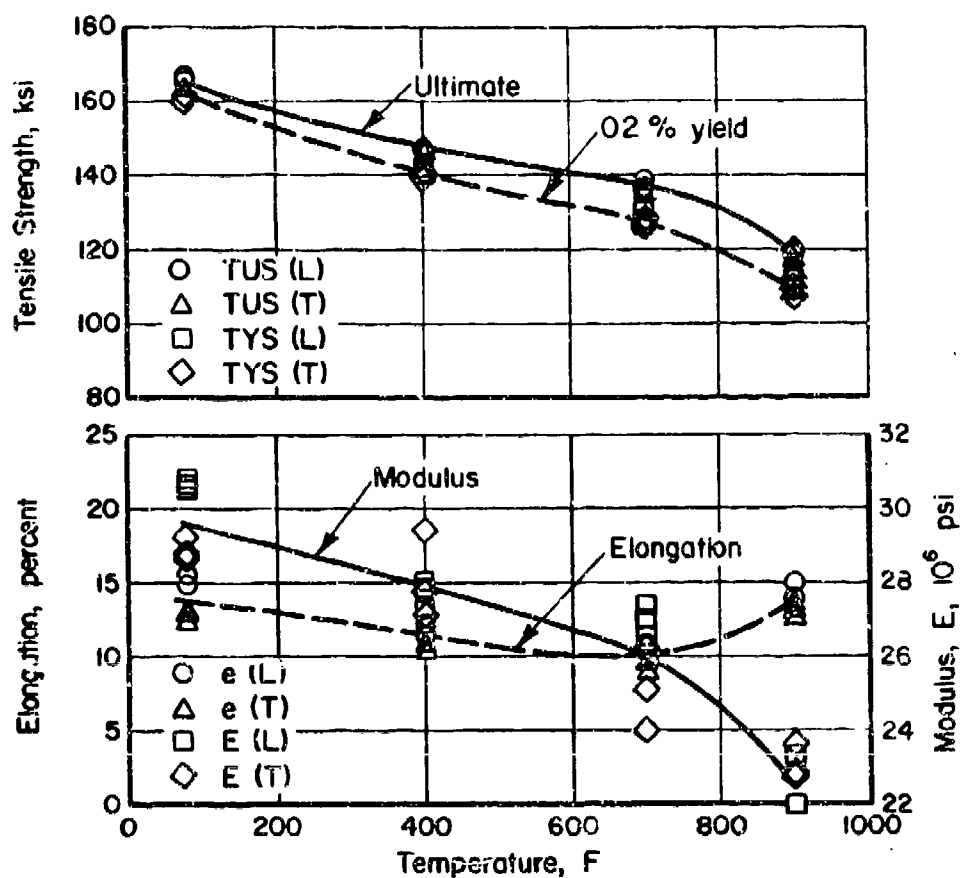


FIGURE 6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 15-5 PH (H1025) FORGED BAR

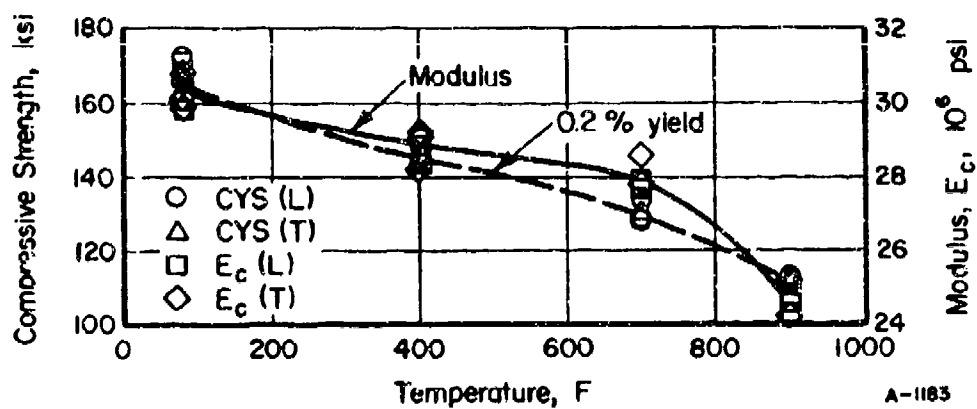


FIGURE 7. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 15-5 PH (H1025) FORGED BAR

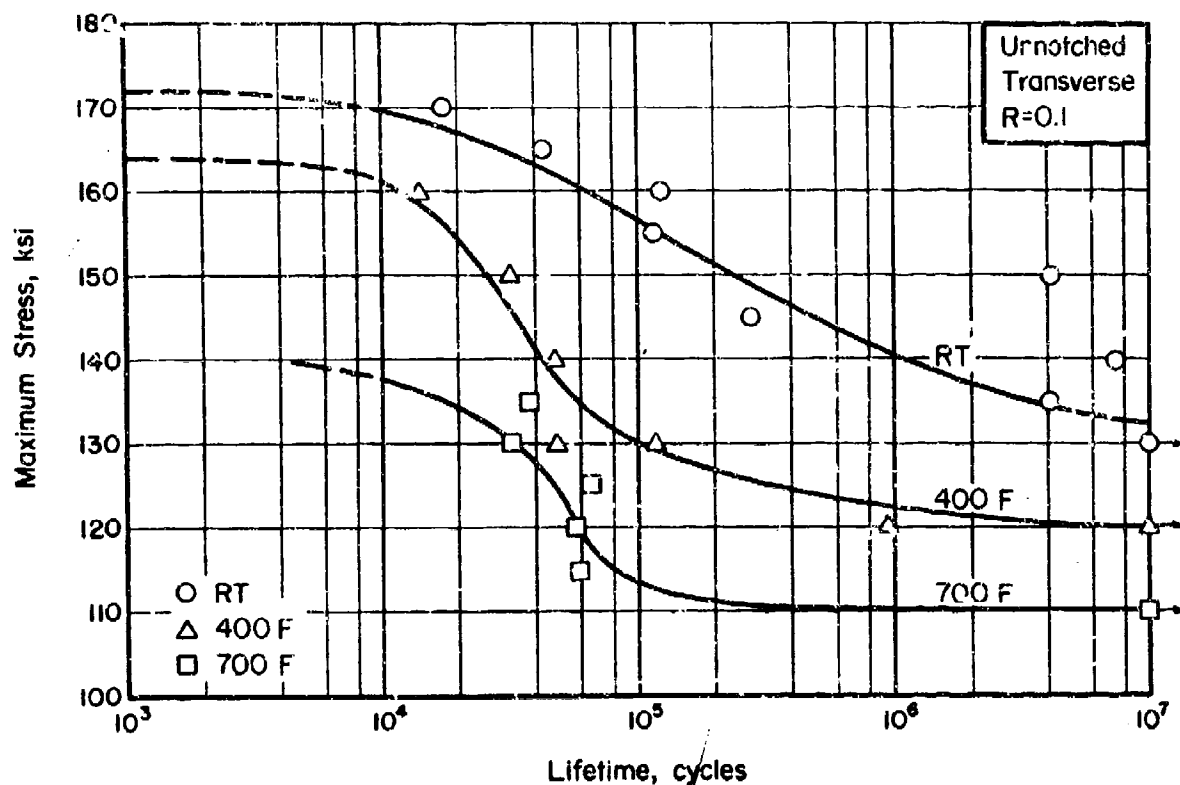


FIGURE 8. AXIAL LOAD FATIGUE BEHAVIOR FOR UNNOTCHED 15-5 PH (H1025) FORGED BAR

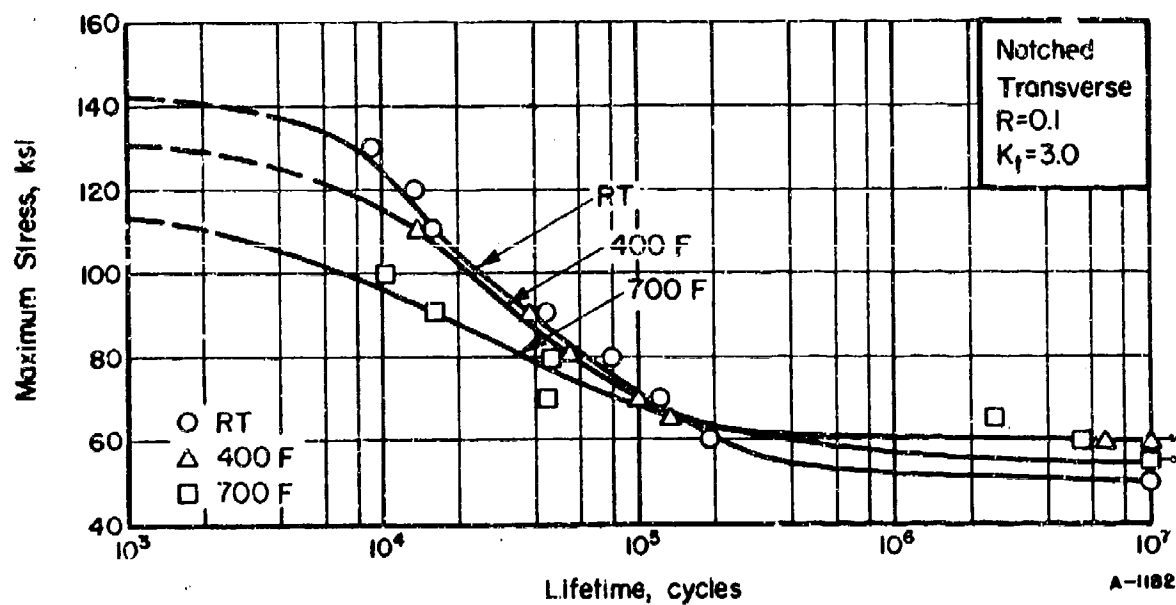


FIGURE 9. AXIAL LOAD FATIGUE BEHAVIOR FOR NOTCHED ($K_t = 3.0$) 15-5 PH (H1025) FORGED BAR

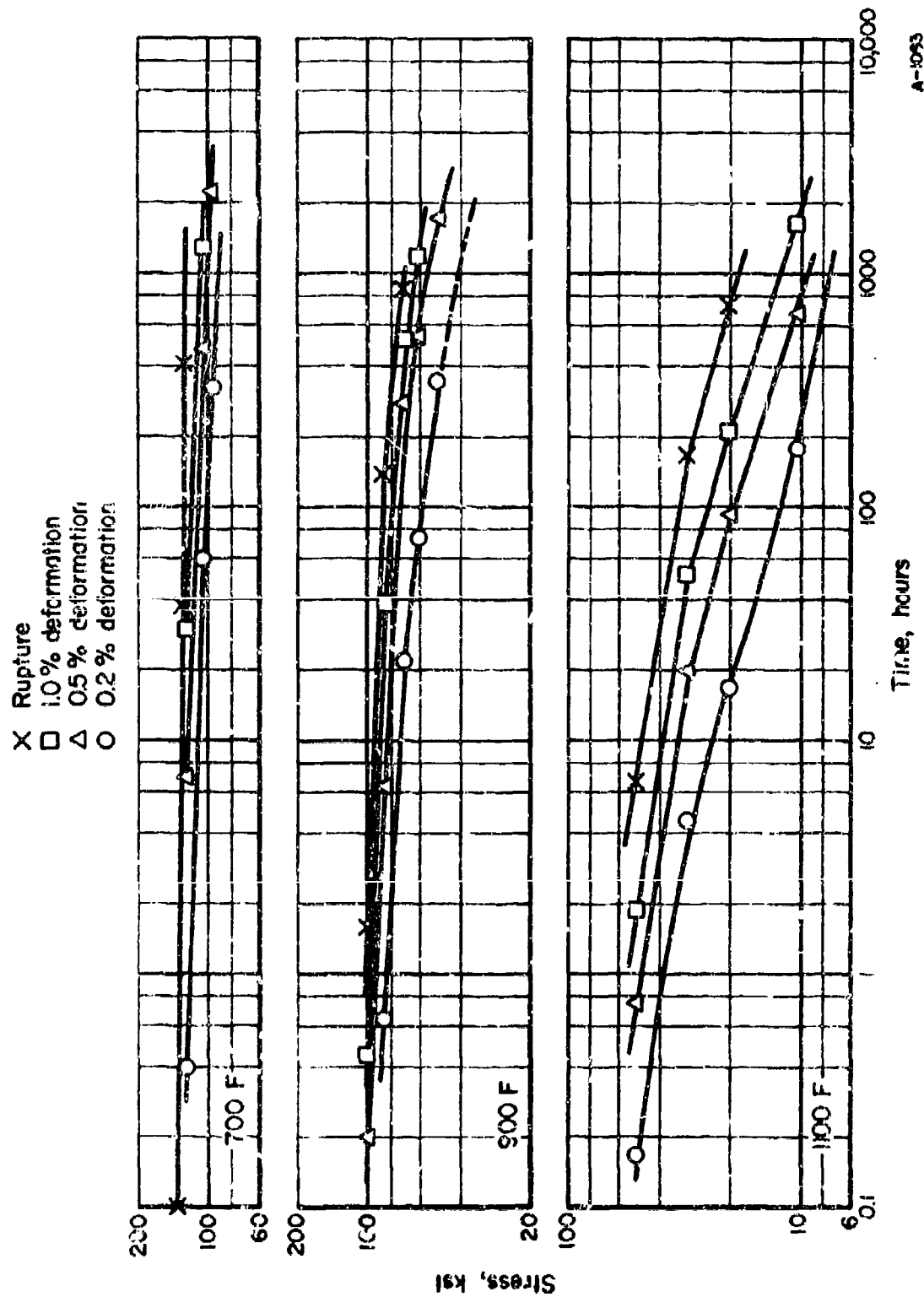


FIGURE 10. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 15-5 PH (H1025) FORGED BAR
(TRANSVERSE)

HP 9Ni-4Co-0.20C Alloy Steel

Material Description

HP 9Ni-4Co-0.20C steel was developed specifically to have high hardenability combined with good fracture toughness. It can be welded in the fully heat-treated condition and achieve essentially 100 percent joint efficiency without preheat or postheat treatment. The 0-20C grade is available as sheet, strip, plate, bars, forgings, and tubing.

The material used for this program was consumable electrode vacuum melted and from Republic Steel Heat 3821003. It was obtained as a 2-1/4 inch x 6-inch x 84 inch forged bar and had the following composition:

<u>Chemical Composition</u>	<u>Percent</u>
Carbon	0.19
Manganese	0.36
Phosphorus	0.008
Sulfur	0.007
Silicon	0.04
Nickel	9.30
Chromium	0.80
Molybdenum	1.04
Vanadium	0.08
Cobalt	4.70
Iron	Balance

Processing and Heat Treating

The specimen layout for this alloy is shown in Figure 11. Specimens were rough machined in the as-received annealed condition, heat treated as follows:

- (1) normalize at 1650 F, 1 hour, air-cool,
- (2) austenitize at 1500 F, 1 hour, oil quench,
- (3) single temper at 1025 F, 6 hours, air cool and then finish machined.

Test Results

Tension. Results of tension tests in the longitudinal and transverse directions at room temperature, 500 F, 700 F, and 900 F are given in Table IX.

52	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252	1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296	1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318	1319	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	1334	1335	1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Stress-strain curves at temperature are presented in Figures 12 and 13. Effect-of-temperature curves are shown in Figure 16.

Compression. Results of compression tests in the longitudinal and transverse directions at room temperature, 500 F, 700 F, and 900 F are given in Table X. Compressive stress-strain and tangent modulus curves at temperature are presented in Figures 14 and 15. Effect-of-temperature curves are shown in Figure 17.

Shear. Test results for pin shear tests in both the longitudinal and transverse directions at room temperature are given in Table XI.

Impact. Charpy test results at room temperature for longitudinal and transverse specimens are given in Table XII.

Fracture Toughness. Results of six slow-bend type tests are given in Table XIII. The size ratio, $2.5 (K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, therefore the K_Q value in the table is not a valid K_{IC} value by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were conducted at room temperature, 500 F, and 700 F for transverse specimens, both unnotched and notched. Results are given in tabular form in Tables XIV and XV. S-N curves are presented in Figures 18 and 19.

Creep and Stress Rupture. Tests were performed at 500 F, 700 F, and 900 F for transverse specimens. Tabular test results are given in Table XVI. Log-stress versus log-time curves are presented in Figure 20.

Stress Corrosion. Specimens were tested as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000 hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this steel is 6.4×10^{-6} in/in/F for 80 F to 900 F.

Density. The density of this alloy is 0.284 lb/in³.

TABLE IX. TENSILE TEST RESULTS FOR HP 9Ni-4Co-0.20C FORGED BAR

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Reduction in Area, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>					
1L-1	198.0	181.0	17.5	67.1	28.0
1L-2	196.0	181.0	17.5	68.2	26.6
1L-3	197.0	180.0	17.5	68.4	26.4
<u>Transverse at Room Temperature</u>					
1T-1	197.0	180.0	14.5	55.0	27.9
1T-2	197.0	180.0	14.5	56.3	27.7
1T-3	197.0	180.0	15.0	57.1	26.4
<u>Longitudinal at 500 F</u>					
1L-4	178.0	165.0	16.0	66.7	25.4
1L-5	182.0	165.0	16.0	65.4	26.0
1L-6	179.0	165.0	15.5	64.4	26.7
<u>Transverse at 500 F</u>					
1T-4	179.0	166.0	14.0	56.0	25.7
1T-5	179.0	166.0	14.0	55.1	25.8
1T-6	179.0	166.0	14.0	55.8	26.2
<u>Longitudinal at 700 F</u>					
1L-7	172.0	155.0	16.0	64.4	24.0
1L-8	170.0	155.0	16.5	69.4	24.3
1L-9	169.0	156.0	16.0	66.4	24.6
<u>Transverse at 700 F</u>					
1T-7	169.0	151.0	14.5	58.4	24.9
1T-8	169.0	154.0	14.5	57.4	24.8
1T-9	168.0	153.0	14.5	57.7	24.4

TABLE IX. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Reduction in Area, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at 900 F</u>					
1L-10	148.0	130.0	18.0	69.6	22.2
1L-11	148.0	130.0	18.0	69.9	22.2
1L-12	147.0	129.0	18.0	59.9	21.7
<u>Transverse at 900 F</u>					
1T-10	147.0	128.0	16.0	61.2	25.3
1T-11	147.0	128.0	16.0	59.5	23.4
1T-12	147.0	131.0	16.0	60.6	22.7

TABLE X. COMPRESSION TEST RESULTS FOR
HP 9Ni-4Co-0.20C FORGED BAR

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>		
2L-1	196.0	27.6
2L-2	198.0	27.7
2L-3	196.0	28.0
<u>Transverse at Room Temperature</u>		
2T-1	194.0	27.1
2T-2	195.0	28.6
2T-3	195.0	28.2
<u>Longitudinal at 500 F</u>		
2L-4	169.0	25.7
2L-5	173.0	26.5
2L-6	173.0	26.9
<u>Transverse at 500 F</u>		
2T-4	171.0	27.0
2T-5	171.0	25.9
2T-6	172.0	25.7
<u>Longitudinal at 700 F</u>		
2L-7	162.0	24.8
2L-8	158.0	25.5
2L-9	157.0	25.0
<u>Transverse at 700 F</u>		
2T-7	159.0	25.1
2T-8	156.0	24.9
2T-9	159.0	25.9

TABLE X . (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at 900 F</u>		
2L-10	137.0	23.3
2L-11	135.0	24.8
2L-12	134.0	25.0
<u>Transverse at 900 F</u>		
2T-10	136.0	23.2
2T-11	135.0	24.5
2T-12	136.0	24.4

TABLE XI. SHEAR TEST RESULTS FOR HP 9Ni-4Co-0.20C
FORGED BAR

Specimen No.	Ultimate Shear Strength, ksi
<u>Longitudinal</u>	
4L-1	123.0
4L-2	124.0
4L-3	124.0
<u>Transverse</u>	
4T-1	120.0
4T-2	124.0
4T-3	123.0

TABLE XII. IMPACT TEST RESULTS FOR
HP 9Ni-4Co-0.20 C FORGED BAR

Specimen Number	Energy, ft/lbs
<u>Longitudinal</u>	
10L-1	73.0
10L-2	37.0
10L-3	62.0
10L-4	63.0
10L-5	77.0
<u>Transverse</u>	
10T-1	50.0
10T-2	54.0
10T-3	52.0
10T-4	56.0
10T-5	54.0

TABLE XIII. FRACTURE TOUGHNESS TEST RESULTS
FOR HP 9N1-4Co-0.20C FORGED BAR

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	$K_Q^{(a)}$
<u>Transverse</u>							
3T	1.254	.648	.631	6,650	5	2.8	107.3
2T	1.255	.640	.632	7,450	5	2.7	115.3
1T	1.255	.692	.631	8,200	5	3.1	146.3
<u>Longitudinal</u>							
2L	1.504	.861	.755	12,650	6	3.4	186.1
3L	1.502	.870	.755	12,800	6	3.5	193.4
1L	1.504	.735	.757	9,450	6	2.5	104.3

(a) Candidate fracture toughness values, K_Q , are invalid as K_{Ic} values since a , T ,
 $< 2.5 \left(\frac{K_Q}{TYS} \right)$.

TABLE XIV. AXIAL LOAD FATIGUE TEST RESULTS
FOR UNNOTCHED HP 9Ni-4Co-0.20C
FORGED BAR (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-1	120	26,900
5-2	110	23,900
5-3	100	34,000
5-4	90	58,200
5-5	80	69,900
5-6	70	124,100
5-7	60	5,024,900
5-8	50	11,920,400 (a)
<u>500 F</u>		
5-17	140	12,000
5-19	135	23,600
5-18	130	21,100
5-20	125	17,400
5-16	120	10,115,000 (a)
5-14	100	109,000
5-15	100	12,916,000 (a)
<u>700 F</u>		
5-26	180	30,000
5-25	160	746,400
5-24	150	360,900
5-22	140	25,600 (b)
5-23	140	2,052,400
5-21	130	2,702,000
5-27	120	50,800
5-28	120	10,277,000 (a)

(a) Did not fail.

(b) Failed at thermocouple.

TABLE XV. AXIAL LOAD FATIGUE TEST RESULTS FOR
NOTCHED ($K_t=3.0$) HP 9Ni-4Co-0.20C
FORGED BAR (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, Cycles
<u>Room Temperature</u>		
5-31	90	11,900
5-37	85	17,900
5-32	80	21,400
5-35	75	13,300
5-33	70	21,600
5-36	65	50,900
5-34	60	12,381,800 ^(a)
<u>500 F</u>		
5-41	90	7,800
5-42	85	11,600
5-43	80	27,300
5-44	75	13,200
5-45	70	25,200
5-46	65	34,400
5-47	60	31,300
5-48	50	99,000
5-59	40	60,600
5-60	40	109,900
5-61	30	10,850,900 ^(a)
<u>700 F</u>		
5-51	90	10,900
5-52	80	14,400
5-53	75	32,400
5-54	70	1,699,300
5-55	65	28,100
5-56	65	85,200
5-57	60	51,900
5-58	50	12,986,000 ^(a)

(a) Did not fail.

TABLE XVI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF HP 9Ni-4Co-0.20 FORGED BAR (TRANSVERSE)

Specimen No.	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent				Initial Strain, Percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
3-3	168	500	---	---	---	---	---	On Loading	8.9	44.7	---
3-5	160	500	0.03	0.10	2750(b)	---	---	816.5(a)	2.245	---	0.00053
3-10	145	500	120	4500(b)	---	---	---	793.9	0.748	---	0.00015
3-1	160	700	0.01	0.02	0.07	0.33	1.5	5.8	12.6	58.1	0.65
3-4	150	700	0.04	0.13	1.5	17.5	6.5	250.7	16.3	56.6	0.015
3-7	125	700	1.5	21	360	1370(b)	---	431.5(a)	1.092	---	0.00044
3-9	105	700	30	350	2650(b)	---	---	598.7(a)	0.777	---	0.00013
3-2	120	900	0.02	0.04	0.12	0.30	0.67	1.5	12.6	58.4	2.6
3-6	95	900	0.15	0.7	12	49	92	100.7	4.4	7.9	0.013
3-8	80	900	1.5	13.5	120	278	450	478.0	3.7	5.6	0.0027
3-11	55	900	25	140	640	1650(b)	---	358.3(a)	0.630	---	0.00062
3-12	35	900	270	740	1700(b)	4100(b)	---	763.9(a)	0.415	---	0.00021

(a) Test discontinued.

(b) Estimate.

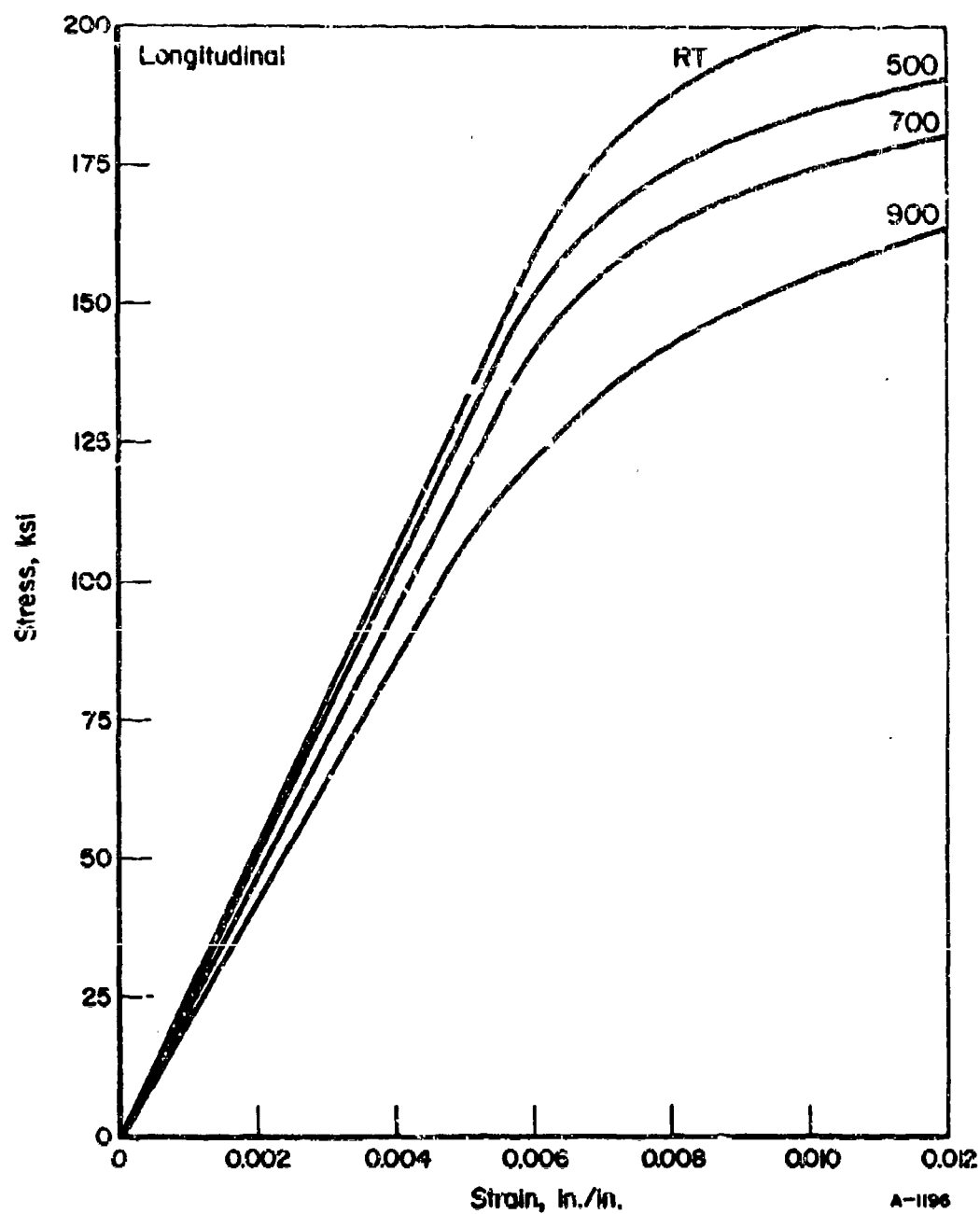


FIGURE 12. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
HP 9Ni-4Co-0.20C FORGED BAR (LONGITUDINAL)

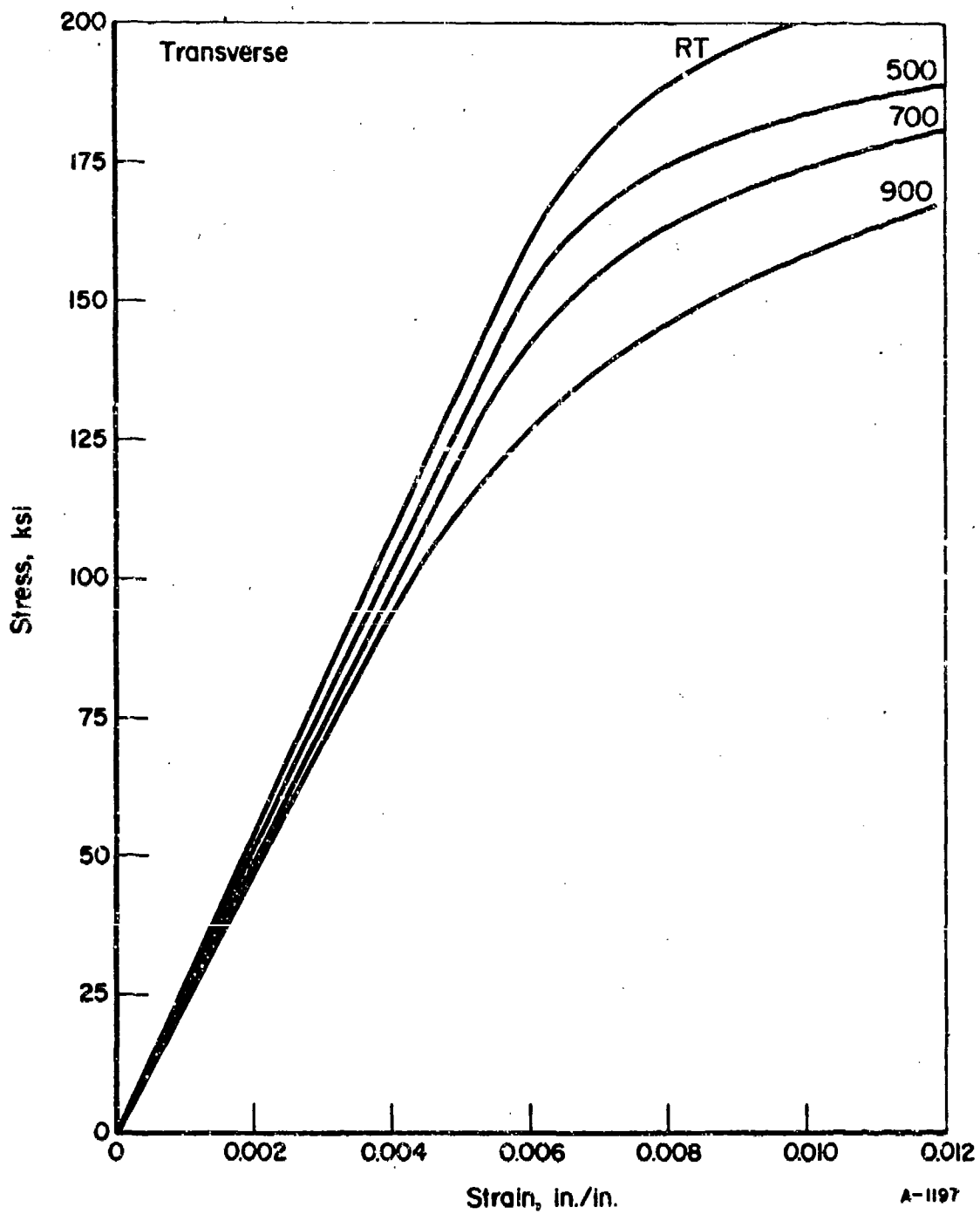


FIGURE 13. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
HP 9Ni-4Co-0.20C FORGED BAR (TRANSVERSE)

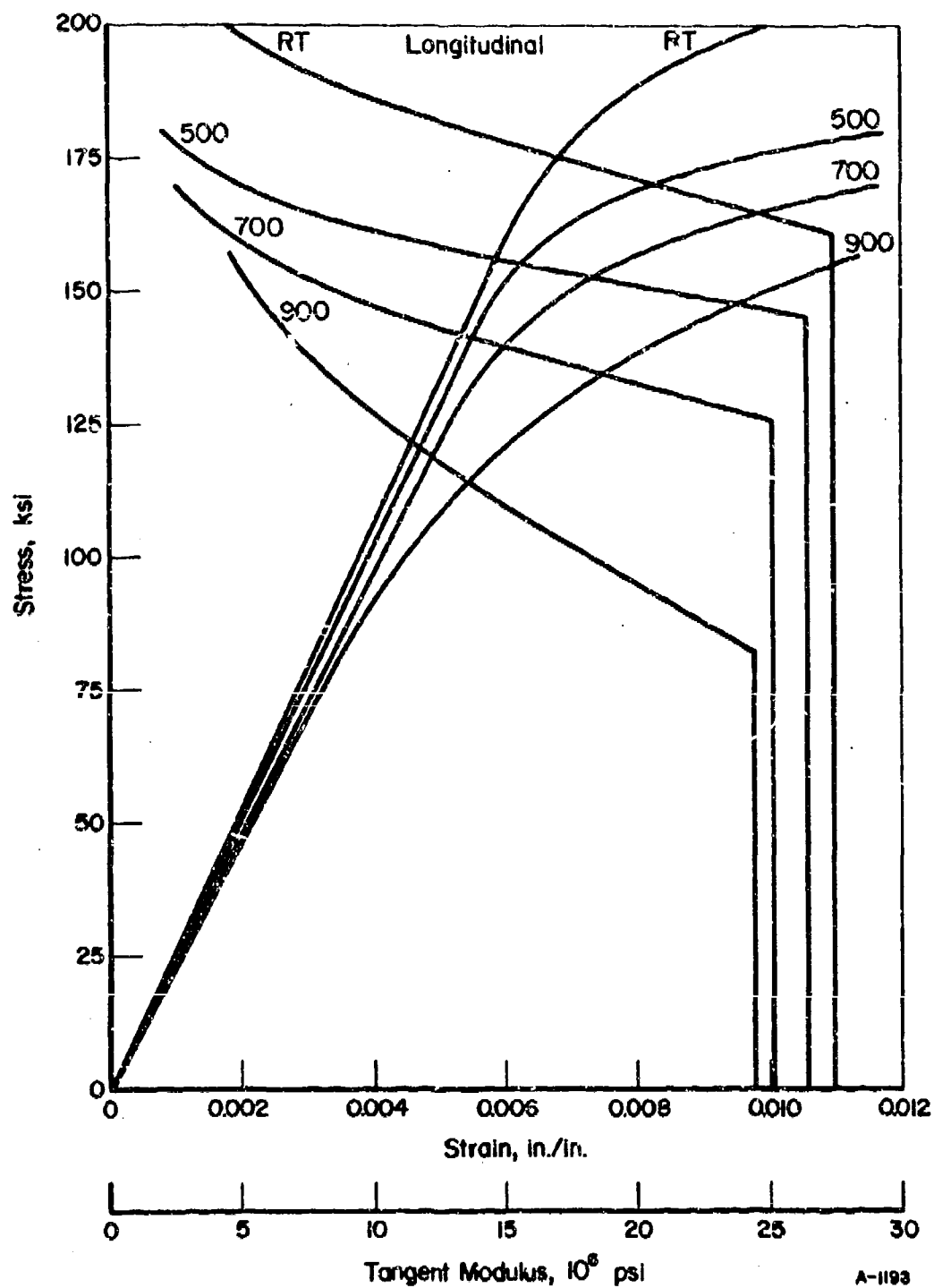


FIGURE 14. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR HP 9Ni-4Co-0.20C FORGED BAR (LONGITUDINAL)

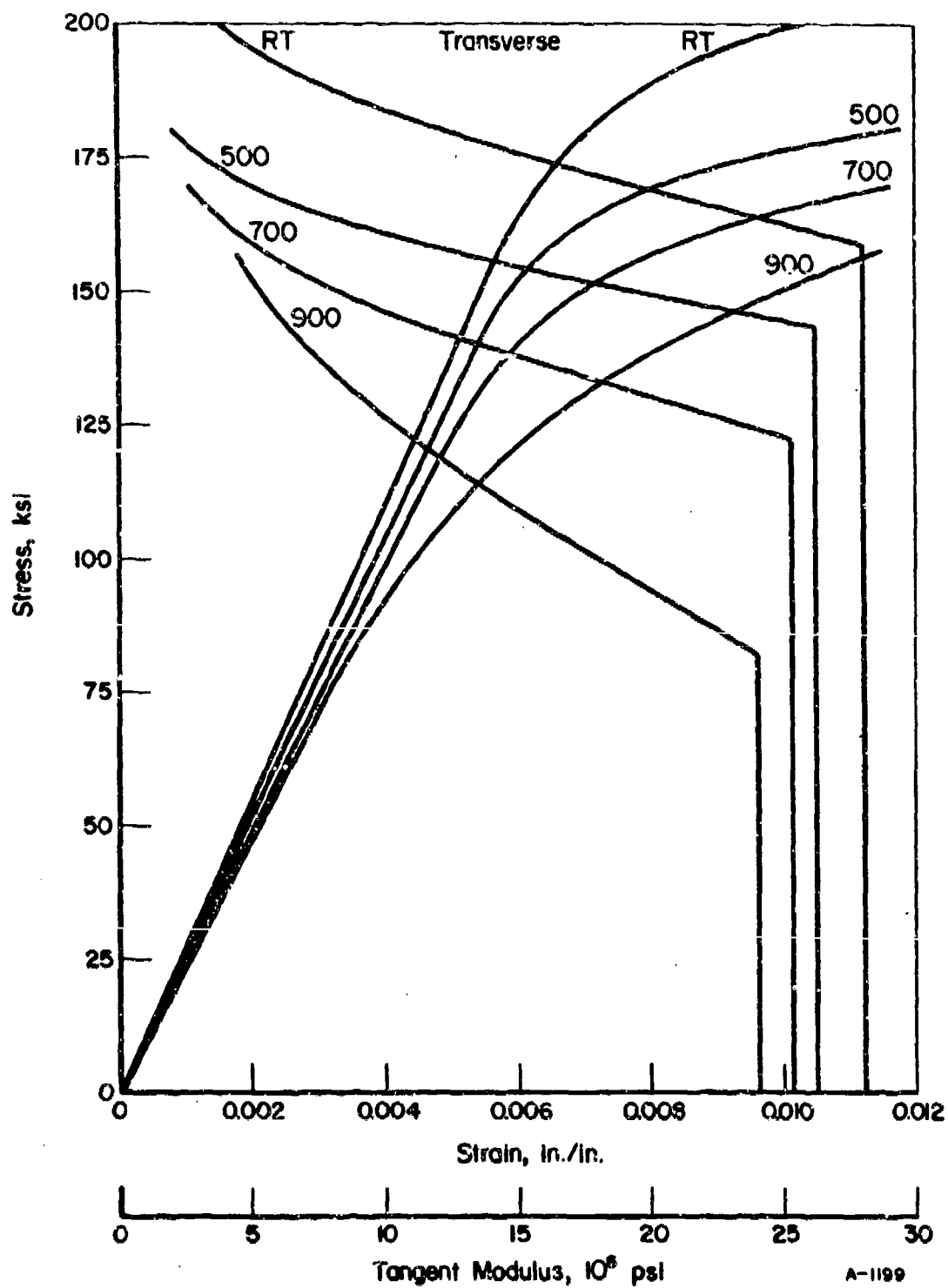


FIGURE 15. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR HP 9Ni-4Co-0.20C FORGED BAR (TRANSVERSE)

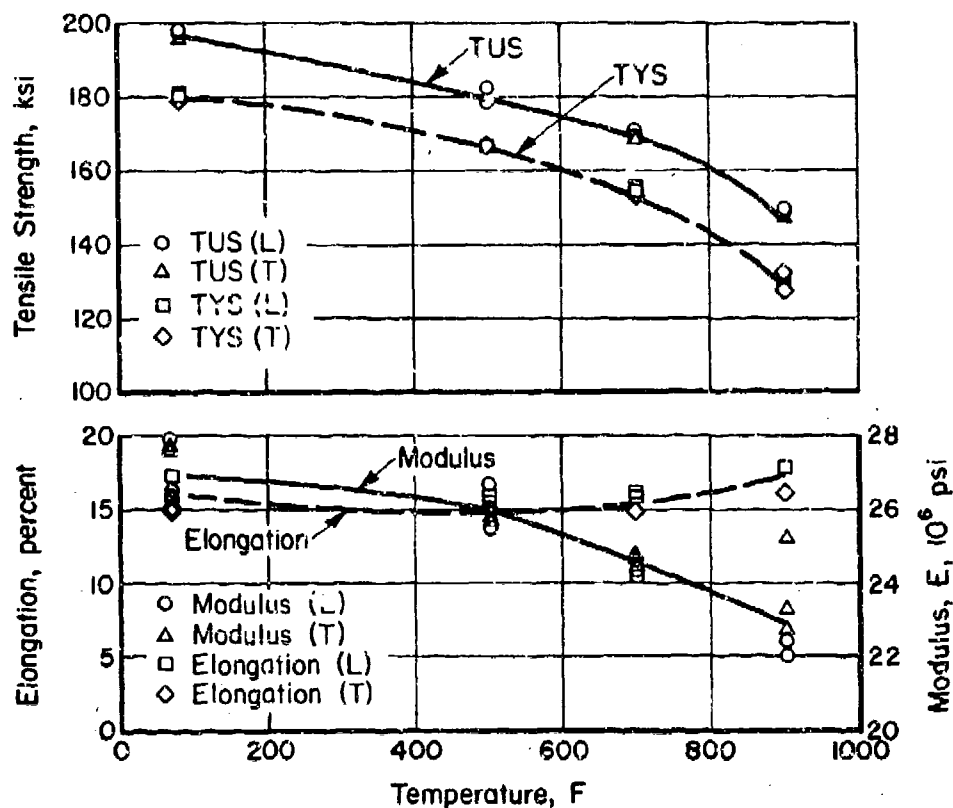


FIGURE 16. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HP 9Ni-4Co-0.20C FORGED BAR

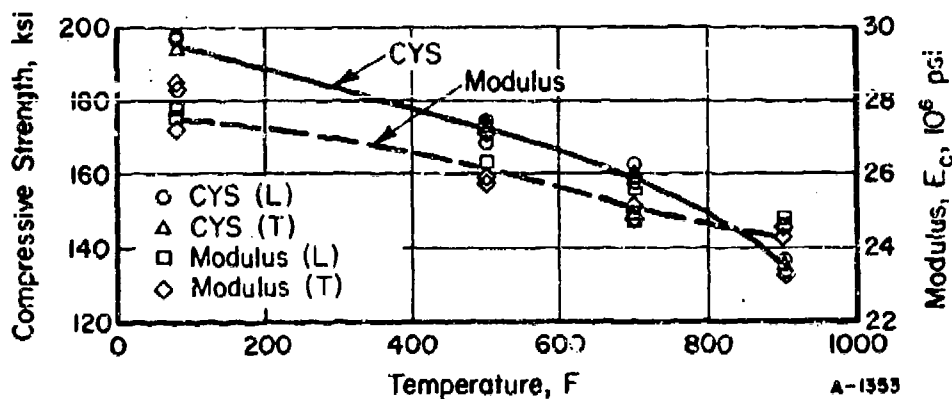


FIGURE 17. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HP 9Ni-4Co-0.20C FORGED BAR

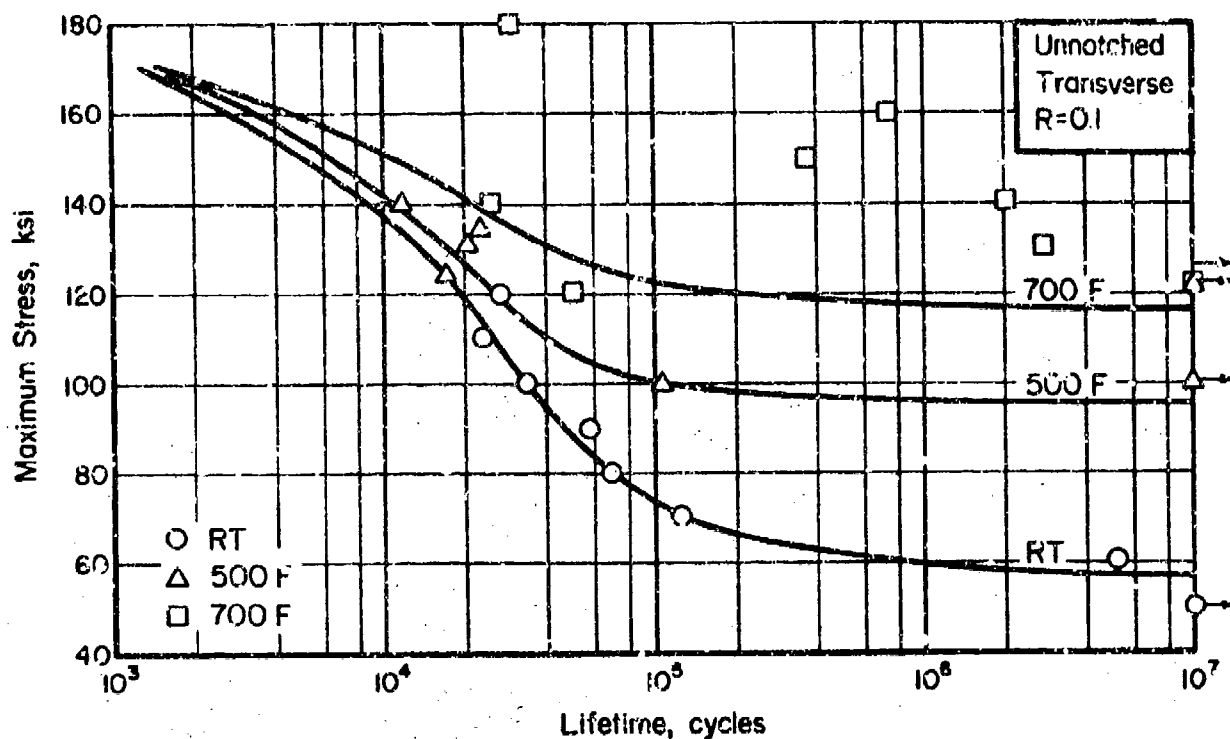


FIGURE 18. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED HP 9Ni-4Co-0.20C FORGED BAR

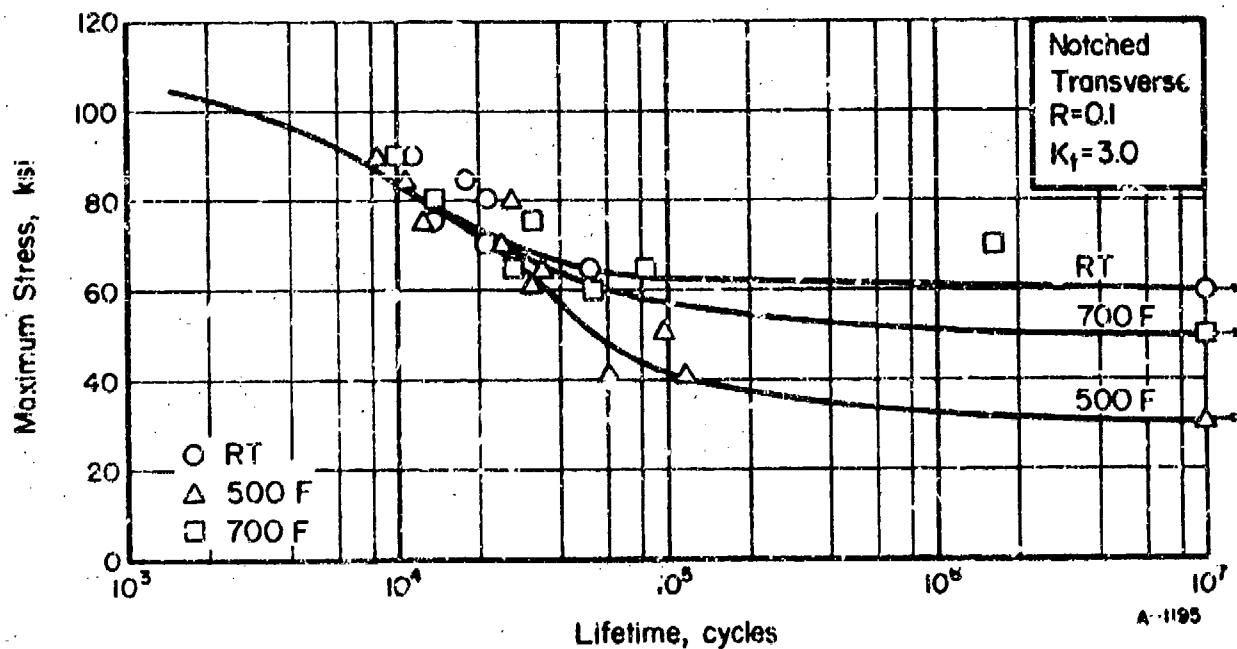


FIGURE 19. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) HP 9Ni-4Co-0.20C FORGED BAR

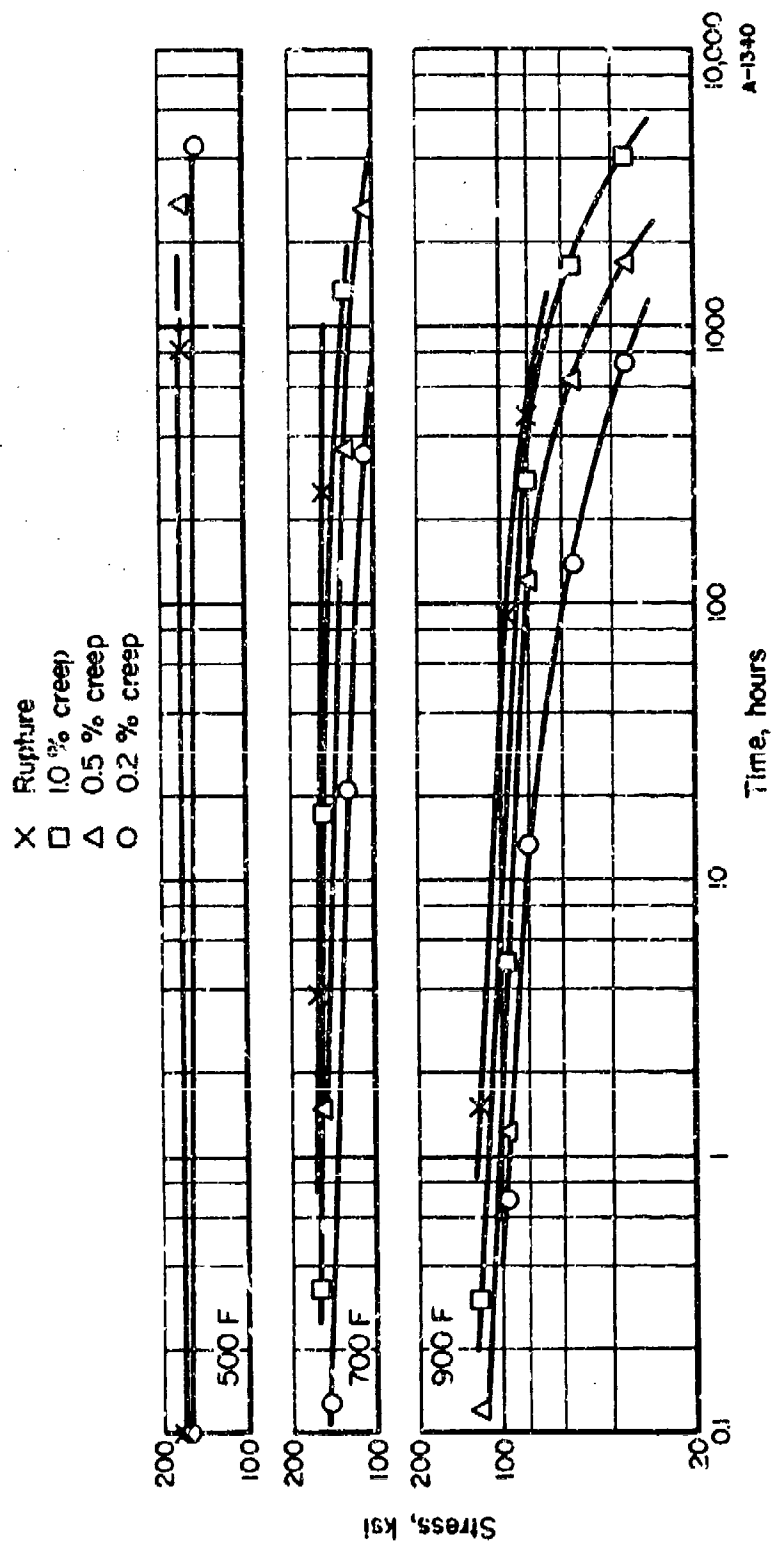


FIGURE 20. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR HP 9Ni-4Co-0.20C FORGED BAR (TRANSVERSE)

PH 13-8 Mo Stainless Steel

Material Description

This alloy is a martensitic precipitation hardenable stainless steel developed by the Armco Steel Corporation. It can be heat treated to high strength levels and exhibits good ductility in the transverse direction. This transverse direction toughness is obtained by composition balance designed to prevent formation of delta ferrite in the structure, low carbon content to minimize grain boundary carbide precipitation, and double vacuum melting to reduce alloy segregation. The alloy reportedly has excellent resistance to stress corrosion cracking in synthetic seawater and excellent resistance to corrosion in a 5 percent salt spray environment.

The material used in this evaluation was obtained as a 4-inch x 5-inch x 5 foot forged bar from Armco Heat 1W0241. The composition was as follows:

<u>Chemical Composition</u>	<u>Percent</u>
Carbon	0.035
Manganese	0.01
Phosphorus	0.002
Sulfur	0.003
Silicon	0.02
Chromium	12.62
Nickel	8.24
Molybdenum	2.16
Aluminum	1.02
Iron	Balance

Processing and Heat Treating

The specimen layout for PH 13-8 Mo is shown in Figure 21. Specimens were machined in the as-received condition A and then heat treated at 1000 F for 4 hours to Condition H 1000.

Test Results

Tension. Results of tests in the longitudinal and transverse directions at room temperature, 500 F, 700 F, and 900 F are given in Table XVII. Tensile stress-strain curves at temperature are shown in Figures 22 and 23. Effect-of-temperature curves are presented in Figure 26.

Compression. Test results are given in Table XVIII for longitudinal and transverse specimens at room temperature, 500 F, 700 F, and 900 F. Compressive stress-strain and tangent modulus curves at temperature are presented in Figures 24 and 25. Effect-of-temperature curves are shown in Figure 27.

51	52	53	54
55	56	57	58
59	510	511	512
513	514	515	516
517	518	519	520

54	524	544	11.4	21.1	21.5	21.9
56	528	548	11.8	21.5	21.9	22.3
512	532	552	11.2	21.5	21.9	22.3
516	536	556	11.6	21.5	21.9	22.3
520	540	560	12.0	21.5	21.9	22.3

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FIGURE 21. SPECIMEN LAYOUT FOR PH 13-8 Mo (H1000) FORGED BAR

Shear. Results of pin shear tests at room temperature for longitudinal and transverse specimens are shown in Table XIX.

Impact. Charpy test results are shown in Table XX.

Fracture Toughness. Results of slow-bend type tests are shown in Table XXI. The size ratio, $2.5 (K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, therefore, the K_Q value shown in the table is not a valid K_{Ic} value by existing ASTM criteria.

Fatigue. Axial load fatigue tests were conducted at room temperature, 400 F, and 700 F for transverse specimens, both unnotched and notched. Test results are given in Tables XXII and XXIII. S-N curves are shown in Figures 28 and 29.

Creep and Stress Rupture. Tests were performed at 500 F, 700 F, and 900 F for transverse specimens. Tabular test results are given in Table XXIV. Log-stress versus log-time curves are presented in Figure 30.

Stress Corrosion. Specimens were tested as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000 hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 6.6×10^{-6} in/in/F for 80 F to 900 F.

Density. The density of this material is 0.279 lb/in³.

TABLE XVII. TENSILE TEST RESULTS FOR PH 13-8 Mo
(H1000) FORGED BAR

Specimen Number	Ultimate Tensile Strength, ksi	0.2 percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Reduction in Area, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>					
1L-1	194.0	190.0	13.0	49.5	27.7
1L-2	193.0	187.0	14.5	58.5	27.6
1L-3	191.0	185.0	12.5	47.5	27.9
<u>Long Transverse at Room Temperature</u>					
1T-1	192.0	187.0	13.0	51.0	27.3
1T-2	188.0	179.0	14.5	55.5	28.3
1T-3	191.0	184.0	14.0	56.0	28.4
<u>Longitudinal at 500 F</u>					
1L-4	170.0	163.0	12.5	58.0	27.4
1L-5	169.0	164.0	13.0	59.0	27.3
1L-6	168.0	163.0	12.0	53.0	26.5
<u>Long Transverse at 500 F</u>					
1T-4	168.0	162.0	11.0	49.5	25.2
1T-5	166.0	163.0	12.5	56.0	25.5
1T-6	171.0	166.0	11.0	50.0	25.2
<u>Longitudinal at 700 F</u>					
1L-7	158.0	148.0	14.0	59.5	24.7
1L-8	158.0	153.0	11.0	45.0	24.9
1L-9	157.0	153.0	13.0	55.0	25.8
<u>Long Transverse at 700 F</u>					
1T-7	159.0	148.0	12.0	51.0	26.2
1T-8	156.0	150.0	12.5	50.0	24.7
1T-9	157.0	151.0	13.0	56.0	24.4
<u>Longitudinal at 900 F</u>					
1L-10	129.0	119.0	21.0	71.5	22.1
1L-11	129.0	119.0	21.5	69.0	20.7
1L-12	127.0	119.0	21.0	71.0	22.8
<u>Long Transverse at 900 F</u>					
1T-10	125.0	116.0	22.5	72.0	20.4
1T-11	128.0	120.0	22.0	71.0	22.3
1T-12	128.0	118.0	20.0	68.5	21.6

TABLE XVIII. COMPRESSION TEST RESULTS
FOR PH 13-8 Mo (H1000)
FORGED BAR

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>		
2L-1	183.0	30.8
2L-2	193.0	30.6
2L-3	187.0	28.7
<u>Long Transverse at Room Temperature</u>		
2T-1	199.0	29.9
2T-2	198.0	30.0
2T-3	202.0	30.0
<u>Longitudinal at 500 F</u>		
2L-4	160.0	25.9
2L-5	155.0	26.1
2L-6	160.0	26.6
<u>Long Transverse at 500 F</u>		
2T-4	170.0	25.9
2T-5	170.0	25.8
2T-6	169.0	25.4
<u>Longitudinal at 700 F</u>		
2L-7	148.0	25.8
2L-8	157.0	25.8
2L-9	147.0	25.7
<u>Long Transverse at 700 F</u>		
2T-7	160.0	23.6
2T-8	159.0	25.2
2T-9	157.0	24.5

TABLE XVIII. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at 900 F</u>		
2L-10	120.0	22.6
2L-11	115.0	23.2
2L-12	120.0	23.7
<u>Long Transverse at 900 F</u>		
2T-10	122.0	23.1
2T-11	119.0	23.0
2T-12	123.0	23.0

TABLE XIX. SHEAR TEST RESULTS FOR PH 13-8 Mo
 (H1000) FORGED BAR

Specimen Number	Ultimate Shear Strength, ksi
<u>Longitudinal</u>	
4L-1	122.0
4L-2	122.0
4L-3	120.0
<u>Long Transverse</u>	
4T-1	123.0
4T-2	123.0
4T-3	123.0

TABLE XX. IMPACT TEST RESULTS FOR
PH 13-8 Mo (H1000)
FORGED BAR

Specimen Number	Energy, ft/lbs
<u>Longitudinal</u>	
10L-1	36.0
10L-2	35.5
10L-3	34.5
10L-4	33.5
10L-5	31.0
10L-6	33.5
<u>Long Transverse</u>	
10T-1	28.0
10T-2	28.0
10T-3	26.0
10T-4	28.0
10T-5q	29.0
10T-6	27.0

TABLE XXI. FRACTURE TOUGHNESS TEST RESULTS FOR PH 13-8 Mo
(H1000) FORGED BAR (LONGITUDINAL)

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	$K_Q^{(a)}$
5L	1.500	.879	.742	10,750	6	3.5	169.0
4L	1.501	.880	.741	10,500	6	3.6	166.0
3L	1.499	.868	.741	10,300	6	3.5	158.9
2L	1.500	.871	.741	9,800	6	3.5	151.9
1L	1.499	.870	.741	10,500	6	3.5	162.8

(a) Candidate fracture toughness values, K_Q , are invalid as K_{Ic} values since a , T ,
 $< 2.5 \left(\frac{K_Q}{TYS} \right)^2$.

TABLE XXII. AXIAL LOAD FATIGUE TEST RESULTS FOR
UNNOTCHED PH 13-8 Mo (H1000)
FORGED BAR (LONGITUDINAL)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-1	215.0	14,490
5-2	210.0	26,120
5-3	205.0	35,190
5-4	200.0	61,570
5-5	195.0	65,470
5-6	190.0	247,050
5-7	180.0	333,330
5-8	175.0	4,404,800
5-9	170.0	785,900
5-10	170.0	730,900
5-11	160.0	458,000
5-12	150.0	10,010,000 ^(a)
<u>400 F</u>		
5-15	200.0	100
5-14	190.0	17,400
5-12	180.0	151,000
5-11	170.0	42,900
5-16	170.0	1,015,600 ^(a)
5-18	165.0	10,329,900 ^(a)
5-17	160.0	10,407,300 ^(a)
<u>700 F</u>		
5-22	170.0	(b)
5-26	165.0	200
5-24	160.0	33,960
5-21	155.0	28,900
5-29	150.0	945,500 ^(a)
5-23	150.0	10,090,700 ^(a)

(a) Did not fail.

(b) Failed on loading.

TABLE XXIII. AXIAL LOAD FATIGUE TEST RESULTS FOR
NOTCHED ($K_t = 3.0$) PH 13-8 Mo (H1000)
FORGED BAR (LONGITUDINAL)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-1	180.0	1,410
5-2	160.0	1,900
5-3	140.0	3,800
5-5	120.0	7,910
5-6	100.0	32,830
5-7	80.0	72,800
5-8	60.0	210,000
5-9	50.0	17,555,600 ^(a)
<u>400 F</u>		
5-11	180.0	1,100
5-12	170.0	1,700
5-13	160.0	1,800
5-14	140.0	1,350
5-15	120.0	1,500
5-16	100.0	8,100
5-17	90.0	26,400
5-18	80.0	60,500
5-20	70.0	14,754,700 ^(a)
5-19	60.0	10,192,200 ^(a)
<u>700 F</u>		
5-21	100.0	3,900
5-23	90.0	18,300
5-26	85.0	16,900
5-22	80.0	599,800
5-27	75.0	1,344,700
5-24	70.0	5,358,700
5-25	60.0	14,928,700 ^(a)

(a) Did not fail.

TABLE XXIV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL)

Specimen No.	Stress, ksi	Temp, °F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0					
3-3	171.5	500	---	---	---	---	---	---	On Loading	9.6	44.2	---
3-4	165	500	---	---	---	---	---	---	0.01	9.6	54.7	---
3-5	160	500	0.12	2.6	107	1100	---	0.904	1078.0 (c)	1.897	---	0.00025
3-10	140	500	2000 (b)	4800 (b)	---	---	---	0.763	1027.5 (a)	0.822	---	0.00004
3-8	140	700	0.07	0.25	1.1	3.6	10	0.894	29.4	14.8	61.4	0.16
3-2	120	700	5	15	130	720	4230 (b)	0.571	836.9 (a)	1.585	---	0.0003
3-9	100	700	70	620	3600 (b)	---	---	0.507	667.6 (a)	0.714	---	0.00010
3-6	200	900	---	0.08	0.15	0.4	0.8	0.637	3.4	21.5	63.8	2.5
3-1	70	900	0.2	0.6	3.5	9.5	33	0.363	196.3	23.9	68.5	0.044
3-7	55	900	1.0	3.3	30	175	540	0.277	1012.8 (c)	2.85	---	0.0018
3-11	30	900	95	625	2600 (b)	---	---	0.033	524.8 (a)	0.233	---	0.00015

(a) Test discontinued.

(b) Estimate.

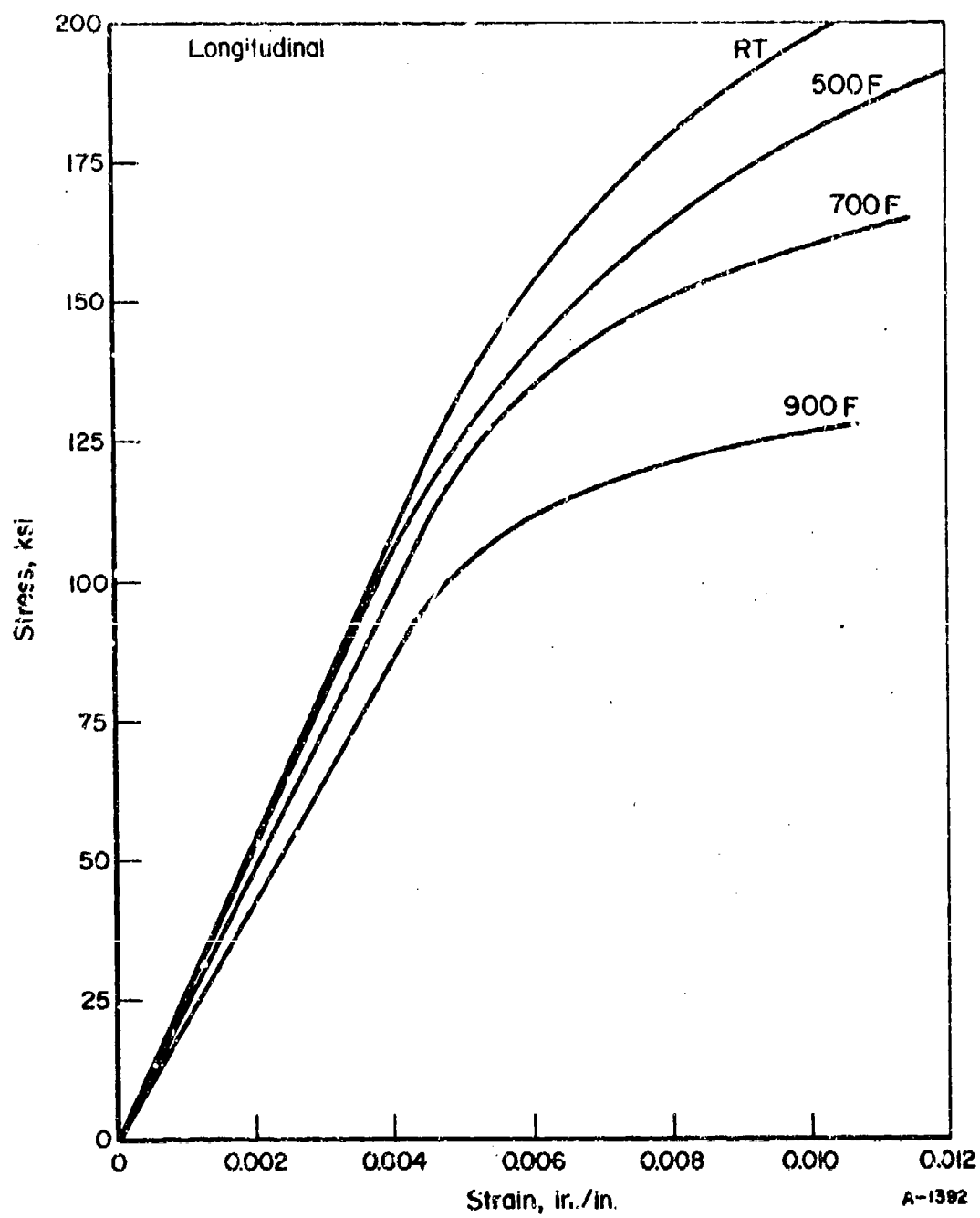


FIGURE 22. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
PH 13-8 Mo (H1000) FORGED BAR
(LONGITUDINAL)

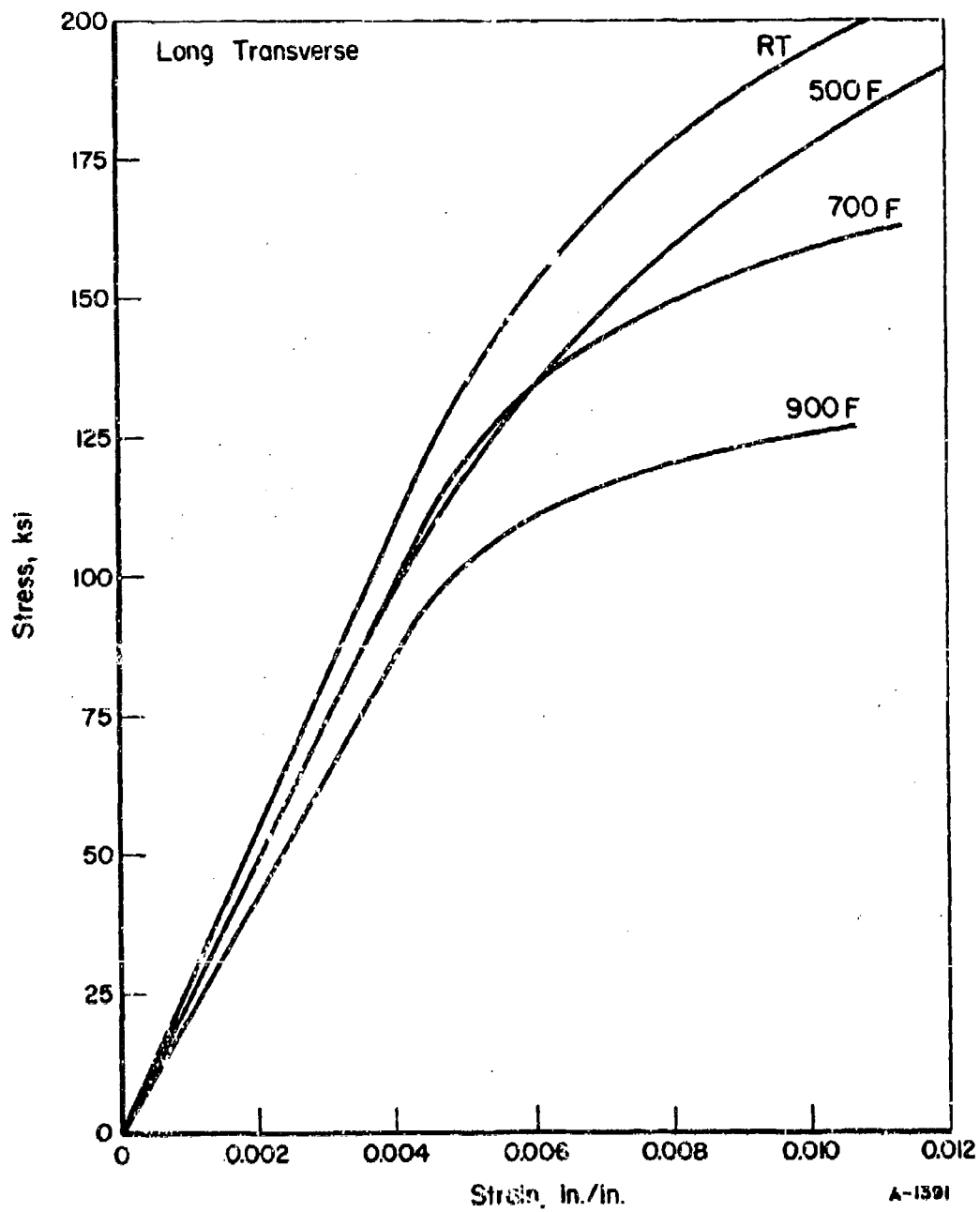


FIGURE 23. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
PH 13-8 Mo (H1000) FORGED BAR
(LONG TRANSVERSE)

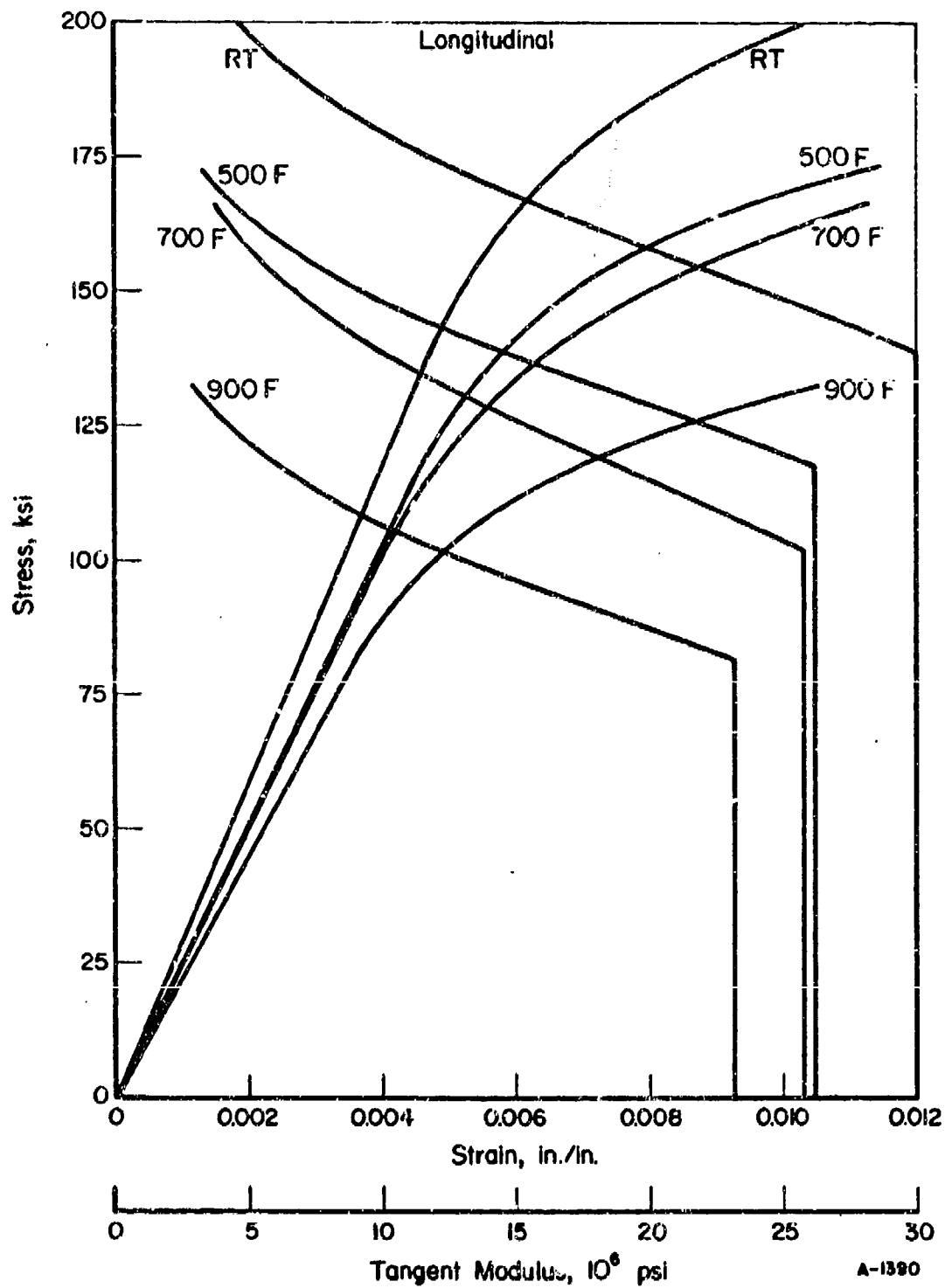


FIGURE 24. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR PH 13-8 Mo (H1000) FORCED BAR (LONGITUDINAL)

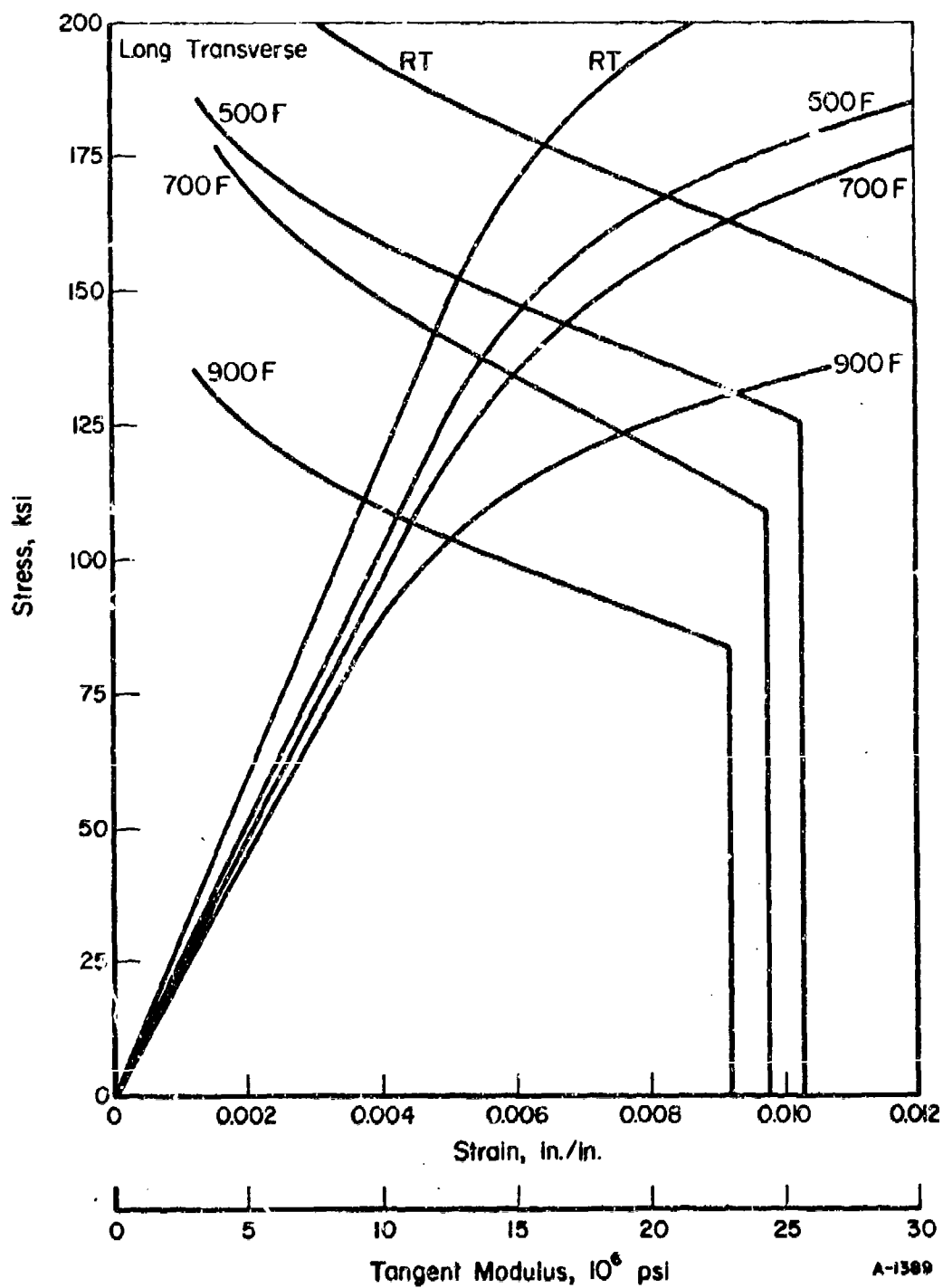


FIGURE 25. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR PH 13-8 Mo (H1000) FORGED BAR (LONG TRANSVERSE)

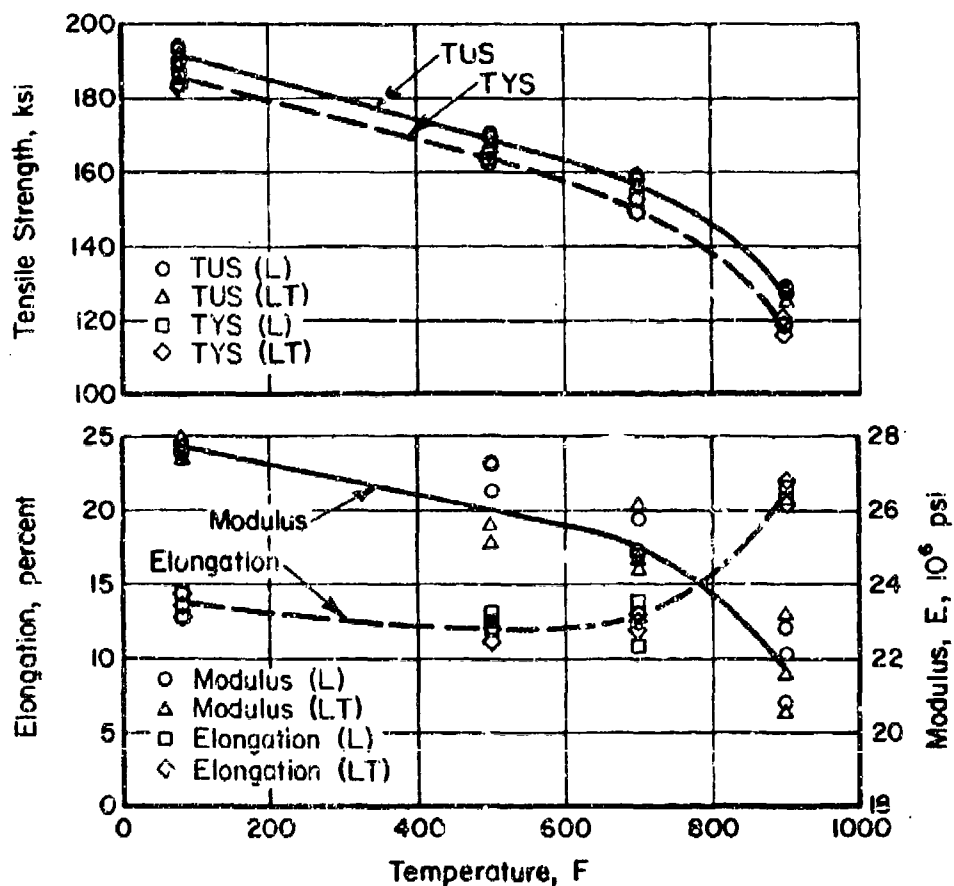


FIGURE 26. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PH 13-8 Mo (H1000) FORGED BAR

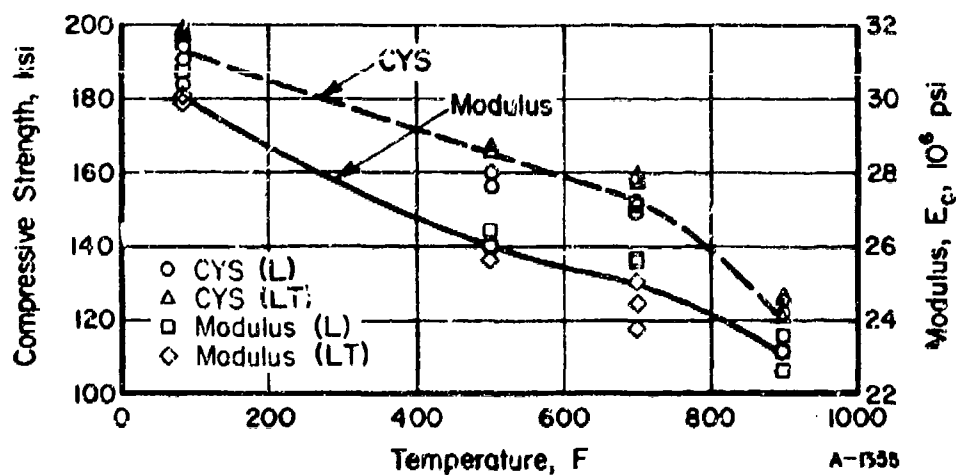


FIGURE 27. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF PH 13-8 Mo (H1000) FORGED BAR

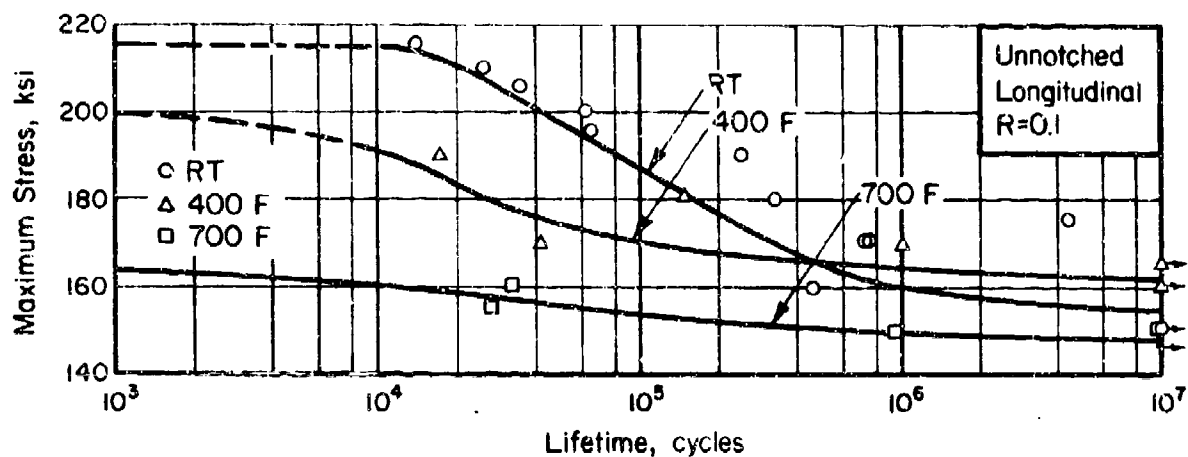


FIGURE 28. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED PH 13-8 Mo (H1000) FORGED BAR

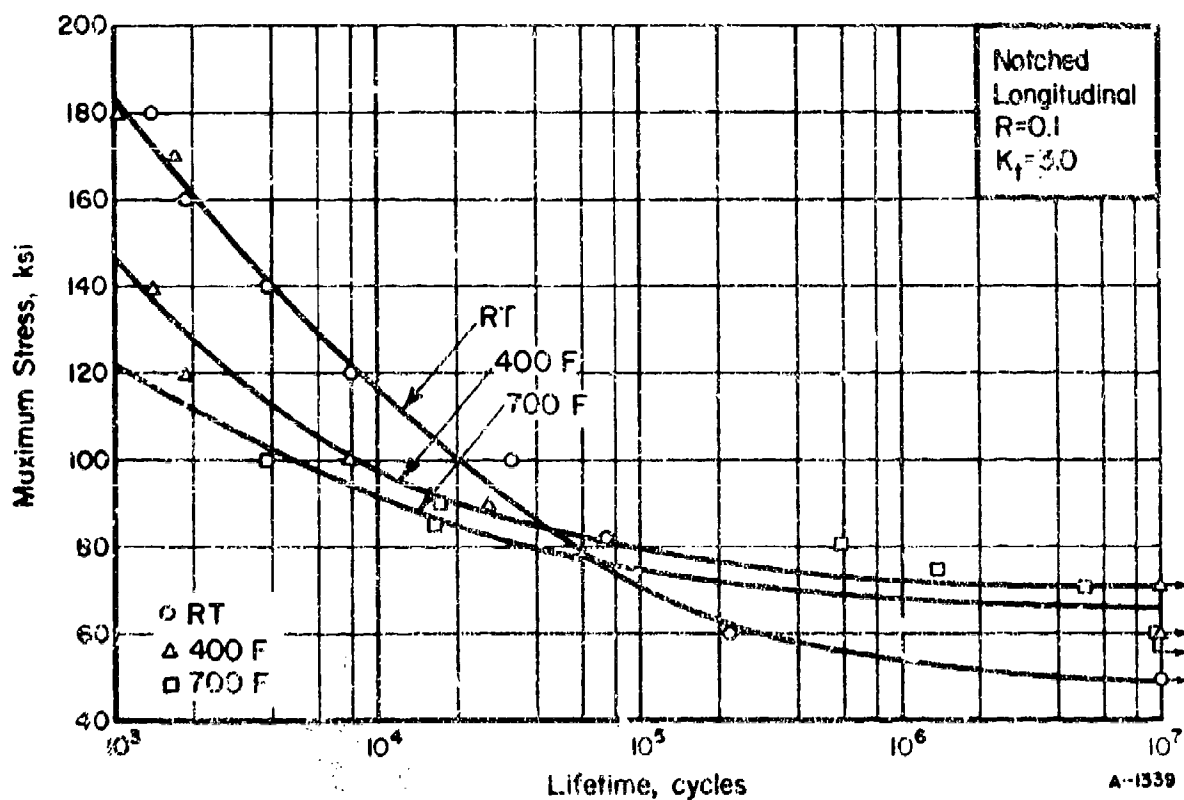


FIGURE 29. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) PH 13-8 Mo (H1000) FORGED BAR

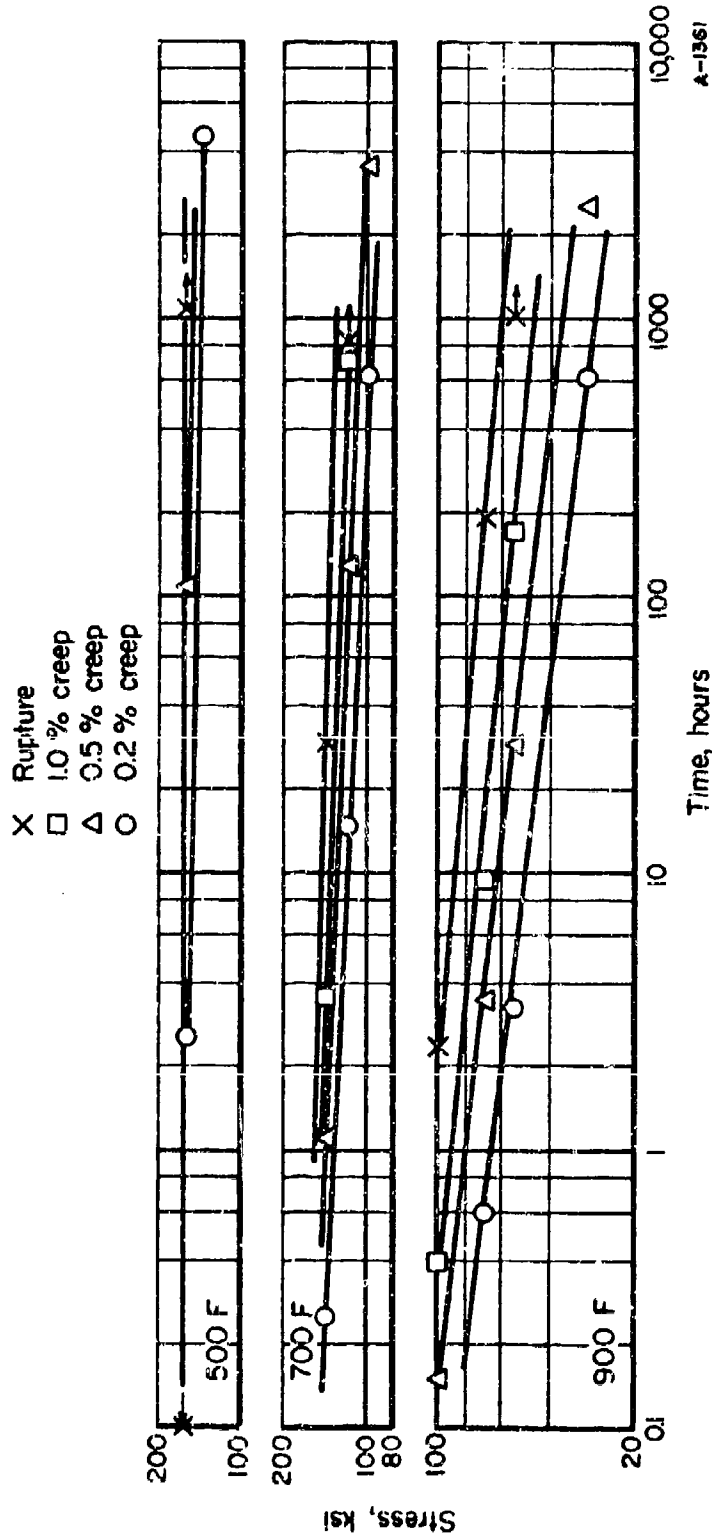


FIGURE 30. STRESS-RUPTURE AND CREEP DEFORMATION CURVES FOR PH 13-8 Mo (H1000) FORCED BAR (LONGITUDINAL.)

7049-T76 Aluminum Extrusions

Material Description

Alloy 7049 was developed by Kaiser Aluminum and Chemical Corporation to have a strength level in the range of 7075-T6 and 7079-T6 coupled with a high resistance to stress corrosion cracking. Initial development and production was in the form of forgings and hand forgings. Further development has been in plates and extrusions.

The material evaluated was a 4-inch x 4-inch extrusion supplied by Kaiser with the following composition:

<u>Chemical Composition</u>	<u>Percent</u>
Zinc	7.6
Magnesium	2.5
Copper	1.5
Chromium	0.15
Silicon	0.25 max
Iron	0.35 max
Titanium	0.10 max
Manganese	0.20 max
Aluminum	Balance

Processing and Heat Treating

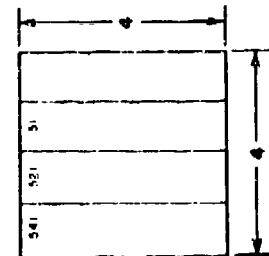
The specimen layout for 7049 is shown in Figure 31. Specimens were tested in the as-received -T76 temper.

Test Results

Tension. Test results for longitudinal and transverse specimens at room temperature, 250 F, 350 F, and 500 F are given in Table XXV. Room temperature short transverse tensile test results are also given in Table XXV. Stress-strain curves at temperature are presented in Figures 32 and 33. Effect-of-temperature curves are shown in Figure 36.

Compression. Test results for longitudinal and transverse specimens at room temperature, 250 F, 350 F, and 500 F are given in Table XXVI. Compressive stress-strain and tangent modulus curves at temperature are presented in Figures 34 and 35. Effect-of-temperature curves are presented in Figure 37.

Shear. Pin shear test results for longitudinal and transverse specimens at room temperature are shown in Table XXVII.



51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	125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Impact. Charpy test results for longitudinal and transverse specimens at room temperature are shown in Table XXVII.

Fracture Toughness. Slow-bend type tests curve performed for six longitudinal specimens. Results are shown in Table XXIX. Since the size ratio, $2.5 (K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, the K_Q values are not valid K_{Ic} values by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were conducted on transverse specimens at room temperature, 250 F, and 350 F. Tabular test results are presented in Tables XXX and XXXI. S-N curves are shown in Figures 38 and 39.

Creep and Stress-Rupture. Results for transverse tests at 250 F, 350 F, and 500 F are shown in Table XXXII. Log-stress versus log-time curves are presented in Figure 40.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000 hour test duration.

Thermal Expansion. Coefficient of thermal expansion for this alloy is 12.9×10^{-6} in/in/F for 80 F to 212 F.

Density. The density for this material is 0.099 lb/in³.

TABLE XXV. TENSILE TEST RESULTS FOR
7049-T76 EXTRUSIONS

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 1 Inch, percent	Reduction in Area, percent	Tensile Modulus, 10 ⁵ psi
<u>Longitudinal at Room Temperature</u>					
1L-1	81.1	72.2	13.0	35.9	10.6
1L-2	82.1	74.6	13.0	34.7	11.0
1L-3	86.9	81.0	12.0	36.3	10.5
<u>Transverse at Room Temperature</u>					
1T-1	76.2	67.2	11.5	23.3	9.5
1T-2	76.2	67.7	11.0	23.2	9.9
1T-3	76.2	67.4	11.0	23.3	10.2
<u>Short Transverse at Room Temperature</u>					
1ST-1	76.2	68.0	12.0	22.6	10.4
1ST-2	76.4	67.8	12.0	22.6	10.3
1ST-3	76.2	67.4	11.0	22.6	10.6
<u>Longitudinal at 250 F</u>					
1L-4	64.1	62.6	22.0	52.4	9.5
1L-5	64.4	63.3	22.0	52.6	9.0
1L-6	64.6	63.8	22.5	54.2	9.5
<u>Transverse at 250 F</u>					
1T-4	58.4	56.0	15.5	34.1	9.3
1T-5	58.4	56.4	18.0	34.5	9.4
1T-6	59.9	56.8	17.0	34.7	9.3
<u>Longitudinal at 350 F</u>					
1L-7	48.1	47.9	24.0	68.2	8.3
1L-8	48.9	48.7	26.0	70.4	8.3
1L-9	48.2	47.8	29.0	74.3	8.0
<u>Transverse at 350 F</u>					
1T-7	44.8	43.5	18.5	50.4	8.4
1T-8	43.9	42.8	22.0	52.0	8.3
1T-9	46.1	45.0	18.0	51.6	8.6
<u>Longitudinal at 500 F</u>					
1L-10	17.0	16.8	40.0	93.0	8.0
1L-11	17.6	17.5	35.0	92.6	8.0
1L-12	18.8	18.6	39.0	93.3	6.9
<u>Transverse at 500 F</u>					
1T-10	16.5	16.2	37.0	88.0	7.2
1T-11	16.6	16.2	29.0	87.2	7.4
1T-12	16.2	15.9	31.0	86.8	7.4

TABLE XXVI. COMPRESSION TEST RESULTS FOR
7049-T76 EXTRUSIONS

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>		
2L-1	75.3	10.6
2L-2	81.4	11.0
2L-3	79.6	11.1
<u>Transverse at Room Temperature</u>		
2T-1	75.0	10.8
2T-2	73.0	9.9
2T-3	76.2	10.9
<u>Longitudinal at 250 F</u>		
2L-4	66.4	9.5
2L-5	71.2	10.0
2L-6	71.7	10.1
<u>Transverse at 250 F</u>		
2T-4	64.0	10.4
2T-5	62.6	9.9
2T-6	63.2	10.2
<u>Longitudinal at 350 F</u>		
2L-7	53.8	8.7
2L-8	53.8	9.1
2L-9	50.4	9.1
<u>Transverse at 350 F</u>		
2T-7	48.8	8.9
2T-8	48.7	9.2
2T-9	49.0	9.1
<u>Longitudinal at 500 F</u>		
2L-10	18.6	6.6
2L-11	19.4	6.3
2L-12	19.0	6.5
<u>Transverse at 500 F</u>		
2T-10	17.6	8.0
2T-11	17.8	7.4
2T-12	17.7	7.7

TABLE XXVII. SHEAR TEST RESULTS FOR
7049-T76 EXTRUSIONS

Specimen Number	Ultimate Shear Strength, ksi
<u>Longitudinal</u>	
4L-1	45.1
4L-2	45.6
4L-3	44.6
4L-4	46.2
<u>Transverse</u>	
4T-1	42.6
4T-2	44.9
4T-3	41.8
4T-4	41.8

TABLE XXVIII. IMPACT TEST RESULTS FOR 7049-T76
EXTRUSIONS AT ROOM TEMPERATURE

Specimen Number	Energy, ft/lbs
<u>Longitudinal</u>	
10L-1	6.5
10L-2	5.0
10L-3	6.5
10L-4	5.0
10L-5	7.0
10L-6	4.5
<u>Transverse</u>	
10T-1	1.5
10T-2	2.0
10T-3	1.5
10T-4	2.0
10T-5	1.0
10T-6	1.5

TABLE XXIX. FRACTURE TOUGHNESS TEST RESULTS FOR 7049-T76 EXTRUSIONS (LONGITUDINAL)

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	$K_Q^{(a)}$
6L	1.500	.830	.750	3,440	6	3.1	47.7
5L	1.500	.848	.7	3,870	6	3.2	55.3
1L	1.50	.866	.751	3,720	6	3.4	56.0
3L	1.501	.850	.750	3,850	6	3.3	55.9
2L	1.502	.859	.750	3,650	6	3.4	54.0
4L	1.500	.854	.750	3,800	6	3.3	55.8

(a) Candidate fracture toughness values, K_Q , are invalid as K_{Ic} values since $a, T,$
 $< 2.5 \left(\frac{K_Q}{TYS} \right)^2$.

TABLE XXX. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED
7049-T76 EXTRUSIONS (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-4	65.0	9,300
5-3	60.0	68,340
5-2	55.0	86,030
5-1	50.0	177,220
5-5	45.0	7,075,410
5-6	40.0	9,717,860
<u>250 F</u>		
5-17	65.0	11,950
5-19	62.5	26,240
5-15	60.0	29,530
5-20	57.5	81,050
5-16	55.0	289,210
5-21	52.5	540,560
5-18	50.0	10,199,430 ^(a)
<u>350 F</u>		
5-7	60.0	19,790
5-10	55.0	54,760
5-8	55.0	217,850
5-12	52.5	45,110
5-11	50.0	1,457,640
5-13	47.5	400,420
5-9	45.0	6,006,900
5-22	40.0	11,429,780 ^(a)

(a) Did not fail.

TABLE XXXI. AXIAL LOAD FATIGUE TEST RESULTS FOR
NOTCHED ($K_t = 3.0$) 7049-T76
EXTRUSIONS (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-19	40.0	6,840
5-1	35.0	15,410
5-2	30.0	19,030
5-3	25.0	31,270
5-4	20.0	144,750
5-5	17.5	334,050
5-6	15.0	558,590
5-7	13.5	331,080
5-8	10.0	15,146,300 ^(a)
<u>250 F</u>		
5-16	35.0	7,640
5-21	32.5	9,690
5-17	30.0	20,040
5-22	27.5	23,810
5-23	25.0	19,860
5-18	25.0	934,090
5-24	20.0	841,400
5-25	10.0	843,100
5-26	5.0	10,016,000 ^(a)
<u>350 F</u>		
5-9	35.0	9,350
5-10	30.0	20,760
5-11	25.0	19,620
5-12	20.0	84,670
5-13	15.0	159,410
5-14	10.0	652,300
5-15	5.0	10,062,800 ^(a)

(a) Did not fail.

TABLE XXXII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF 7049-T76 ALUMINUM EXTRUSIONS (TRANSVERSE)

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, Percent				Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
7049-31	50	250	0.2	0.7	2.7	6.4	---	20.7	11.1	43.0	0.14
7049-33	40	250	10	50	183	322	450	580.4	14.1	48.7	0.0018
7049-36	35	250	40	145	---	---	---	264.3 (a)	0.726	--	--
7049-39	30	250	50	350	1670 (b)	---	---	550.7 (a)	0.571	--	0.00021
7049-32	25	350	0.8	2.4	6.5	9	---	15.2	15.6	68.8	0.062
7049-34	15	350	22	52	125	260	270	337.8	18.5	77.1	0.0027
7049-35	9.5	350	145	390	1160 (b)	---	---	432.8 (a)	0.353	--	0.00042
7049-37	7	500	0.4	1.0	2.6	4.5	7.1	14.6	50.4	85.5	0.17
7049-38	5	500	1.7	5.0	12	25	43	124.6	40.0	73.1	0.037
7049-310	3.5	500	5	25	80	160	320	1192.4	26.6	45.5	0.0066
7049-31.	1.5	500	60	425	2100 (b)	---	---	748.8 (a)	0.322	--	0.00018

(a) Test discontinued.

(b) Estimate.

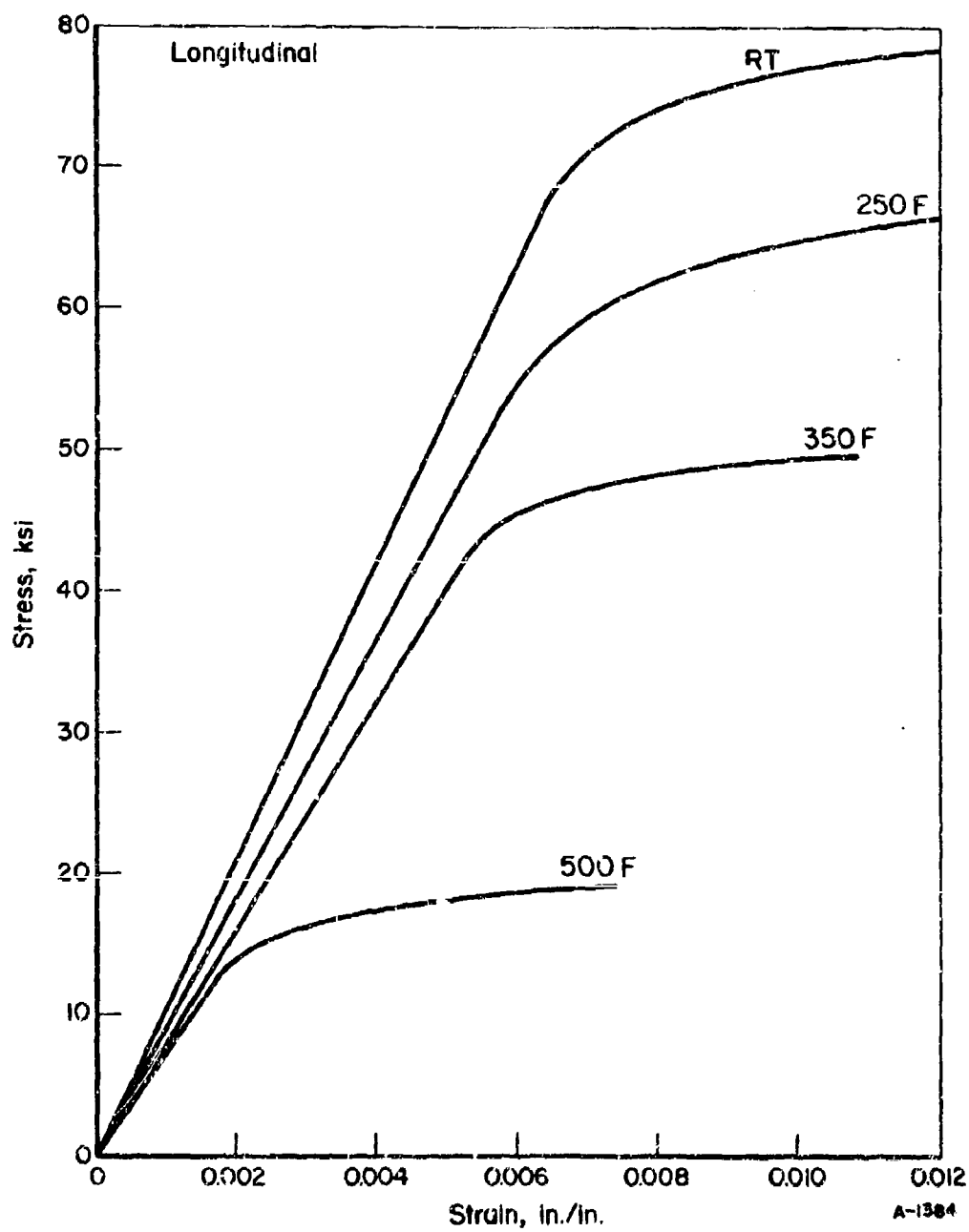


FIGURE 32. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 7049-T76 EXTRUSIONS (LONGITUDINAL)

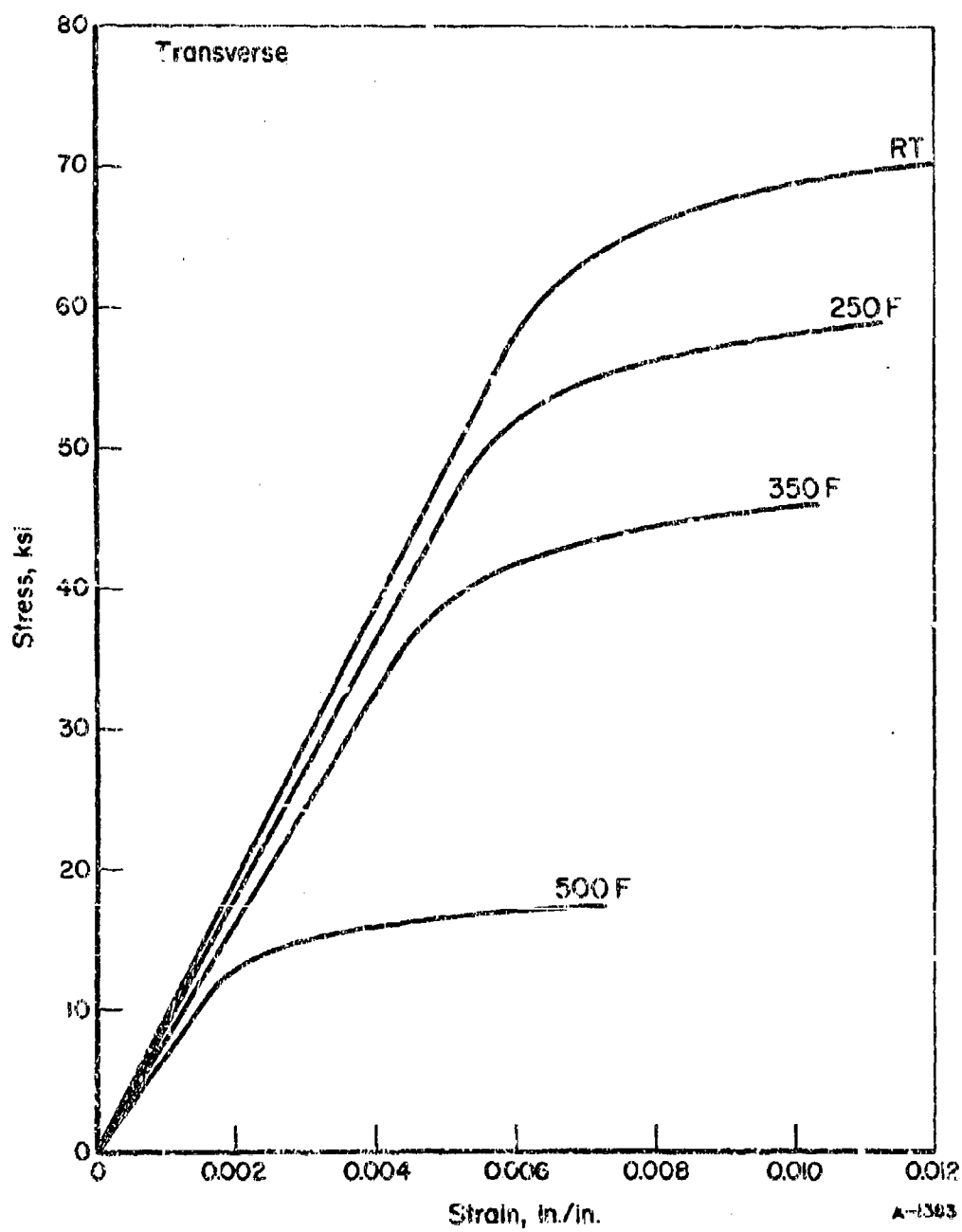


FIGURE 33. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 7049-T7C EXTRUSIONS (TRANSVERSE)

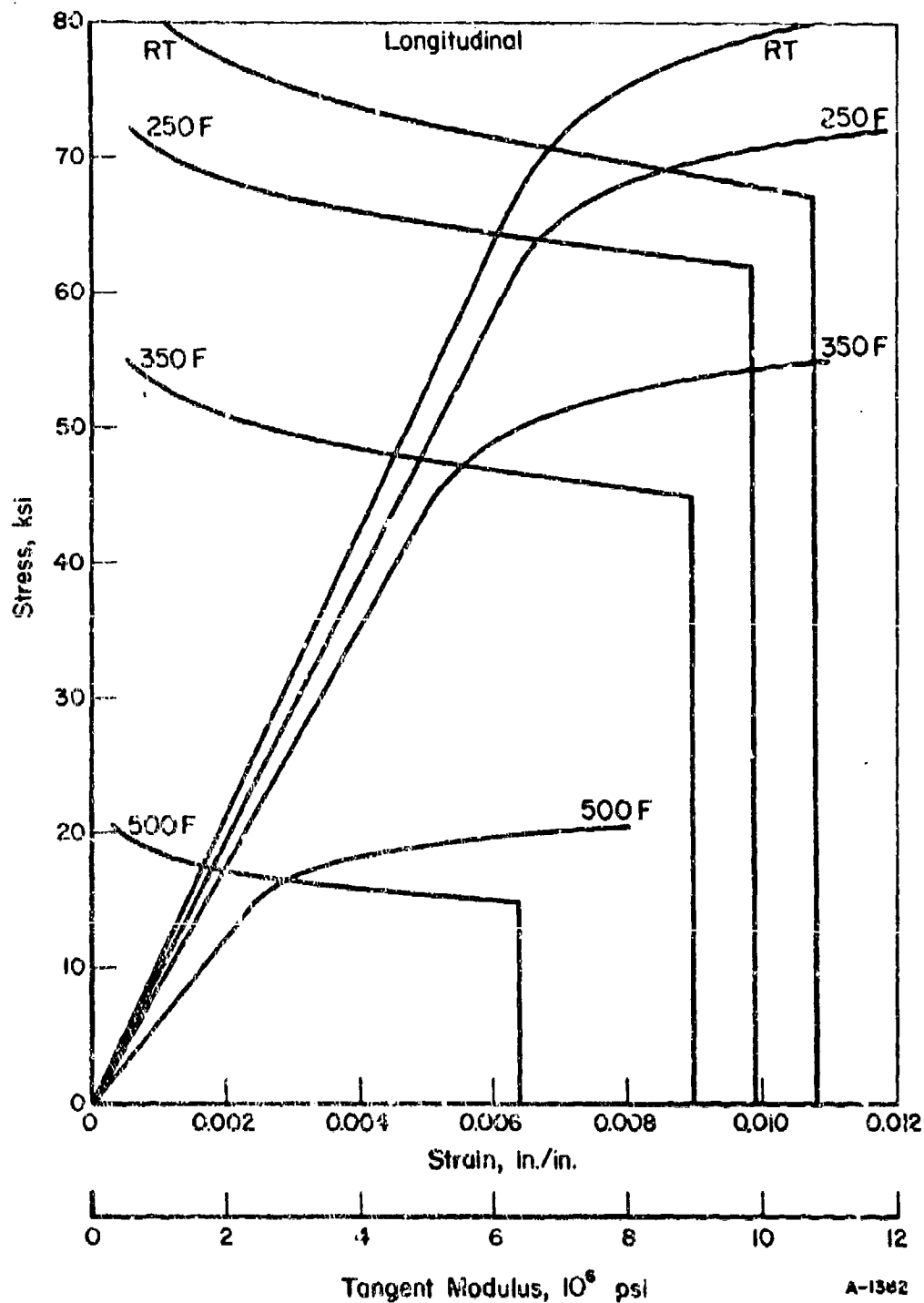


FIGURE 34. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 7049-T76 EXTRUSION (LONGITUDINAL)

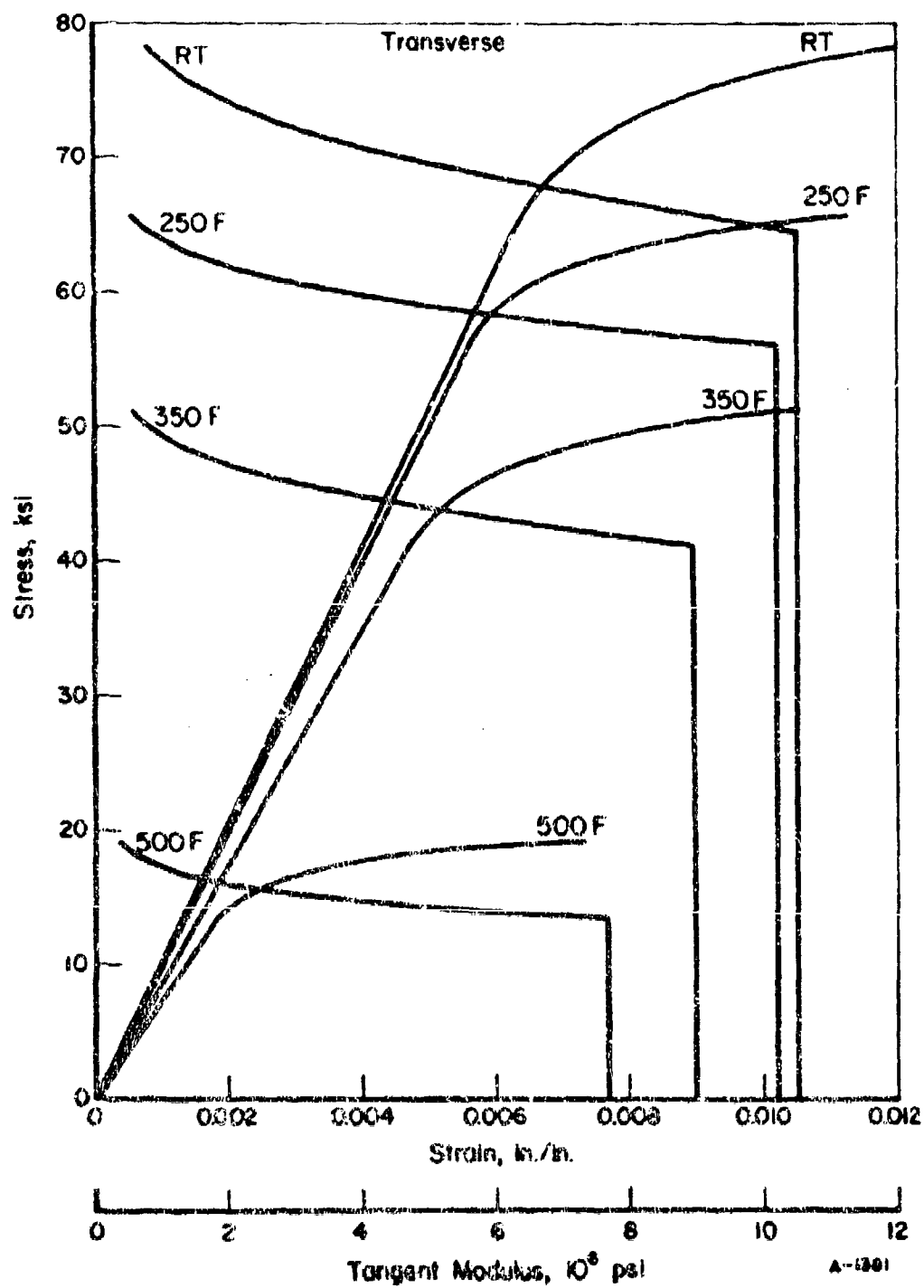


FIGURE 35. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 7049-176 EXTRUSION (TRANSVERSE)

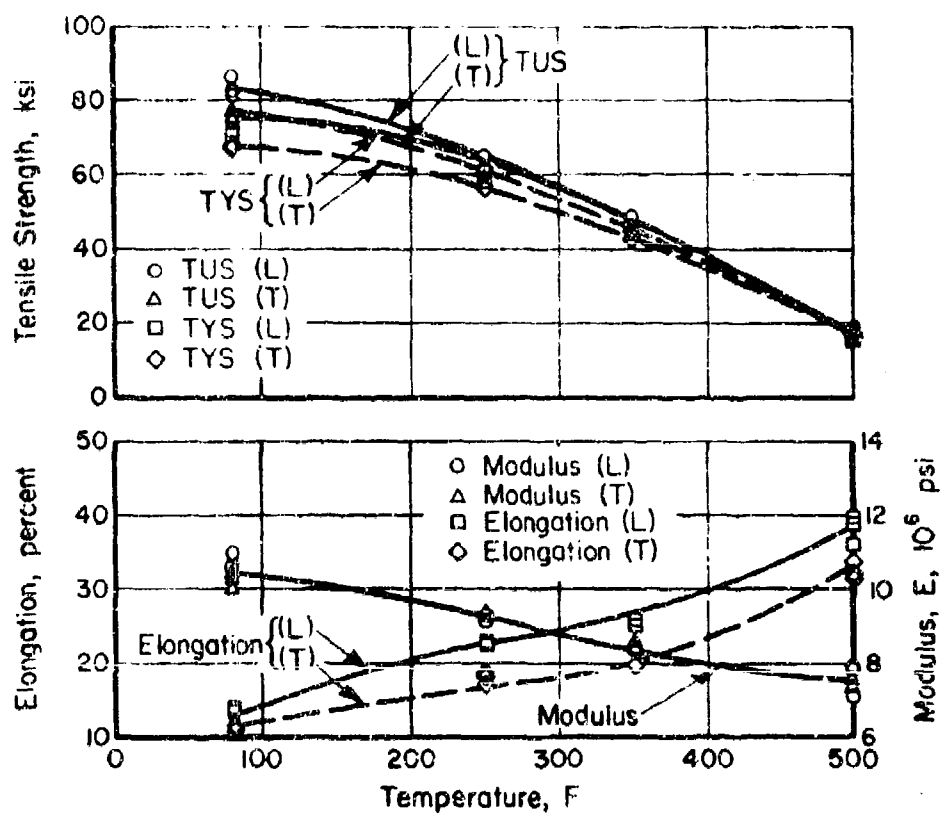


FIGURE 36. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T76 EXTRUSION

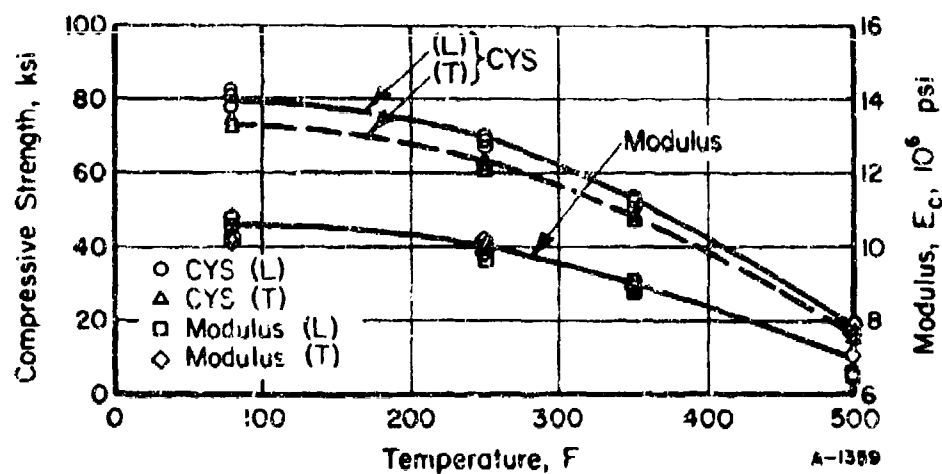


FIGURE 37. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T76 EXTRUSION

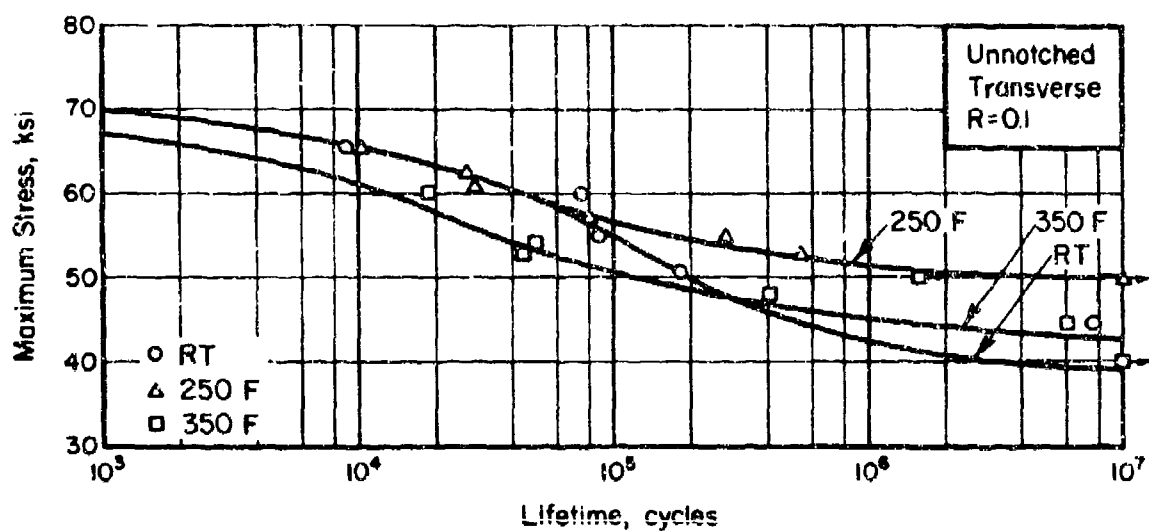


FIGURE 38. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 70'9-T76 EXTRUSIONS

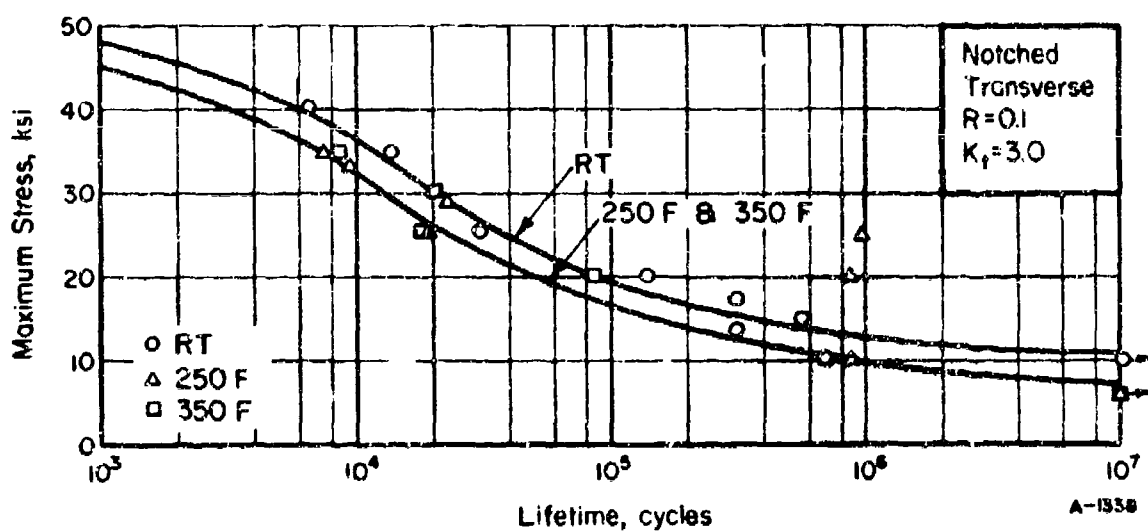


FIGURE 39. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) 7049-T76 EXTRUSIONS

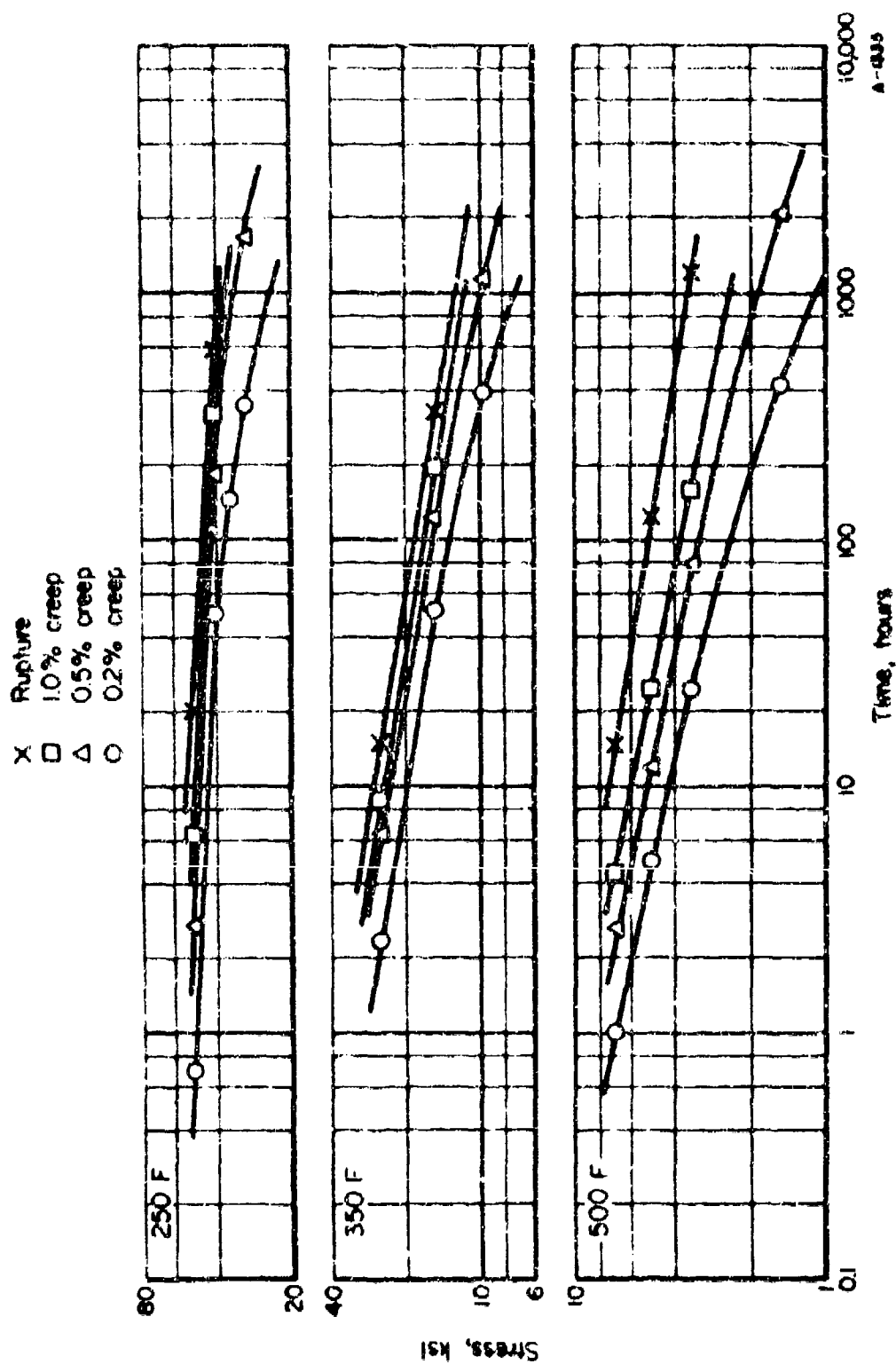


FIGURE 40. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7049-T76 EXTRUSIONS (TRANSVERSE)

Ti-6Al-2Sn-4Zr-6Mo Alloy

Material Description

Initially, this alloy was developed by the Titanium Metals Corporation as an off-shoot of the Ti-6Al-2Sn-4Zr-2Mo high temperature alloy. Studies had shown that increasing the molybdenum content beyond the 2 percent level resulted in an alloy having improved room and elevated temperature strength with good creep resistance. During early development, investigations were limited to the evaluation of the alloy as a heavy section forging alloy. Promising high temperature properties achieved in heat-treated sections up to 3 inches suggested the alloy might also be useful as a sheet alloy since it should be air hardenable at sheet gages.

The material used in this evaluation was 0.075 inch sheet obtained from TMCA. It had the following composition:

<u>Chemical Composition</u>	<u>Percent</u>
Aluminum	5.98
Tin	1.99
Zirconium	3.94
Molybdenum	5.86
Iron	0.057
Oxygen	0.10
Nitrogen	0.004
Titanium	Balance

Processing and Heat Treating

The specimen layout for this alloy is shown in Figure 41. Specimens were machined in the as-received condition and heat-treated as follows:

- (1) 1600 F, 15 minutes, air cooled,
- (2) 1325 F, 15 minutes, air cooled,
- (3) 1100 F, 2 hours, air cooled.

This was suggested by TMCA and is called the "strengthened and heat-treated" condition.

Test Results

Tension. Results of tests in the longitudinal and transverse directions at room temperature, 400 F, 700 F, and 1000 F are given in Table XXXIII. Stress-

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93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000
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strain curves at temperature are presented in Figures 42 and 43. Effect-of-temperature curves are shown in Figure 46.

Compression. Test results for longitudinal and transverse specimens at room temperature, 400 F, 700 F, and 1000 F are shown in Table XXXIV. Stress-strain and tangent modulus curves at temperature are presented in Figures 44 and 45. Effect-of-temperature curves are presented in Figure 47.

Shear. Test results for single-shear sheet-type specimens tested in both the longitudinal and transverse directions at room temperature are given in Table XXXV.

Fracture Toughness. Test specimens were the full sheet thickness (0.075-inch) x 18 inch x 36 inch with an EDM flaw in the center. The 36 inch specimen dimension was parallel to longitudinal grain direction of sheets. The average K_{Ic} value obtained was 132 ksi $\sqrt{\text{in}}$. The net section yield stress at fracture was less than the tensile yield strength of the material. Therefore, the K_{Ic} value is considered valid.

Fatigue. Results of axial-load fatigue tests for transverse specimens, both unnotched and notched, at room temperature, 400 F, and 700 F are given in Tables XXXVI and XXXVII. S-N curves are presented in Figures 48 and 49.

Creep and Stress-Rupture. Tests were conducted at 700 F, 900 F, and 1100 F. Tabular results are given in Table XXXVIII. Log-stress versus log-time curves are presented in Figure 50.

Stress Corrosion. Testing was conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000 hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 5.5×10^{-6} in/in/F for 80 F to 1000 F.

Density. The density of this alloy is 0.165 lb/in³.

TABLE XXXIII. TENSILE TEST RESULTS FOR Ti-6Al-2Sn-4Zr-0.5P SHEET

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile Modulus, 10^6 psi
<u>Longitudinal at Room Temperature</u>				
1L-1	168.0	160.0	16.0	17.5
1L-2	168.0	160.0	10.0	17.7
1L-3	168.0	160.0	11.0	17.5
<u>Transverse at Room Temperature</u>				
1T-1	169.0	163.0	10.0	17.2
1T-2	170.0	163.0	11.0	17.2
1T-3	169.0	163.0	14.0	17.2
<u>Longitudinal at 400 F</u>				
1L-4	149.0	129.0	14.5	16.4
1L-5	148.0	127.0	15.0	16.2
1L-6	148.0	127.0	15.0	16.4
<u>Transverse at 400 F</u>				
1T-4	150.0	130.0	14.0	15.4
1T-5	150.0	131.0	14.5	15.7
1T-6	150.0	131.0	14.0	15.9
<u>Longitudinal at 700 F</u>				
1L-7	141.0	114.0	14.0	14.9
1L-8	141.0	115.0	14.0	15.4
1L-9	140.0	114.0	15.5	15.0
<u>Transverse at 700 F</u>				
1T-7	141.0	117.0	15.0	14.7
1T-8	142.0	117.0	14.0	14.5
1T-9	143.0	117.0	14.0	14.7

TABLE XXXIII. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at 1000 F</u>				
1L-10	107.0	98.2	29.0	13.1
1L-11	104.0	96.0	41.0	12.6
1L-12	105.0	97.8	39.0	12.6
<u>Transverse at 1000 F</u>				
1T-10	106.0	98.5	35.0	12.6
1T-11	108.0	99.5	35.0	12.8
1T-12	106.0	98.8	36.0	13.0

TABLE XXXIV. COMPRESSION TEST RESULTS FOR
Ti-6Al-2Sn-4Zr-6Mo SHEET

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁵ psi
<u>Longitudinal at Room Temperature</u>		
2L-1	167.0	19.1
2L-2	167.0	19.6
2L-3	168.0	19.4
<u>Transverse at Room Temperature</u>		
2T-1	169.0	18.8
2T-2	171.0	18.9
2T-3	172.0	18.9
<u>Longitudinal at 400 F</u>		
2L-4	133.0	17.9
2L-5	133.0	17.9
2L-6	134.0	18.0
<u>Transverse at 400 F</u>		
T-4	138.0	17.5
2T-5	138.0	17.8
2T-6	138.0	17.6
<u>Longitudinal at 700 F</u>		
2L-7	123.0	16.2
2L-8	124.0	16.4
2L-9	123.0	16.3
<u>Transverse at 700 F</u>		
2T-7	127.0	16.1
2T-8	127.0	16.1
2T-9	126.0	16.1

TABLE XXXIV. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at 1000 F</u>		
2L-10	110.0	13.8
2L-11	113.0	14.1
2L-12	109.6	13.7
<u>Transverse at 1000 F</u>		
2T-10	112.0	13.4
2T-11	113.0	13.7
2T-12	113.0	13.7

TABLE XXXV SHEAR TEST RESULTS FOR Ti-6Al-2Sn-4Zr-6Mo
SHEET AT ROOM TEMPERATURE

Specimen No.	Ultimate Shear Strength, ksi
<u>Longitudinal</u>	
4L1	97.3
4L2	96.4
4L3	(a)
4L4	96.8
<u>Transverse</u>	
4T1	(a)
4T2	98.2
4T3	98.1
4T4	98.0

(a) Did not fail in shear.

TABLE XXXVI. AXIAL LOAD FATIGUE TEST RESULTS FOR
UNNOTCHED Ti-6Al-2Sn-4Zr-6Mo SHEET
(TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-7	120.0	102,620
5-1	115.0	43,920
5-5	112.5	1,864,250
5-2	110.0	59,270
5-4	107.5	6,079,870
5-6	105.0	495,200
5-8	90.0	12,007,080 ^(a)
<u>400 F</u>		
5-19	125.0	28,600
5-20	122.5	17,100
5-18	120.0	1,666,400
5-22	117.5	68,700
5-21	115.0	5,420,300
5-23	110.0	64,300
5-24	100.0	573,000
5-25	90.0	12,837,200 ^(a)
<u>700 F</u>		
5-9	120.0	9,300
5-10	115.0	14,800
5-11	110.0	14,700
5-12	105.0	17,000
5-13	100.0	192,200 ^(a)
5-17	100.0	10,796,000 ^(a)
5-15	90.0	11,032,000 ^(a)

(a) Did not fail.

TABLE XXXVII. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED
($K_t = 3.0$) Ti-6Al-2Sn-4Zr-6Mo
SHEET (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>ROOM TEMPERATURE</u>		
5-1	100.0	1,130
5-2	90.0	2,510
5-3	70.0	1,510
5-4	50.0	6,310
5-5	40.0	17,500
5-7	35.0	272,700
5-6	30.0	10,157,600 ^(a)
<u>400 F</u>		
5-7	60.0	15,000
5-8	55.0	19,000
5-9	50.0	19,840
5-10	45.0	27,750
5-11	40.0	43,590
5-12	35.0	10,119,850 ^(a)
<u>700 F</u>		
5-13	60.0	7,400
5-14	55.0	12,800
5-15	50.0	18,100
5-16	45.0	215,600
5-17	40.0	188,600
5-18	40.0	152,800
5-19	35.0	84,300
5-20	30.0	4,457,600
5-21	25.0	10,074,800 ^(a)

(a) Did not fail.

TABLE XXVIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES
OF T1-6Al-2Si-4Zr-6Mo SHEET (TRANSVERSE)

Specimen Number	Stress, ksi	Temper- ature, °F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 inches, percent	Minimum Creep Rate percent/hr
			0.1	0.2	0.5	1.0	2.0				
3-16	149	700	--	--	--	--	--	--	On Loading	12.5	--
3-15	135	700	2	9	41	126	535	8.255	624.2 ^(a)	10.45	0.0022
3-9	120	700	27	77	190	625	1200 ^(b)	2.233	672.3 ^(a)	3.36	0.0018
3-5	110	700	67	170	505	1120 ^(b)	2250 ^(b)	0.800	746.0 ^(a)	1.472	0.0008
3-8	130	900	--	--	--	--	--	7.97	0.3	17.3	--
3-4	100	900	0.3	0.8	2.5	5.8	13.0	0.769	200.6	31.5	0.062
3-10	60	900	4.0	12	55	220 ^(b)	--	0.571	119.6 ^(a)	1.284	0.0031
3-11	30	900	25	95	428 ^(b)	--	--	0.144	143.7 ^(a)	0.391	0.0009
3-12	15	900	110	925	3900 ^(b)	--	--	0.200	792.0 ^(a)	0.386	0.00016
3-1	60	1100	0.06	0.04	0.14	0.34	0.67	0.569	2.3	24.9	2.5
3-2	35	1100	0.09	0.22	0.8	1.9	4.0	0.324	20.4	71.1	0.47
3-3	15	1100	0.6	1.8	8.5	17	30	0.109	195.0	143.5	0.042
3-6	8	1100	1.2	5.0	20	40	75	0.060	900.0	302.0	0.022
3-13	3	1100	10	28	114	260 ^(b)	--	0.066	95.4 ^(a)	0.498	0.0035
3-14	1	1100	425	1300 ^(b)	4300 ^(b)	--	--	0	666.4 ^(a)	0.133	0.0001

(a) Test discontinued.

(b) Estimate

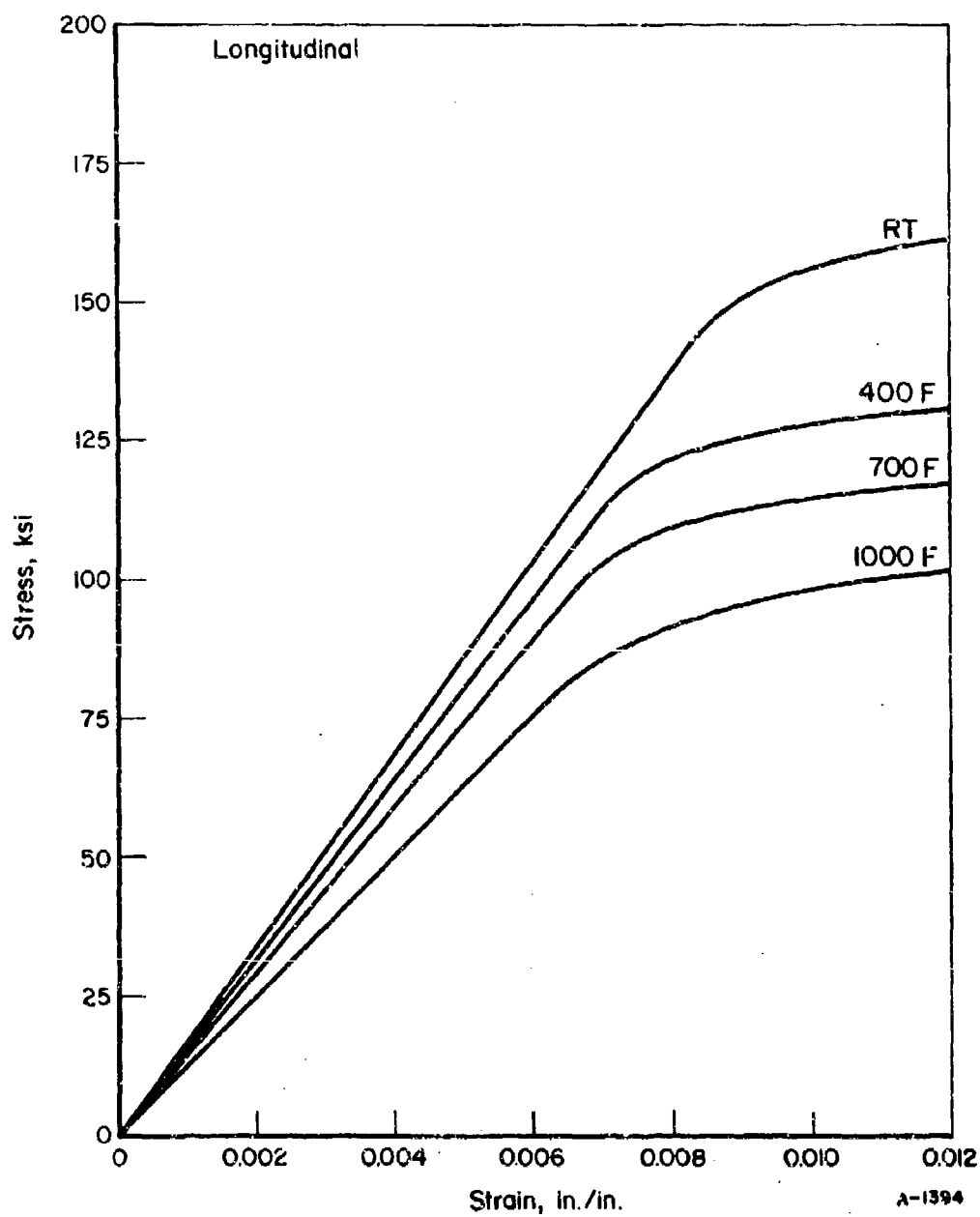


FIGURE 42. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
Ti-6Al-2Sn-4Zr-6Mo SHEET (LONGITUDINAL)

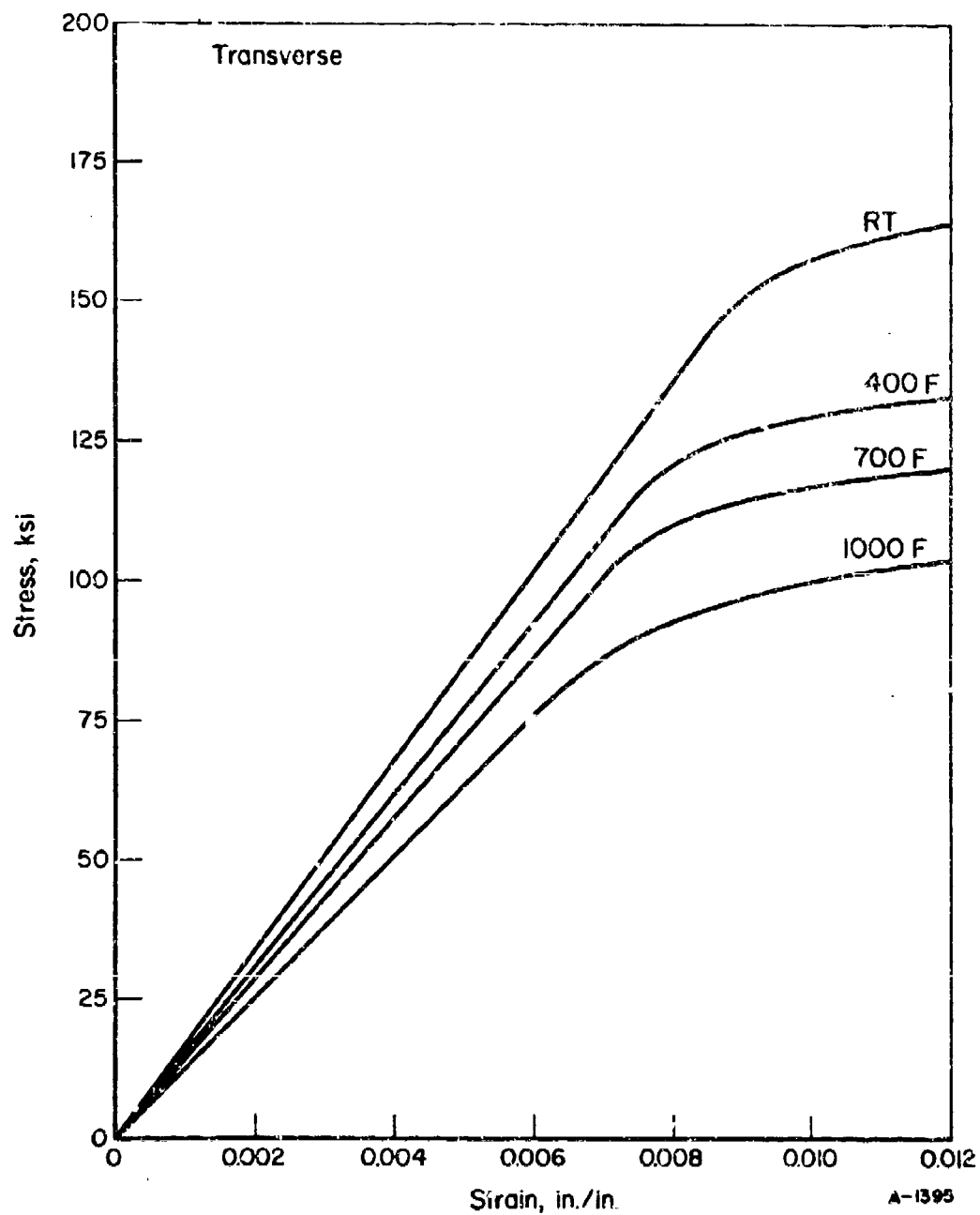


FIGURE 43. TYPICAL TENSILE STRESS-STRAIN CURVES FOR
Ti-6Al-2Sn-4Zr-6Mo SHEET (TRANSVERSE)

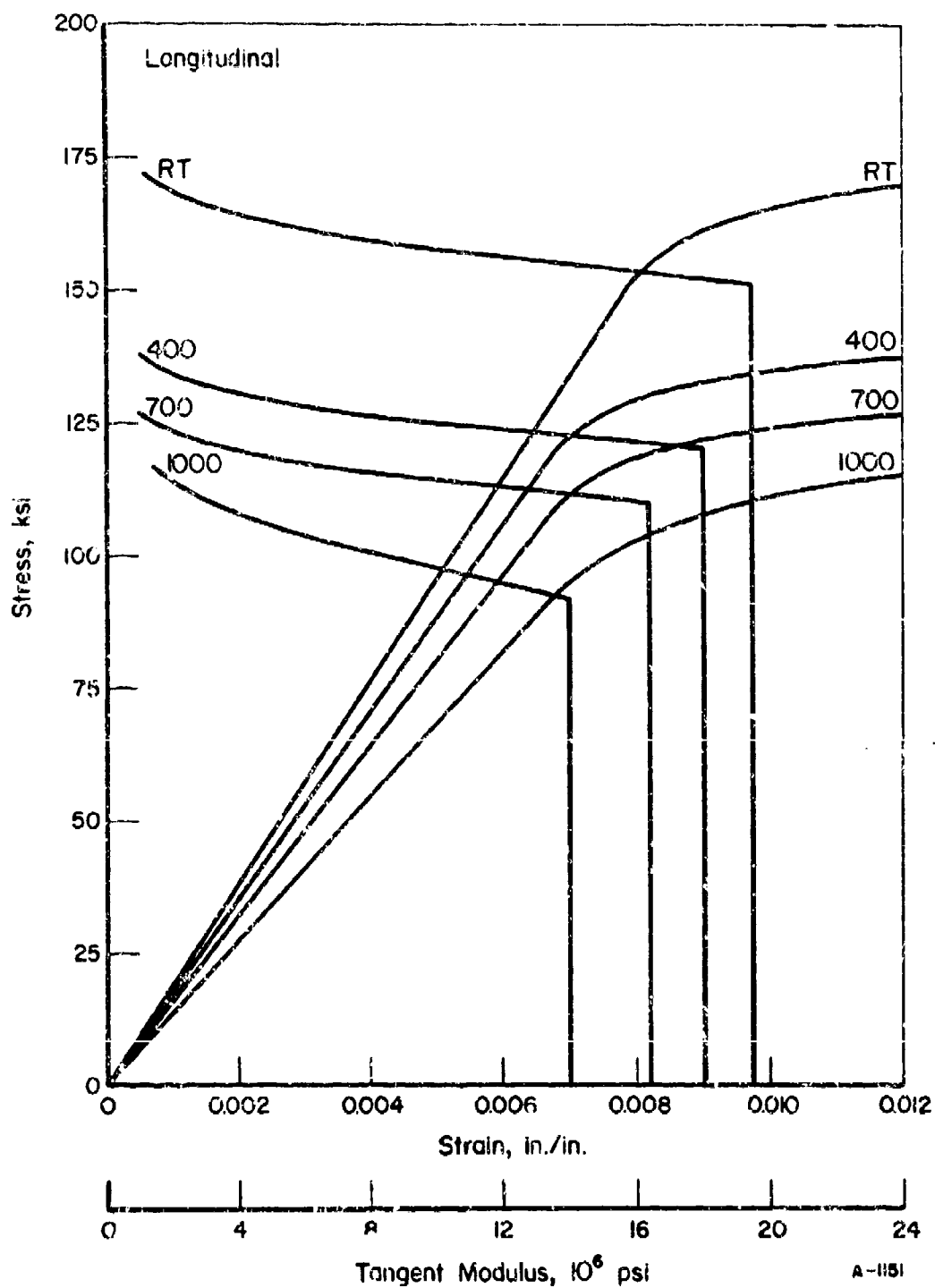


FIGURE 44. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR Ti-6Al-2Sn-4Zr-6Mo SHEET (LONGITUDINAL)

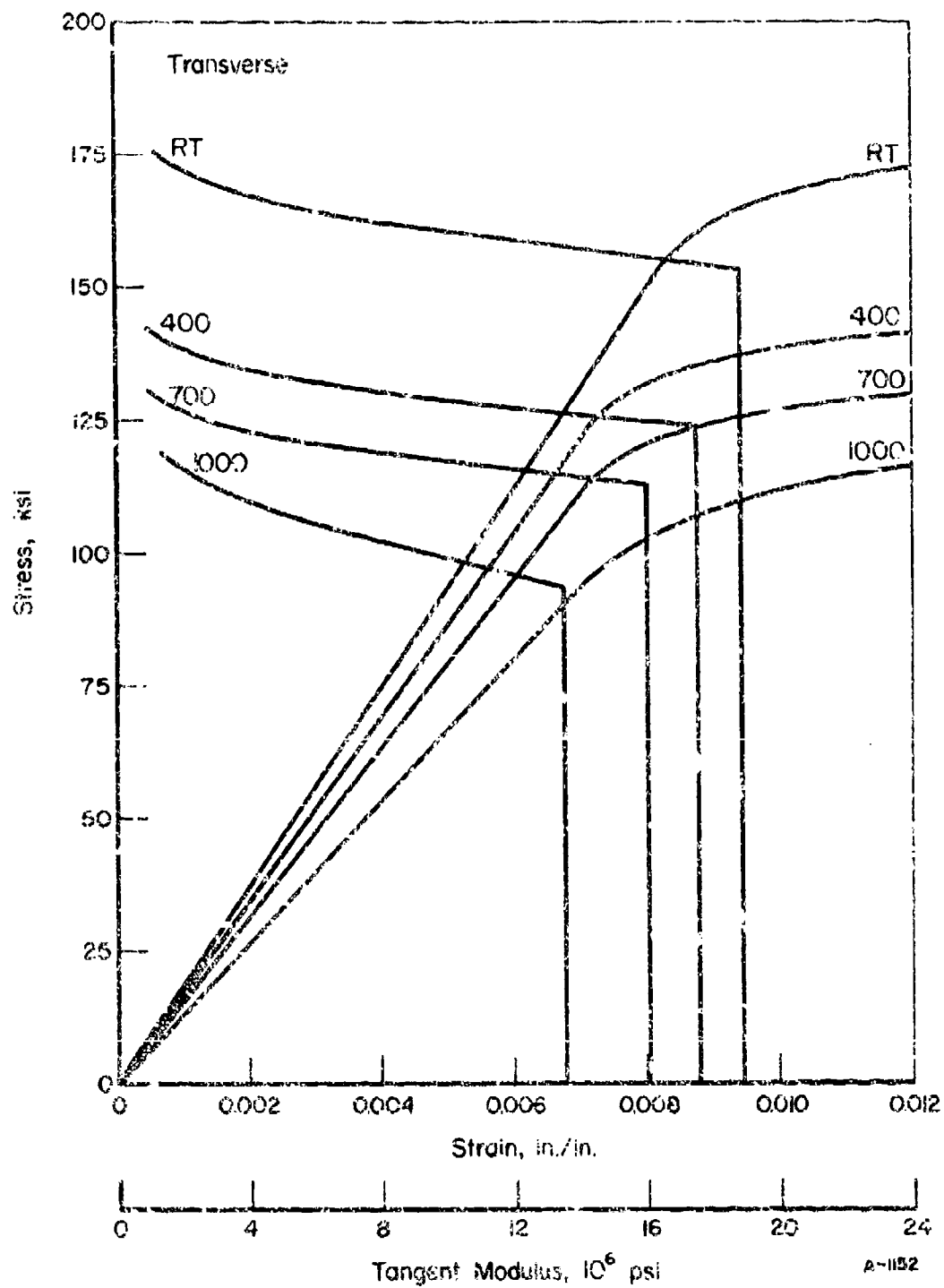


FIGURE 45. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR Ti-6Al-2Sn-4Zr-6Mo SHEET (TRANSVERSE)

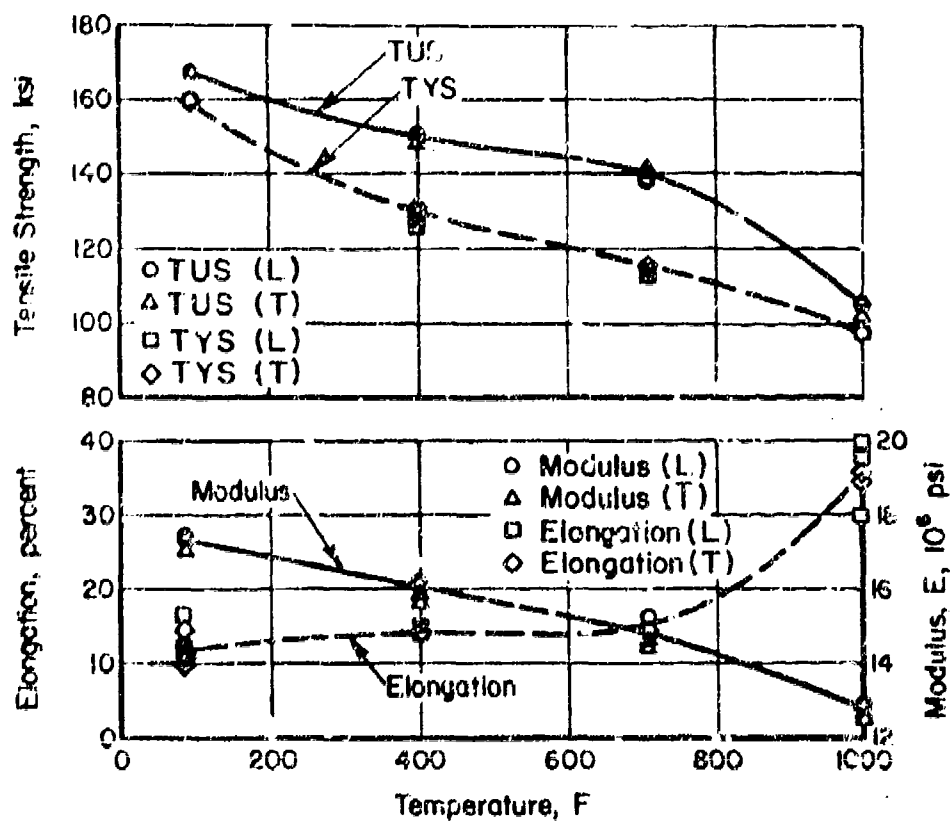


FIGURE 46. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-6Mo SHEET

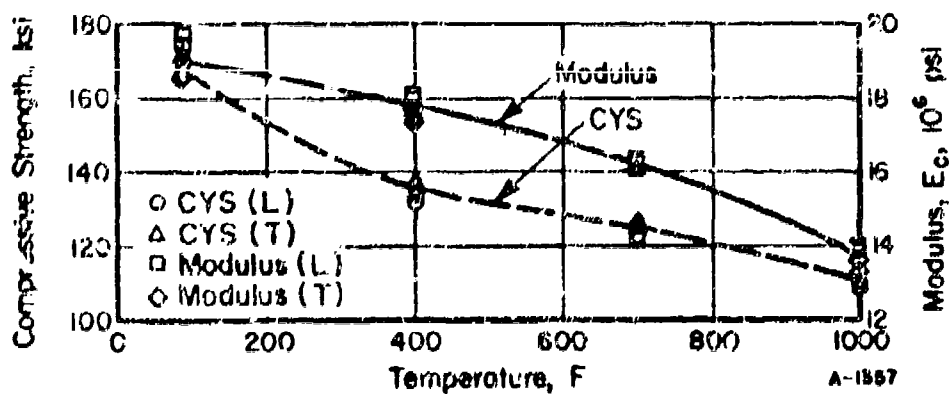


FIGURE 47. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-2Sn-4Zr-6Mo SHEET

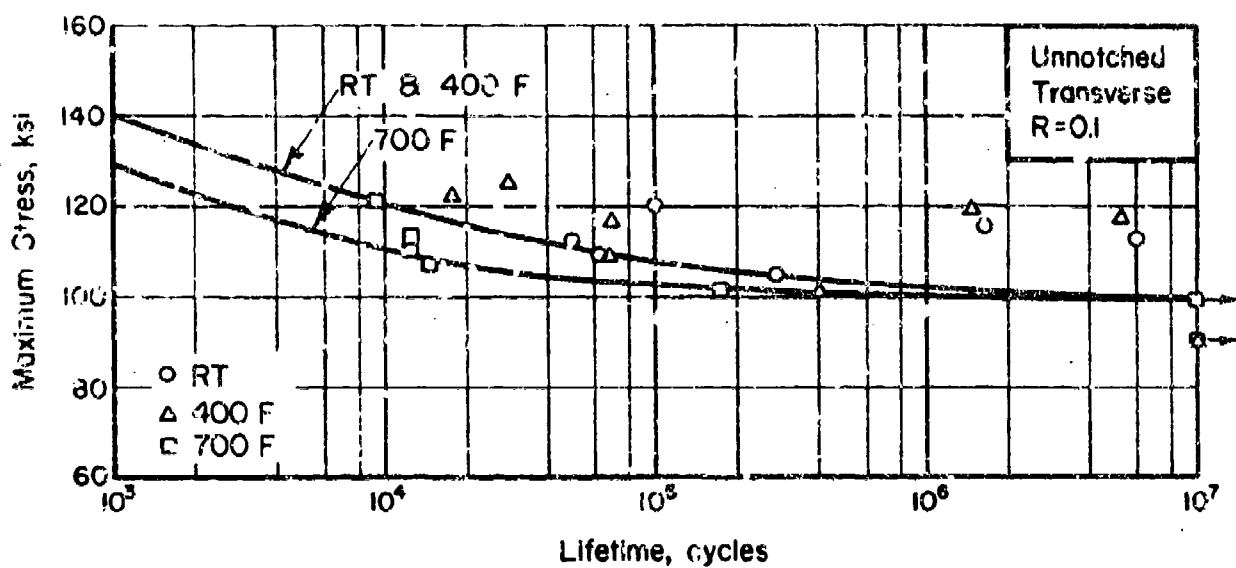


FIGURE 48. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED T1-6Al-2Sn-4Zr-6Mo SHEET

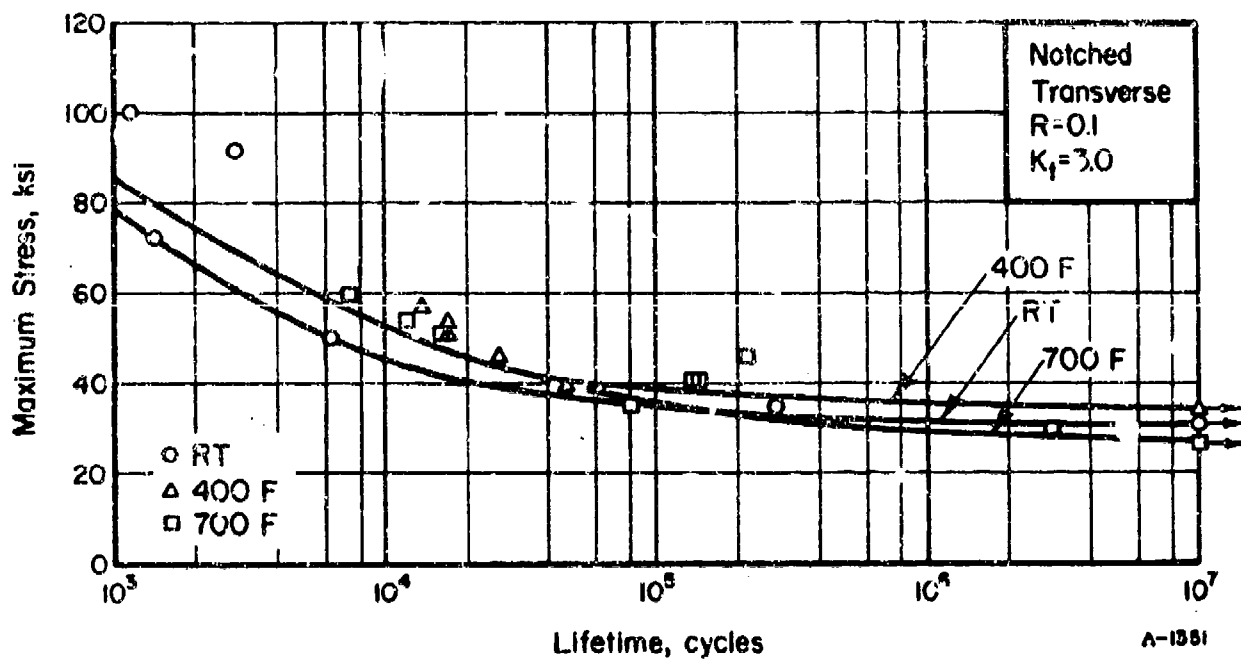


FIGURE 49. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) T1-6Al-2Sn-4Zr-6Mo SHEET

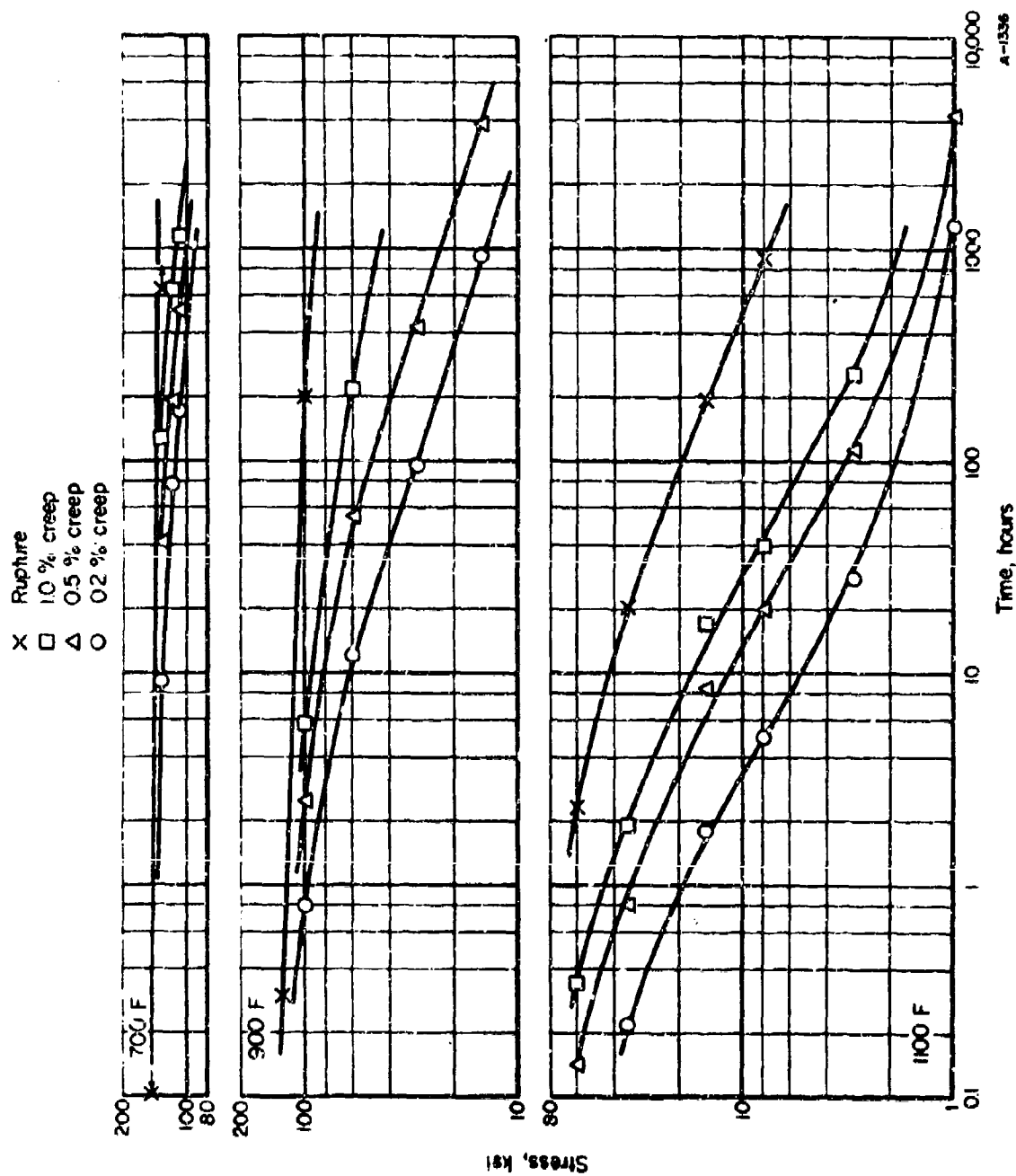


FIGURE 50. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES
FOR Ti-6Al-2Sn-4Zr-6Mo SHEET (TRANSVERSE)

Inconel 702 Alloy

Material Description

Inconel alloy 702 contains high aluminum content for excellent resistance to oxidation at temperatures up to 2400 F. At elevated temperatures, the surface of a nickel-rich, nickel-chromium alloy becomes covered with a compact layer of uniformly thick oxide; the aluminum content of alloy 702 improves the protective action of the oxide. Alloy 702 has good mechanical strength at high temperatures; age hardening improves the strength of the alloy up to about 1500 F.

The material used in this evaluation was 0.050 inch sheet from Huntington Alloy Products Division, Heat HT38C3DS. The composition was as follows:

<u>Chemical Composition</u>	<u>Percent</u>
Carbon	0.01
Manganese	0.02
Iron	0.32
Sulfur	0.007
Silicon	0.11
Copper	0.01
Chromium	16.34
Aluminum	3.12
Titanium	0.54
Nickel	79.50

Processing and Heat Treating

The specimen layout for Inconel 702 sheet is shown in Figure 51. Specimens were machined in the as-received annealed condition and then aged at 1400 F for 5 hours.

Test Results

Tension. Results of tests on longitudinal and transverse specimens at room temperature, 600 F, 1000 F, and 1400 F are given in Table XXXIX. Tensile stress-strain curves at temperature are shown in Figures 52 and 53. Effect-of-temperature curves are presented in Figure 56.

Compression. Compression test results at room temperature, 600 F, 1000 F, and 1400 F for longitudinal and transverse specimens are given in Table XL. Stress-strain and tangent modulus curves at temperature are presented in Figures 54 and 55. Effect-of-temperature curves are presented in Figure 57.

Shear. Test results for longitudinal and transverse specimens at room temperature are given in Table XL7.

Fracture Toughness. Tests were conducted on specimens of full sheet thickness (0.050-inch) by 18 inches by 36 inches with EDM flaw in center. The net section yield stress at fracture was greater than the tensile yield strength of the materials; therefore, the K values are considered not valid.

Fatigue. Axial-load fatigue test results for unnotched and notched transverse specimens at room temperature, 600 F, and 1000 F are given in Tables XLII and XLIII. S-N curves are presented in Figures 58 and 59.

Creep and Stress-Rupture. Tests were conducted at 800 F, 1100 F, and 1400 F for transverse specimens. Tabular results are given in Table XLIV. Log-stress versus log-time curves are presented in Figure 60.

Stress Corrosion. Tests were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000 hour test duration.

Thermal Expansion. Coefficient of thermal expansion value for this alloy is 5.7×10^{-6} in/in/F for 70 F to 1500 F.

Density. The density of this material is 0.305 lb/in³.

TABLE XXIX. TENSILE TEST RESULTS FOR INCONEL 702 SHEET (AGED)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>				
1L-1	152.0	94.6	34.5	34.8
1L-2	153.0	94.8	35.0	35.2
1L-3	153.0	94.8	35.0	33.5
<u>Transverse at Room Temperature</u>				
1T-1	151.0	94.5	34.0	34.4
1T-2	151.0	94.5	34.5	33.8
1T-3	151.0	95.3	34.0	32.9
<u>Longitudinal at 600 F</u>				
1L-4	139.0	85.0	35.0	30.1
1L-5	139.0	86.0	38.5	29.5
1L-6	139.0	86.0	34.0	29.2
<u>Transverse at 600 F</u>				
1T-4	137.0	86.3	36.0	31.6
1T-5	138.0	86.3	37.0	30.0
1T-6	138.0	86.4	37.5	31.1
<u>Longitudinal at 1000 F</u>				
1L-7	131.0	85.5	36.0	28.3
1L-8	131.0	84.1	36.0	30.6
1L-9	130.0	84.0	37.0	28.8
<u>Transverse at 1000 F</u>				
1T-7	129.0	85.7	34.5	28.3
1T-8	128.0	84.9	36.0	26.9
1T-9	128.0	85.2	36.0	27.8

TABLE XXXIX. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at 1400 F</u>				
1L-10	66.3	63.8	8.5	19.7
1L-11	66.8	64.5	9.5	20.0
1L-12	65.4	62.4	10.0	21.0
<u>Transverse at 1400 F</u>				
1T-10	67.1	64.6	9.0	19.9
1T-11	67.5	64.9	8.5	19.6
1T-12	68.0	65.8	7.0	22.9

TABLE XL. COMPRESSION TEST RESULTS FOR
INCONEL 702 SHEET (AGED)

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, psi x 10 ⁶
<u>Longitudinal at Room Temperature</u>		
2L-1	99.0	34.2
2L-2	99.4	34.2
2L-3	99.8	34.8
<u>Transverse at Room Temperature</u>		
2T-1	101.0	34.5
2T-2	101.0	34.5
2T-3	101.0	35.0
<u>Longitudinal at 600 F</u>		
2L-4	91.0	34.5
2L-5	91.3	34.4
2L-6	90.8	36.1
<u>Transverse at 600 F</u>		
2T-4	94.4	33.0
2T-5	93.6	34.8
2T-6	92.8	32.2
<u>Longitudinal at 1000 F</u>		
2L-7	90.7	31.3
2L-8	90.3	29.2
2L-9	89.6	30.0
<u>Transverse at 1000 F</u>		
2T-7	90.9	31.3
2T-8	90.3	30.4
2T-9	91.9	30.1
<u>Longitudinal at 1400 F</u>		
2L-10	67.5	20.7
2L-11	68.1	22.0
2L-12	68.3	20.2
<u>Transverse at 1400 F</u>		
2T-10	70.4	20.2
2T-11	70.6	21.0
2T-12	70.5	20.9

TABLE XLI. SHEAR TEST RESULTS FOR INCONEL
702 SHEET (AGED)

Specimen Number	Ultimate Shear Strength, ksi
<u>Longitudinal</u>	
4L1	117.0
4L2	115.0
4L3	117.0
4L4	116.0
<u>Transverse</u>	
4T1	117.0
4T2	116.0
4T3	113.0
4T4	117.0

TABLE XLII. AXIAL LOAD FATIGUE TEST RESULTS
FOR UNNOTCHED INCONEL 702 SHEET
(AGED) (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-4	75.0	98,300
5-3	65.0	209,900
5-2	55.0	591,700
5-1	45.0	1,594,800
5-8	40.0	7,086,400
5-5	35.0	3,403,100
5-7	30.0	10,138,000 ^(a)
5-6	25.0	10,130,000 ^(a)
<u>600 F</u>		
5-11	75.0	117,500
5-12	65.0	184,400
5-13	55.0	584,200
5-14	45.0	4,809,000
5-16	40.0	10,226,700 ^(a)
5-15	35.0	12,376,900 ^(a)
<u>1000 F</u>		
5-21	75.0	12,400
5-22	65.0	245,300
5-23	65.0	536,200
5-26	60.0	5,428,800
5-24	55.0	4,337,200
5-25	50.0	10,097,700 ^(a)
5-27	45.0	10,331,300 ^(a)

(a) Did not fail.

TABLE XLIII. AXIAL LOAD FATIGUE TEST RESULTS FOR
NOTCHED ($K_t = 3.0$) INCONEL 702 SHEET
(AGED) (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-4	65.0	31,900
5-3	55.0	111,100
5-2	45.0	336,200
5-7	40.0	782,400
5-8	40.0	1,651,000
5-1	35.0	1,511,600
5-6	30.0	636,000
5-5	25.0	10,537,500 ^(a)
<u>600 F</u>		
5-13	65.0	15,700
5-11	55.0	75,300
5-15	50.0	821,200
5-12	45.0	250,400
5-24	42.5	6,248,000
5-25	40.0	3,672,800 ^(a)
5-16	37.5	24,268,000 ^(a)
5-14	35.0	10,069,500 ^(a)
<u>1000 F</u>		
5-21	65.0	12,900
5-22	55.0	51,500
5-27	50.0	719,200
5-23	45.0	1,274,800
5-35	40.0	7,917,100
5-34	35.0	10,549,600 ^(a)

(a) Did not fail.

TABLE XV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF INCONEL 702 SHEET (AGED) (TRANSVERSE)

Specimen Number	Stress, ksi	Temper- ature, °F	Hours to Indicated Creep Deformation,					Initial Strain, %	Rupture Time, hr	Elongation in 2 in., percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
3-13	132	800	--	--	--	--	--	--	On Loading	38.7	--
3-10	130	800	--	--	--	--	--	--	486.0 (a)	--	--
3-1	120	800	12	50	380	1250 (b)	--	14.520	764.7 (a)	15.24	0.0057
3-11	110	800	50	280	1150 (b)	--	--	9.204	290.0 (a)	9.406	0.0003
3-14	100	800	--	--	--	--	--	4.618	194.5 (a)	4.647	--
3-7	85	1100	0.6	1.5	5	12.8	28	0.447	38.1	4.4	0.063
3-2	75	1100	3	10	38	75	--	0.269	105.2	3.1	0.010
3-5	65	1100	15	45	137	220	--	0.316	262.7	2.0	0.003
3-8	50	1100	70	325	835	1125	--	0.198	1165.0	1.8	0.0004
3-3	30	1400	0.8	2.7	6.5	--	--	0.164	15.0	3.1	0.053
3-4	24	1400	4.0	12.0	30	44	--	0.135	63.1	3.1	0.013
3-6	17	1400	17	48	124	198	255	0.067	261.9	3.1	0.0038
3-9	12	1400	60	140	315	485	550	0.051	884.8	13.3	0.001
3-12	6	1400	435	655	1100 (b)	--	--	0.018	642.5 (d)	0.211	0.0001

(a) Test discontinued.

(b) Estimate.

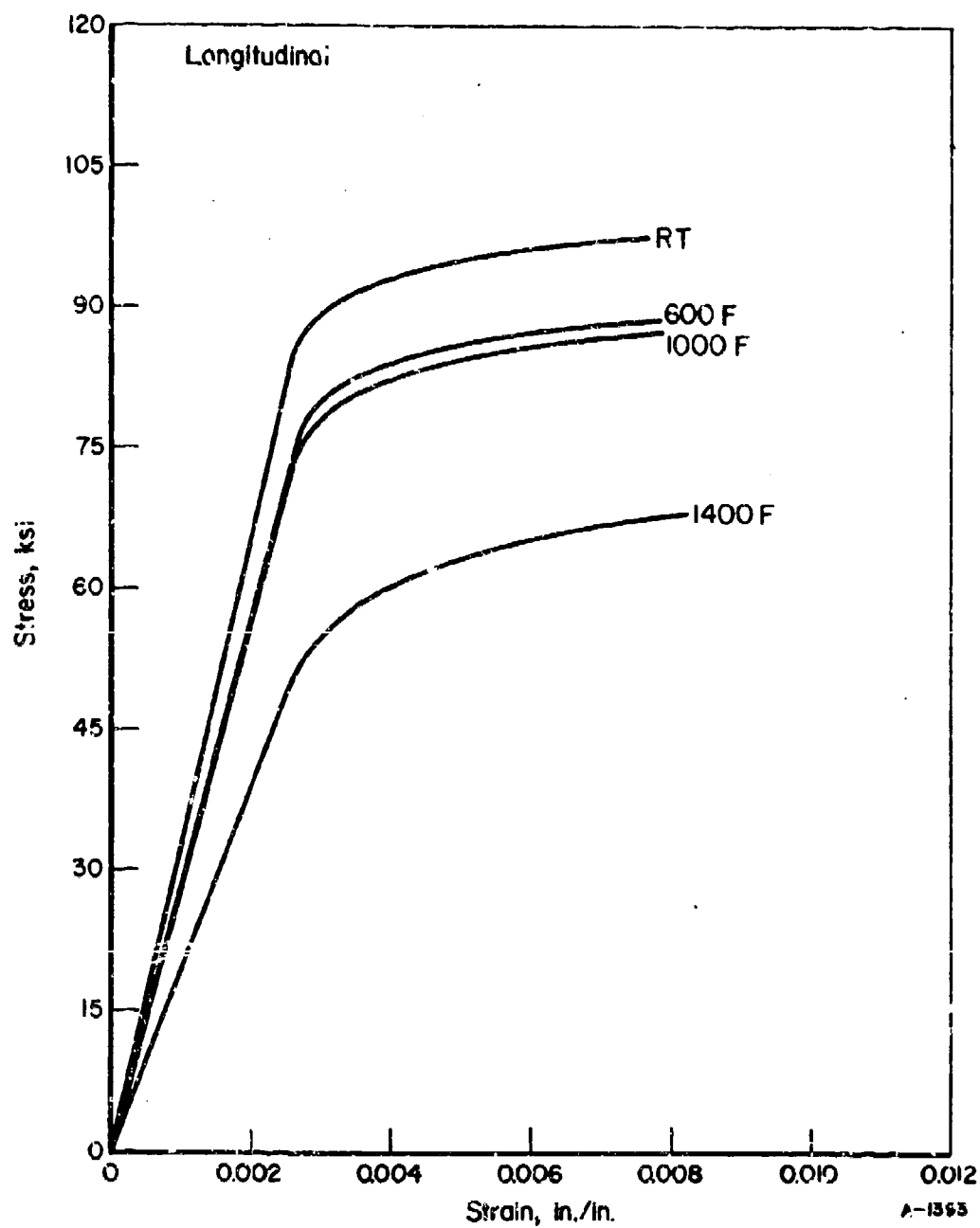


FIGURE 52. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 702 SHEET (AGED) (LONGITUDINAL)

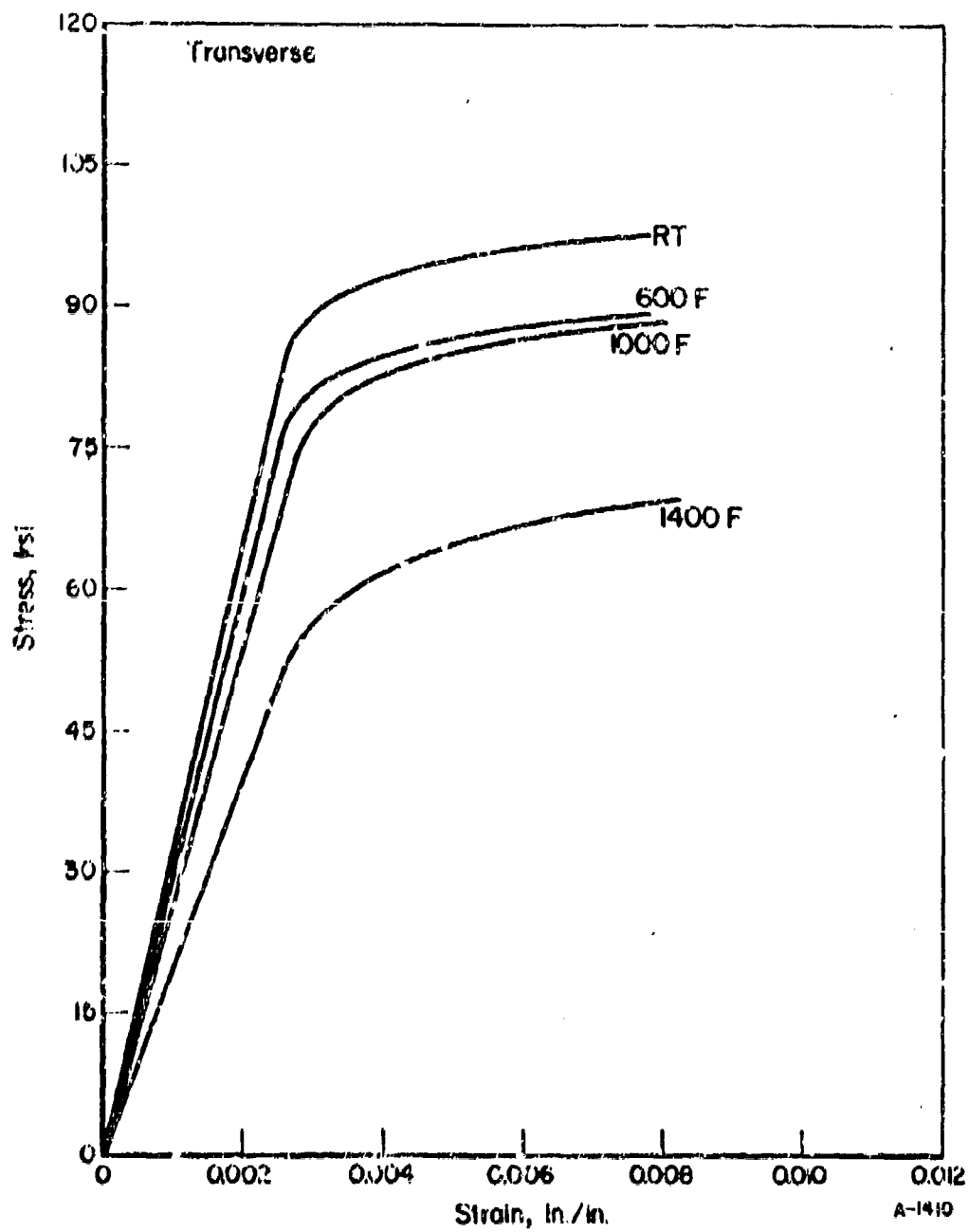


FIGURE 53. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 702 SHEET (AGED) (TRANSVERSE)

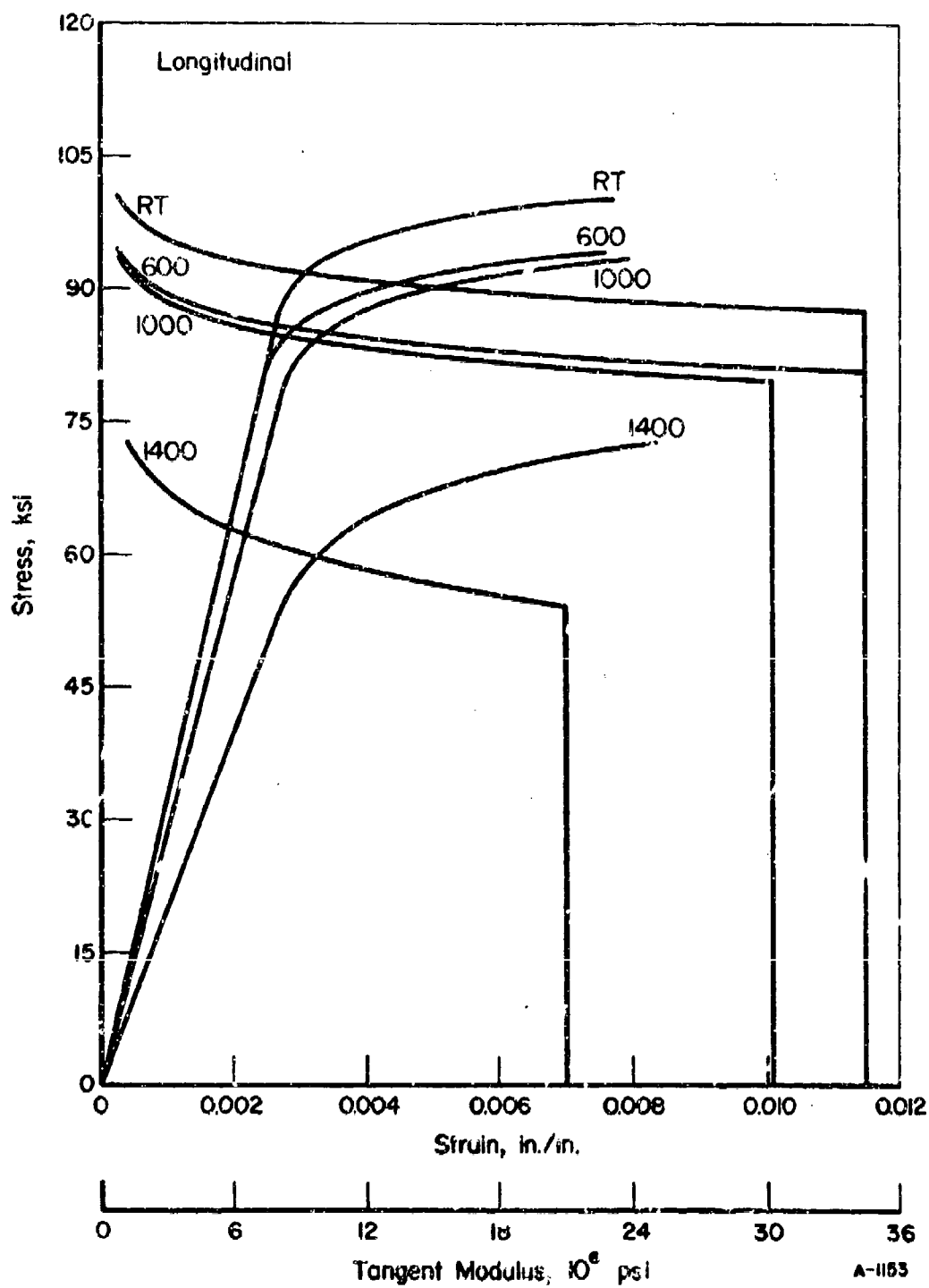


FIGURE 54. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 702 SHEET (AGED) (LONGITUDINAL)

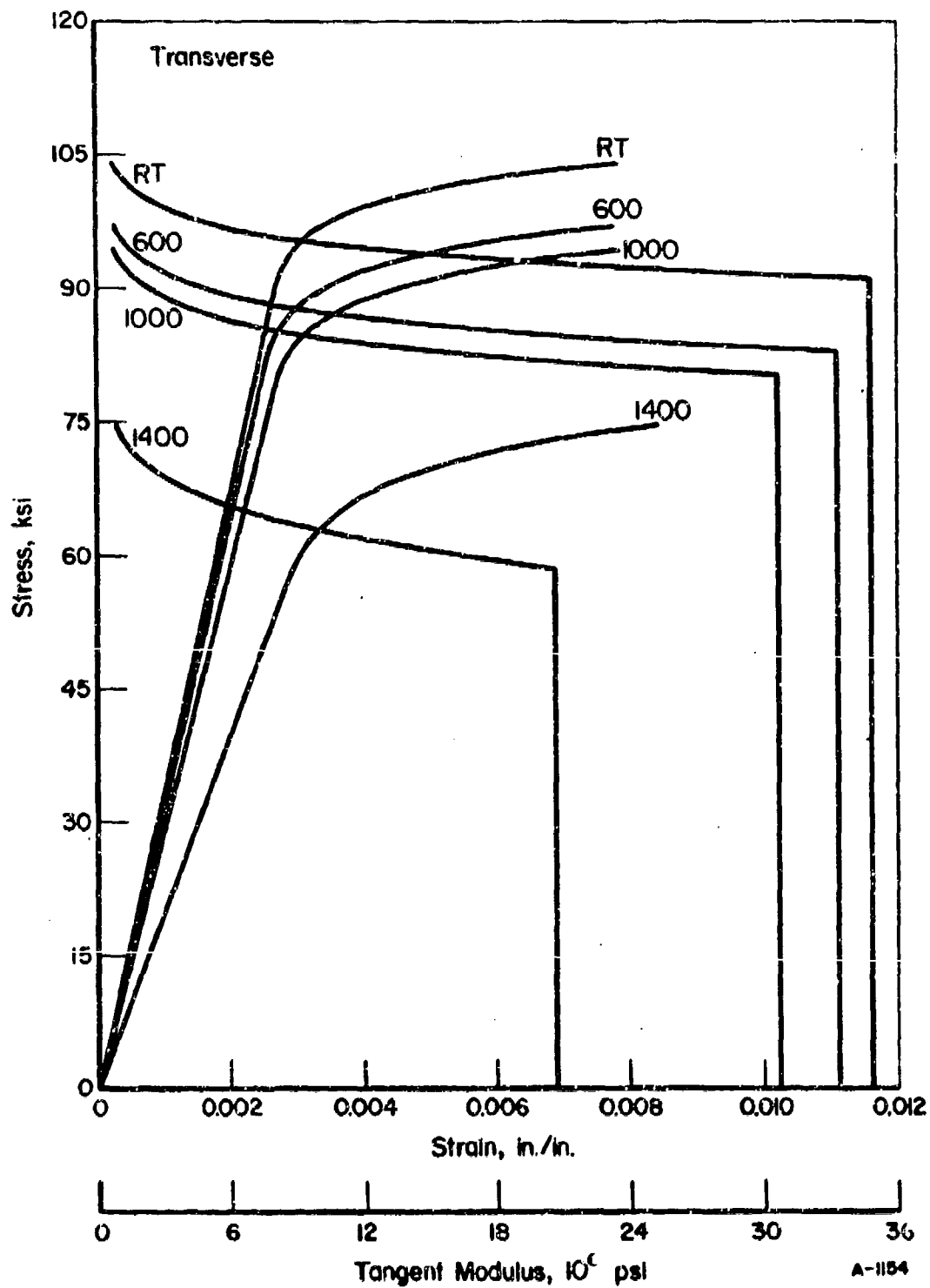


FIGURE 55. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 702 SHEET (AGED) (TRANSVERSE)

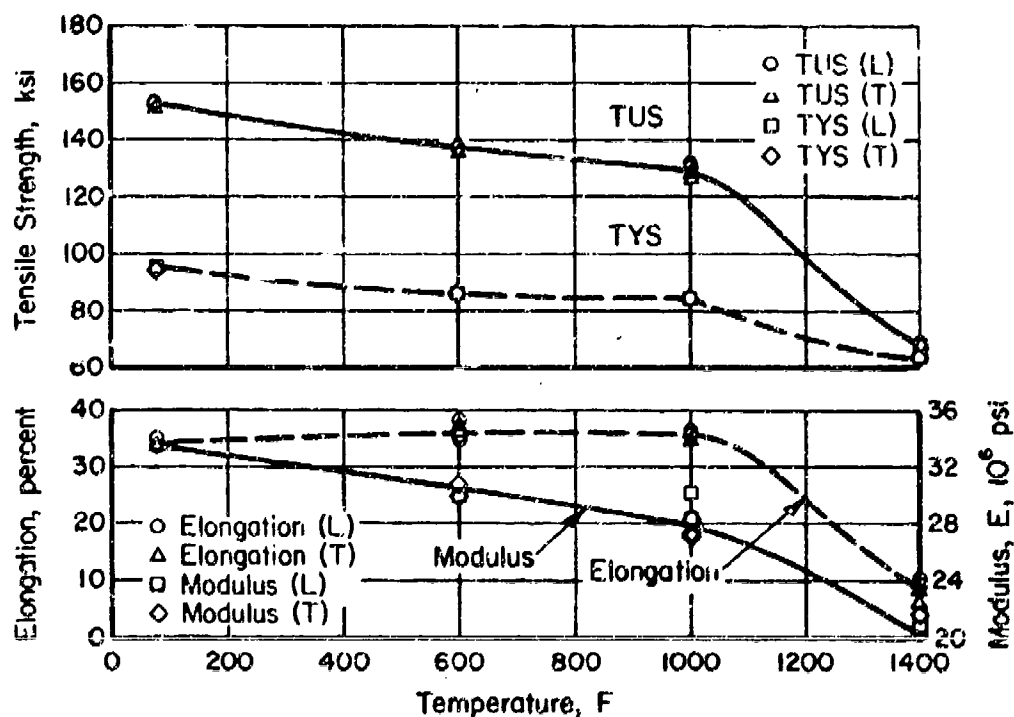


FIGURE 56. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 702 SHEET (AGED)

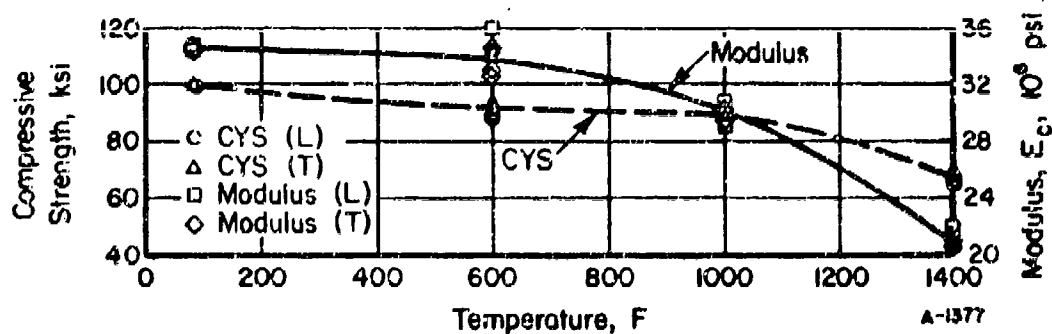


FIGURE 57. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 702 SHEET (AGED)

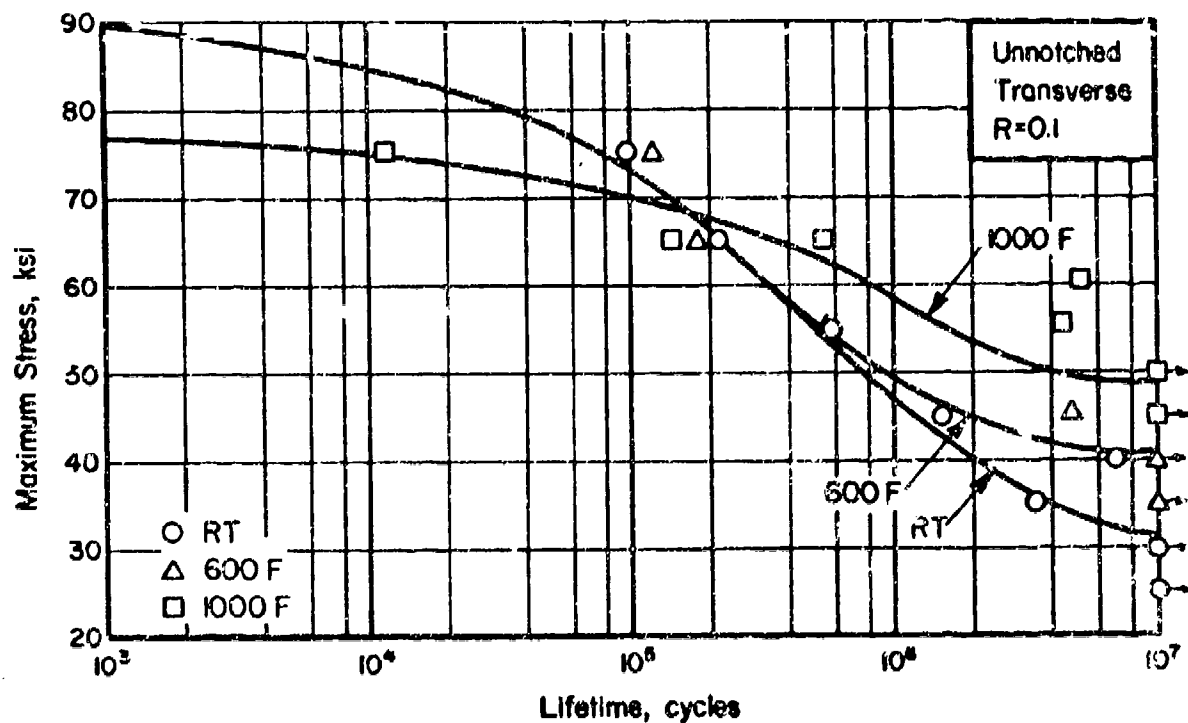


FIGURE 58. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED INCONEL 702 SHEET (AGED)

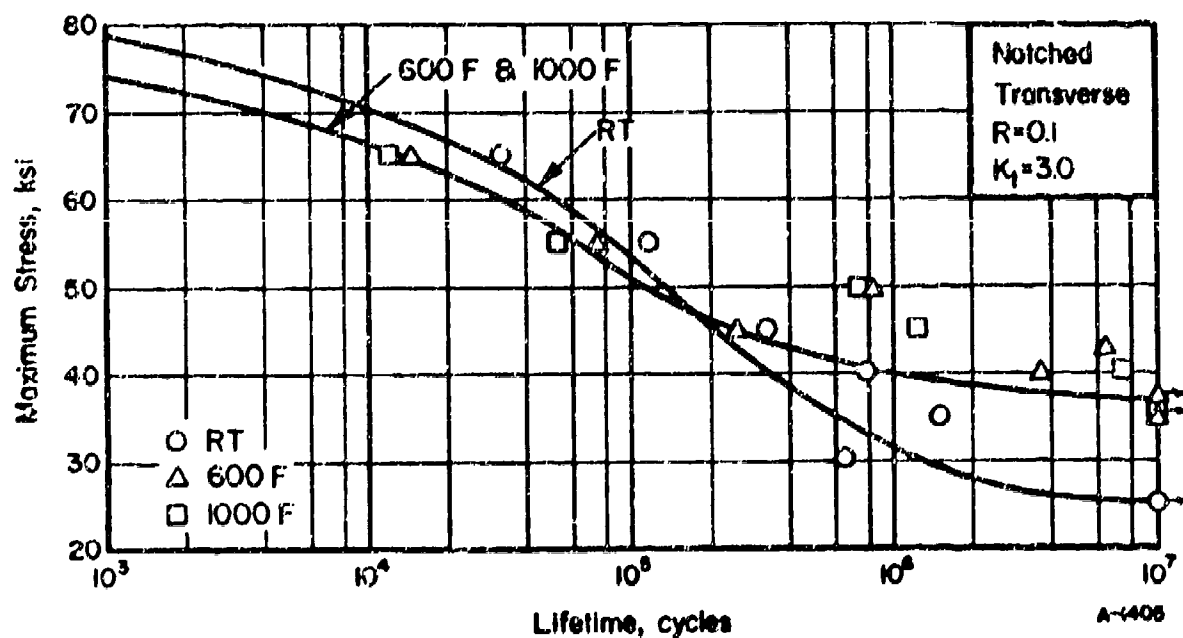


FIGURE 59. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) INCONEL 702 SHEET (AGED)

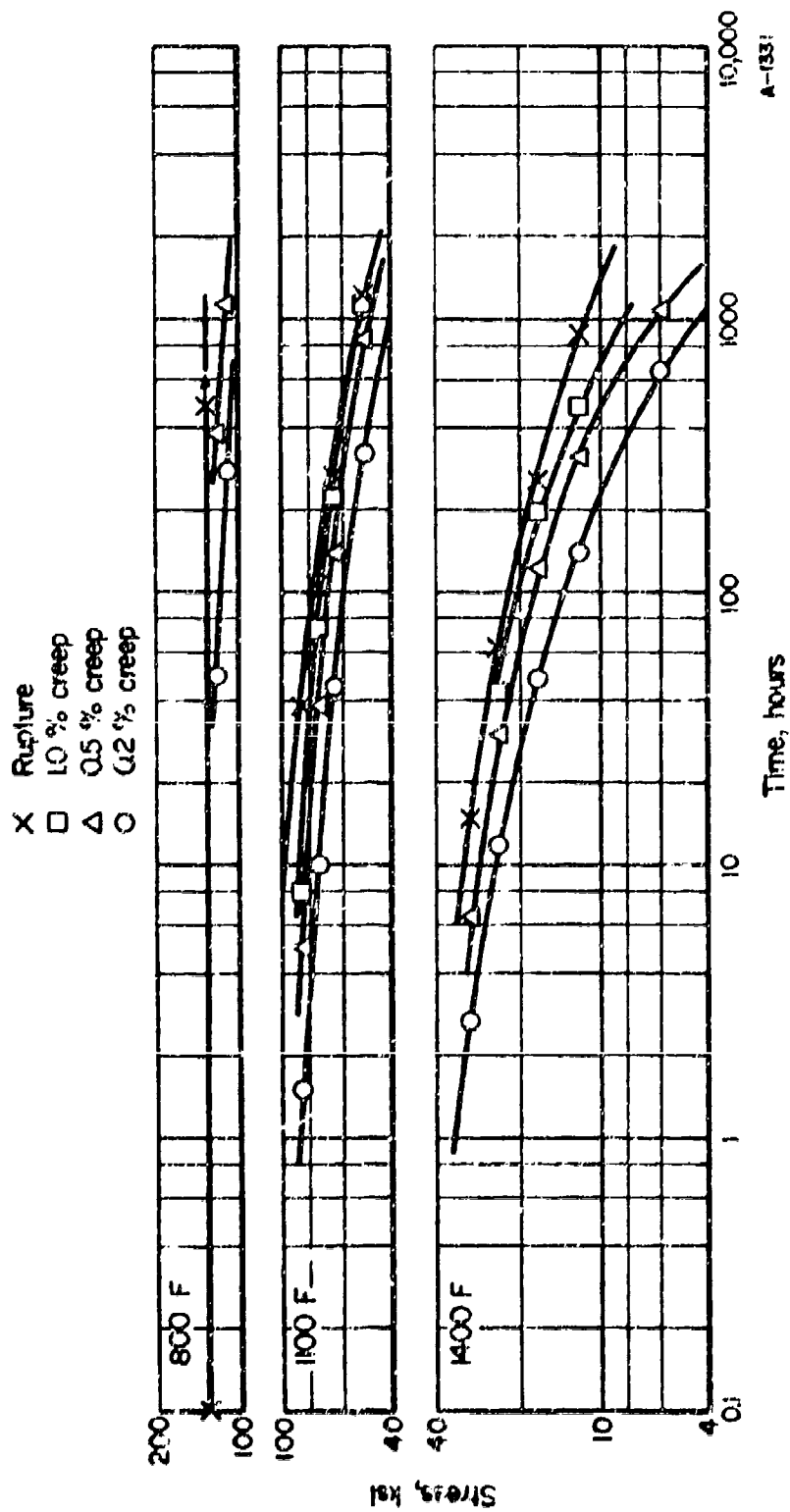


FIGURE 60. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR INCONEL 702 SHEET (AGED) (TRANSVERSE)

Inconel 706 Alloy

Material Description

Inconel alloy 706 is a precipitation-hardenable, nickel-iron-chromium alloy with characteristics similar to those of Inconel 718, except that 706 has improved machinability. It has high strength at temperatures ranging from cryogenic to 1300 F. It also has good resistance to oxidation and corrosion over a broad range of temperatures and environments.

Fabrication of the alloy is enhanced by its good formability and weldability. Alloy 706 has excellent resistance to postweld strain-age cracking.

The material used in this evaluation was obtained as a 6-inch-square forging from INCO, Heat HT50C3HK. The composition was as follows:

<u>Chemical Composition</u>	<u>Percent</u>
Carbon	0.03
Manganese	0.12
Iron	36.37
Sulfur	0.007
Silicon	0.13
Copper	0.02
Chromium	16.32
Aluminum	0.28
Titanium	1.62
Columbium plus Tantalum	2.96
Nickel	42.12

Processing and Heat Treating

The 6-inch-square material was press forged to a 2 inch x 6 inch bar to make specimen blanks easier to obtain. The specimen layout is shown in Figure 61. After machining, specimens were heat treated as follows for optimum creep-rupture strength:

- (1) 1800 F, 2 hours, air cool,
- (2) 1550 F, 3 hours, air cool,
- (3) 1325 F, 8 hours, furnace cool to 1150 F, hold for 8 hours, air cool.

Test Results

Tension. Results of longitudinal and transverse tests at room temperature, 800 F, 1000 F, and 1200 F are given in Table XLV. Stress-strain curves at

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temperature are shown in Figures 62 and 63. Effect-of-temperature curves are shown in Figure 66.

Compression. Results of longitudinal and transverse tests at room temperature, 800 F, 1000 F, and 1200 F are given in Table XLVI. Stress-strain and tangent-modulus curves at temperature are shown in Figures 64 and 65. Effect-of-temperature curves are presented in Figure 67.

Shear. Pin shear test results for longitudinal and transverse specimens at room temperature are given in Table XLVII.

Impact. Charpy test results for room temperature longitudinal and transverse specimens are given in Table XLVIII.

Fracture Toughness. Results of slow bend tests at room temperature are given in Table XLIX. The size ratio, $2.5 (K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, therefore the K_Q value in the table is not a valid K_{IC} value by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were performed on transverse specimens, both notched and unnotched, at room temperature, 600 F, and 1000 F. Test results are given in Tables L and LI. S-N curves are presented in Figures 68 and 69.

Creep and Stress-Rupture. Tests were conducted at 800 F, 1000 F, and 1200 F. Results are given in Table LII. Log-stress versus log-time curves are presented in Figure 70.

Stress Corrosion. No failures or cracks occurred in the 1000 hour test duration as described in the experimental procedure section of this report.

Thermal Expansion. The coefficient of thermal expansion for Inconel 706 is 9.8×10^{-6} in/in/F for 70 F to 1500 F.

Density. The density of this material is 0.291 lb/in³.

TABLE XLV. TENSILE TEST RESULTS FOR
INCONEL 704 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)

Specimen Number	Ultimate Tensile Strength, ksi	0.2 percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Reduction in Area, percent	Tensile Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>					
1L-1	177.0	138.0	22.0	32.5	30.9
1L-2	178.0	139.0	22.5	33.5	28.9
1L-3	178.0	139.0	23.0	32.5	27.9
<u>Transverse at Room Temperature</u>					
1T-1	176.0	140.0	21.5	30.0	29.7
1T-2	176.0	140.0	22.0	31.5	28.6
1T-3	176.0	140.0	22.5	31.5	31.6
<u>Longitudinal at 800 F</u>					
1L-4	157.0	120.0	22.0	37.0	24.3
1L-5	155.0	120.0	21.0	39.0	23.9
1L-6	157.0	122.0	22.0	36.5	24.4
<u>Transverse at 800 F</u>					
1T-4	158.0	121.0	21.0	36.5	24.8
1T-5	157.0	122.0	20.5	33.5	25.9
1T-6	157.0	123.0	19.0	34.5	23.3
<u>Longitudinal at 1000 F</u>					
1L-7	152.0	119.0	20.0	38.0	22.1
1L-8	152.0	120.0	20.5	40.0	20.4
1L-9	151.0	119.0	22.5	40.5	21.2
<u>Transverse at 1000 F</u>					
1T-7	152.0	120.0	19.0	33.5	22.0
1T-8	153.0	121.0	19.5	35.5	21.2
1T-9	154.0	122.0	18.0	35.0	21.3
<u>Longitudinal at 1200 F</u>					
1L-10	139.0	117.0	25.0	39.5	21.4
1L-11	138.0	116.0	25.5	40.5	21.4
1L-12	138.0	115.0	26.0	41.5	20.3
<u>Transverse at 1200 F</u>					
1T-10	139.0	116.0	23.0	40.0	20.1
1T-11	139.0	117.0	24.0	36.0	20.7
1T-12	139.0	118.0	21.5	37.5	20.9

TABLE XLVI. COMPRESSION TEST RESULTS FOR
INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ⁶ psi
<u>Longitudinal at Room Temperature</u>		
2L-1	149.0	31.8
2L-2	150.0	30.9
2L-3	150.0	30.6
<u>Transverse at Room Temperature</u>		
2T-1	149.0	30.8
2T-2	149.0	31.1
2T-3	149.0	32.4
<u>Longitudinal at 800 F</u>		
2L-4	127.0	23.9
2L-5	124.0	25.2
2L-6	129.0	23.7
<u>Transverse at 800 F</u>		
2T-4	129.0	24.6
2T-5	131.0	24.0
2T-6	128.0	23.9
<u>Longitudinal at 1000 F</u>		
2L-7	123.0	23.2
2L-8	123.0	23.0
2L-9	124.0	22.8
<u>Transverse at 1000 F</u>		
2T-7	125.0	24.5
2T-8	125.0	23.4
2T-9	124.0	24.0

TABLE XLVI (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 ³ psi
<u>Longitudinal at 1200 F</u>		
2L-10	118.0	23.3
2L-11	120.0	22.0
2L-12	122.0	22.1
<u>Transverse at 1200 F</u>		
2T-10	120.0	22.2
2T-11	120.0	22.2
2T-12	124.0	22.2

TABLE XLVII. SHEAR TEST RESULTS FOR INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)

Specimen Number	Ultimate Shear Strength, ksi
<u>Longitudinal</u>	
4L-1	117.0
4L-2	117.0
4L-3	117.0
4L-4	118.0
<u>Transverse</u>	
4T-1	117.0
4T-2	117.0
4T-3	117.0
4T-4	117.0

TABLE XLVIII. IMPACT TEST RESULTS FOR INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)

Specimen Number	Energy, ft/lbs
<u>Longitudinal</u>	
10L-1	29.5
10L-2	32.0
10L-3	33.0
10L-4	31.5
10L-5	33.0
10L-6	32.0
<u>Transverse</u>	
10T-1	28.0
10T-2	26.0
10T-3	28.0
10T-4	26.5
10T-5	25.0
10T-6	27.0

TABLE XLIX. FRACTURE TOUGHNESS TEST RESULTS
FOR INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)

Specimen Number	W, inches	a, inches	l, inches	P, lbs	Span, inches	$\frac{a}{f(\bar{w})}$	$K_Q^{(a)}$
<u>Longitudinal</u>							
1L	1.498	.737	.750	9,800	4.5	2.6	83.3
2L	1.499	.754	.751	9,900	4.5	2.6	86.9
3L	1.500	.760	.750	10,250	4.5	2.7	91.1
<u>Transverse</u>							
1T	1.497	.747	.750	10,150	4.5	2.6	88.3
2T	1.490	.749	.747	9,850	4.5	2.6	84.3
3T	1.497	.735	.749	10,750	4.5	2.6	91.3

(a) Candidate fracture toughness values, K_Q , are invalid as K_{Ic} values since a ,
 l , $< 2.5 \left(\frac{K_Q}{\sigma_{YS}} \right)^2$.

TABLE L. AXIAL LOAD FATIGUE TEST RESULTS FOR
UNNOTCHED INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)
(TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-3	125.0	88,100
5-4	115.0	150,300
5-2	105.0	227,500
5-1	95.0	364,400
5-5	85.0	679,000
5-6	75.0	2,199,400
5-7	65.0	8,446,000
5-8	60.0	10,025,200(a)
<u>600 F</u>		
5-17	125.0	25,220
5-18	115.0	42,700
5-19	105.0	82,100
5-20	95.0	139,900
5-21	85.0	164,300
5-22	75.0	422,300
5-23	65.0	6,226,100
5-24	55.0	10,792,700(a)
<u>1000 F</u>		
5-9	125.0	14,000
5-10	115.0	42,700
5-11	105.0	31,300
5-12	95.0	163,600
5-13	85.0	165,300
5-14	75.0	722,300
5-15	65.0	2,232,100
5-16	55.0	5,557,700
5-25	45.0	12,239,200(a)

(a) Did not fail.

TABLE LI. AXIAL LOAD FATIGUE TEST RESULTS FOR
NOTCHED ($K_t = 3.0$) INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT)
(TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
<u>Room Temperature</u>		
5-1	105.0	9,900
5-2	95.0	14,100
5-3	85.0	32,000
5-4	75.0	29,000
5-5	65.0	47,200
5-6	55.0	88,300
5-7	45.0	150,000
5-8	35.0	445,900
5-23	30.0	475,000
5-9	25.0	4,770,490
5-10	20.0	11,953,000 ^(a)
<u>600 F</u>		
5-11	75.0	25,300
5-12	65.0	44,900
5-13	55.0	74,000
5-14	45.0	204,700
5-25	40.0	255,100
5-15	35.0	529,500
5-26	30.0	10,012,000 ^(a)
5-16	25.0	13,091,900 ^(a)
<u>1000 F</u>		
5-17	75.0	12,200
5-18	65.0	25,700
5-19	55.0	46,900
5-20	45.0	116,300
5-21	40.0	17,555,700 ^(a)
5-21	35.0	7,421,600
5-22	30.0	11,685,000 ^(a)

(a) Did not fail.

TABLE III. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT) (TRANSVERSE)

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent				Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
3-1	158	800	---	---	---	---	---	On Loading	16.9	34.7	--
3-2	155	800	95	735 (b)	---	---	14.345	476.8 (a)	14.520	--	0.00010
3-10	150	800	---	---	---	---	5.404	144.7 (a)	6.410	--	--
3-2	150	1000	0.02	0.04	0.1	0.22	0.51	1.3	11.5	34.7	3.1
3-7	140	1000	0.5	2.0	10	35	100	243.3	9.2	13.2	0.014
3-4	130	1000	8	45	280	900	1800 (b)	743.8 (a)	2.580	--	0.001
3-8	120	1000	450	1400 (b)	---	---	---	791.2 (a)	0.962	--	0.00001
3-5	110	1200	0.15	0.4	1.1	3.1	7.7	20.4	6.1	20.4	0.22
3-6	100	1200	1.5	6.0	31	50	76	140.0	13.9	22.1	0.011
3-6	80	1200	300	570	1000 (b)	---	---	719.5 (a)	0.816	--	0.0028

(a) Test discontinued.

(b) Estimate.

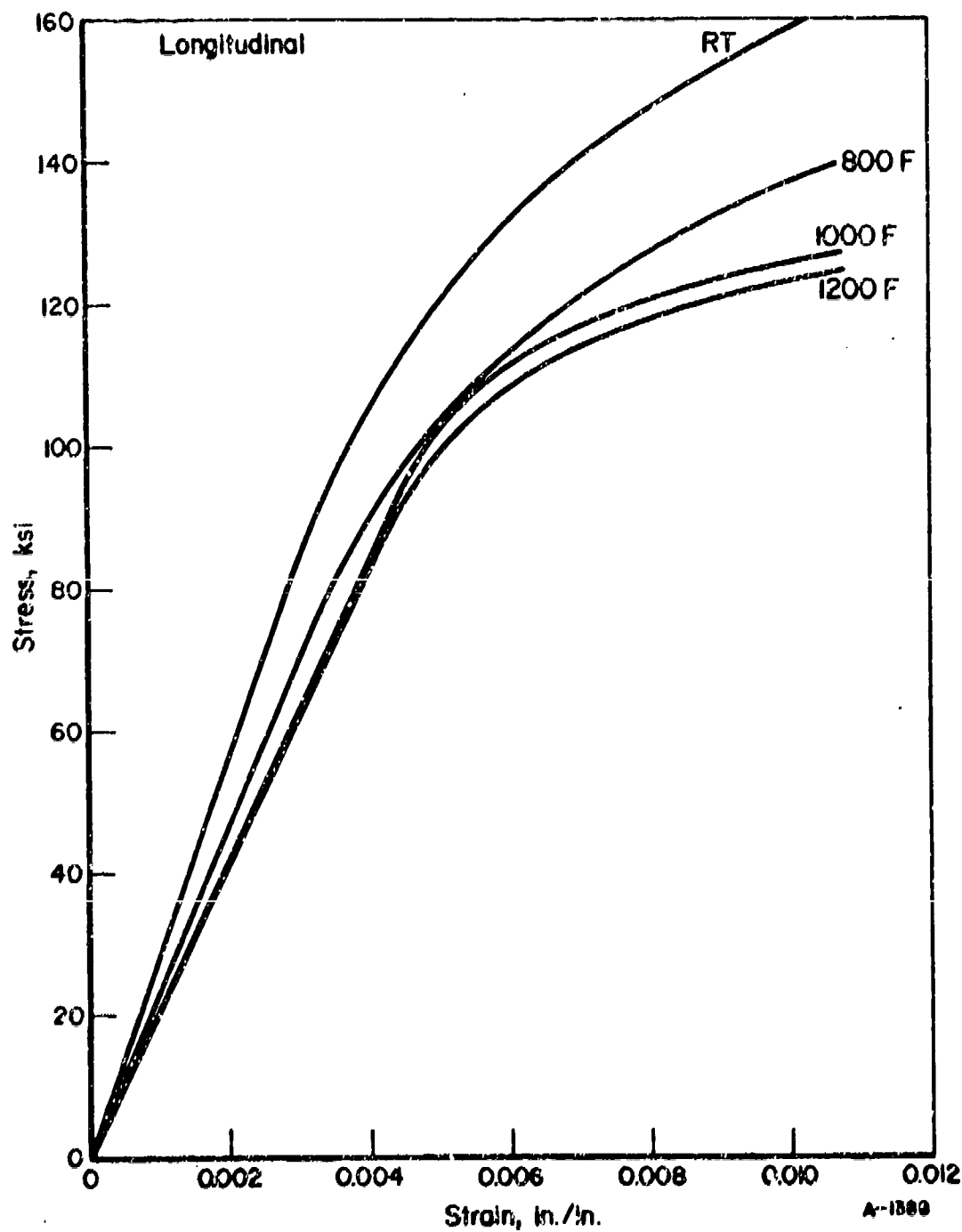


FIGURE 62. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 706 FORGED BAR (LONGITUDINAL) (STRESS-RUPTURE HEAT TREATMENT)

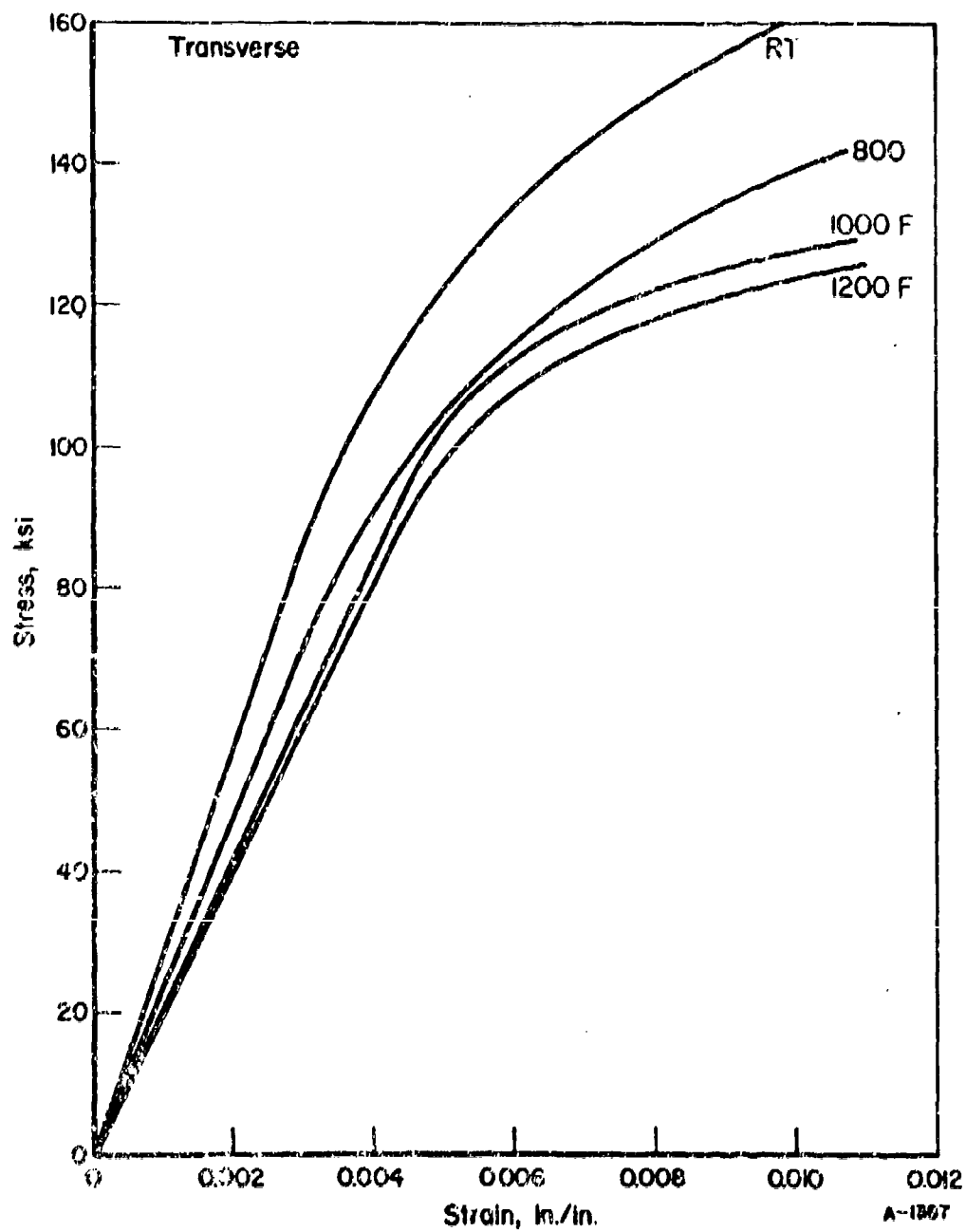


FIGURE 63. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 706 FORGED BAR (TRANSVERSE) (STRESS-RUPTURE HEAT TREATMENT)

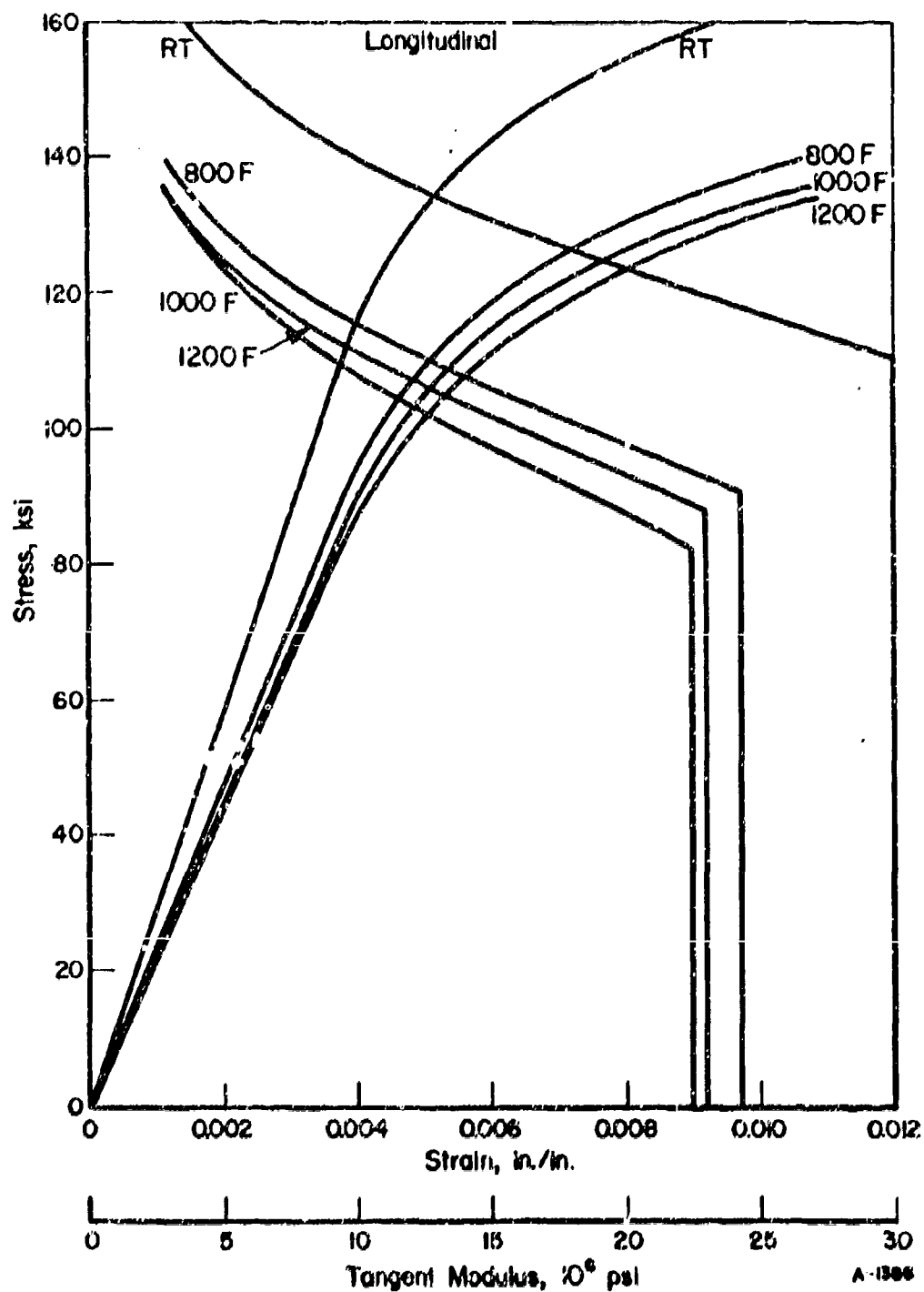


FIGURE 64. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 706 FORGED BAR (LONGITUDINAL) (STRESS-RUPTURE HEAT TREATMENT)

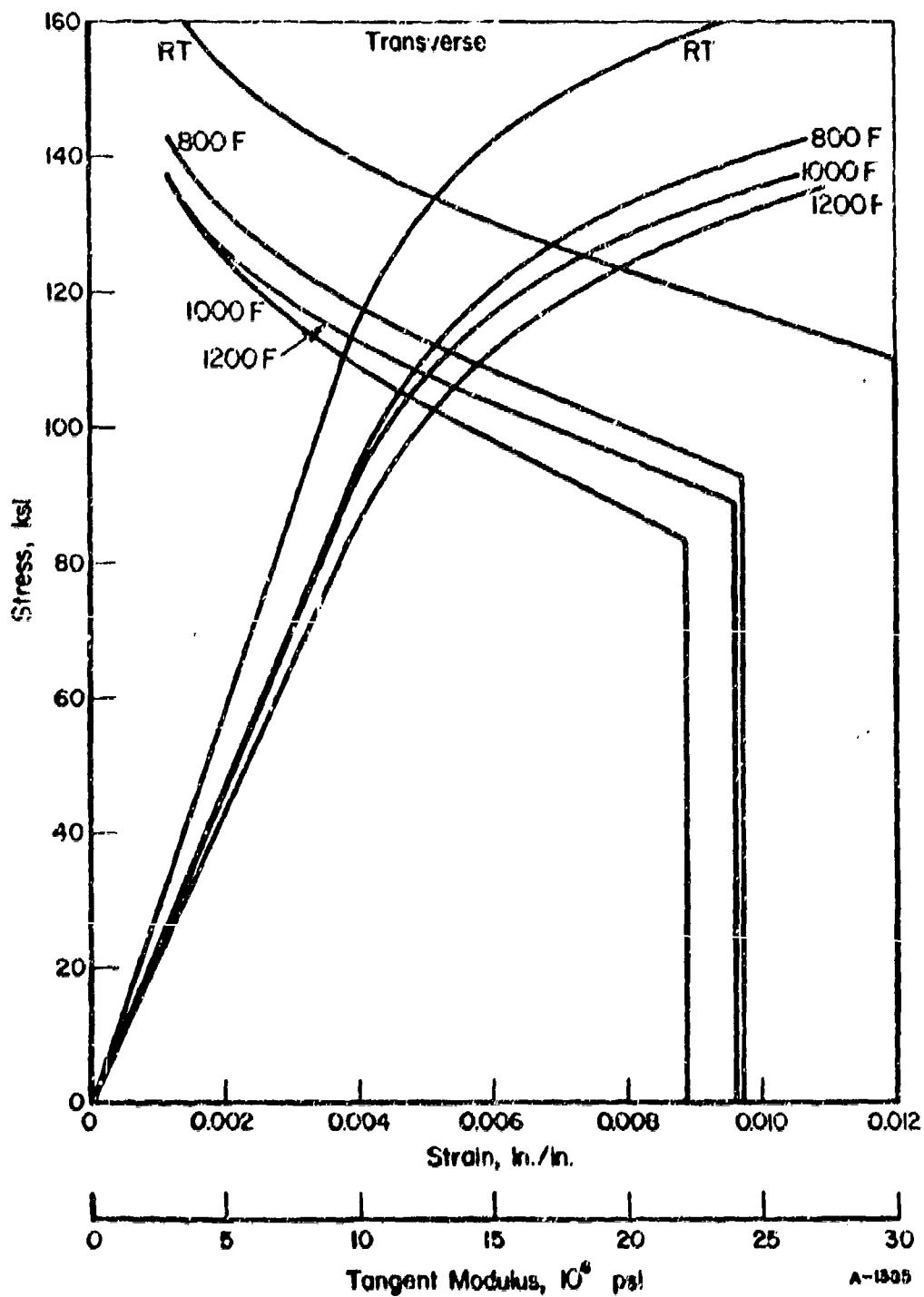


FIGURE 65. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 706 FORGED BAR (TRANSVERSE) (STRESS-RUPTURE HEAT TREATMENT)

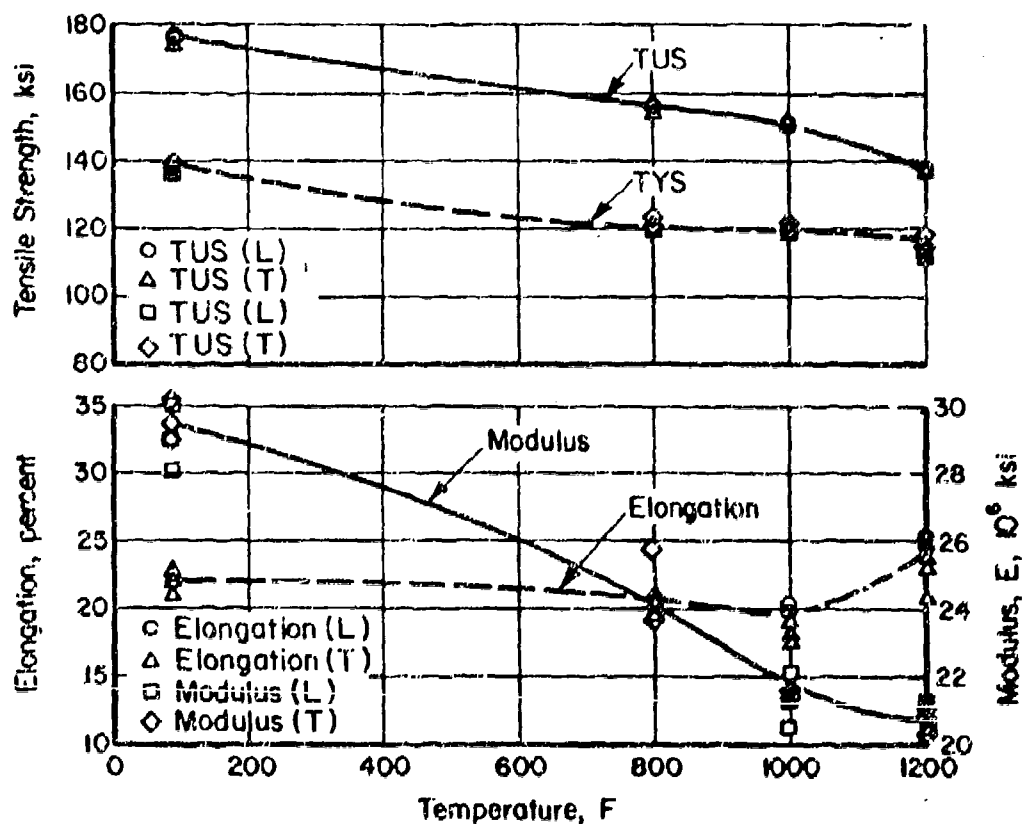


FIGURE 66. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

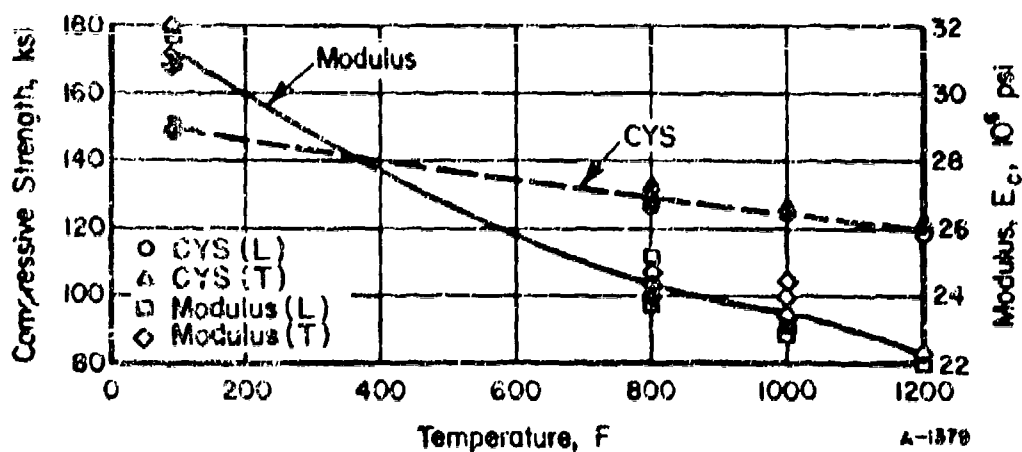


FIGURE 67. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

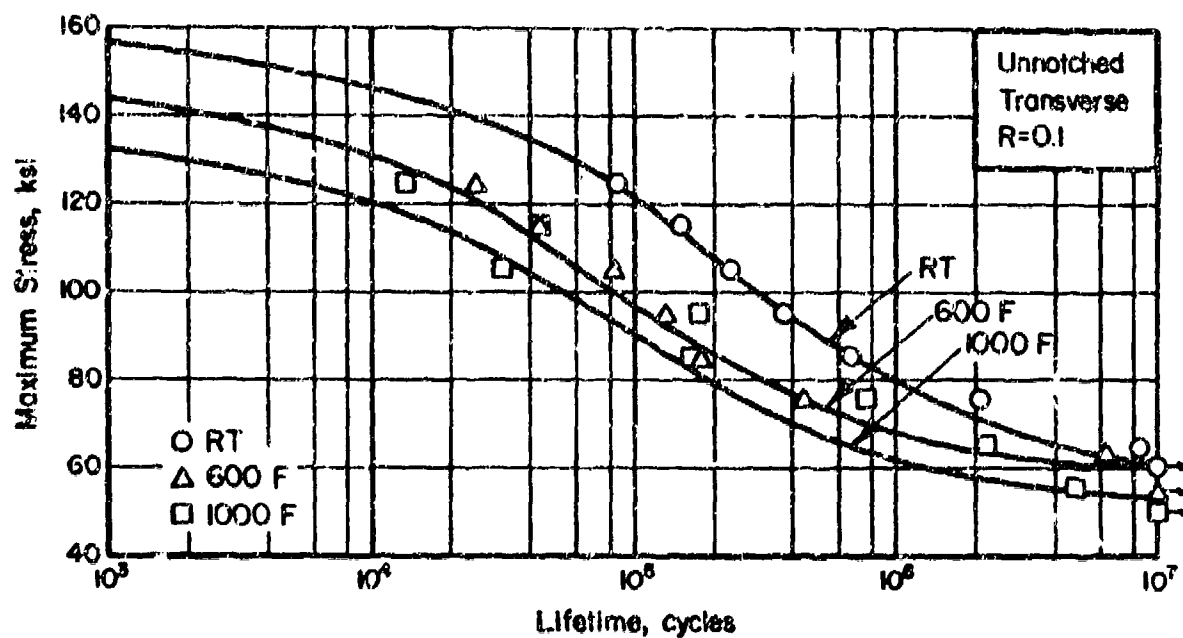


FIGURE 68. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

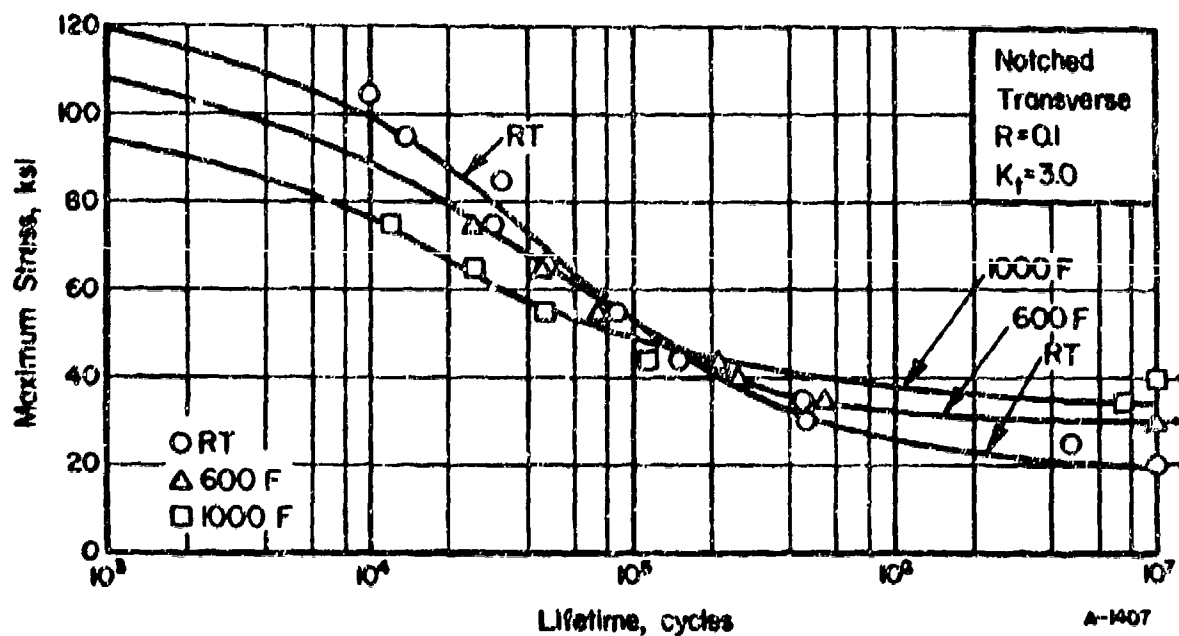


FIGURE 69. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

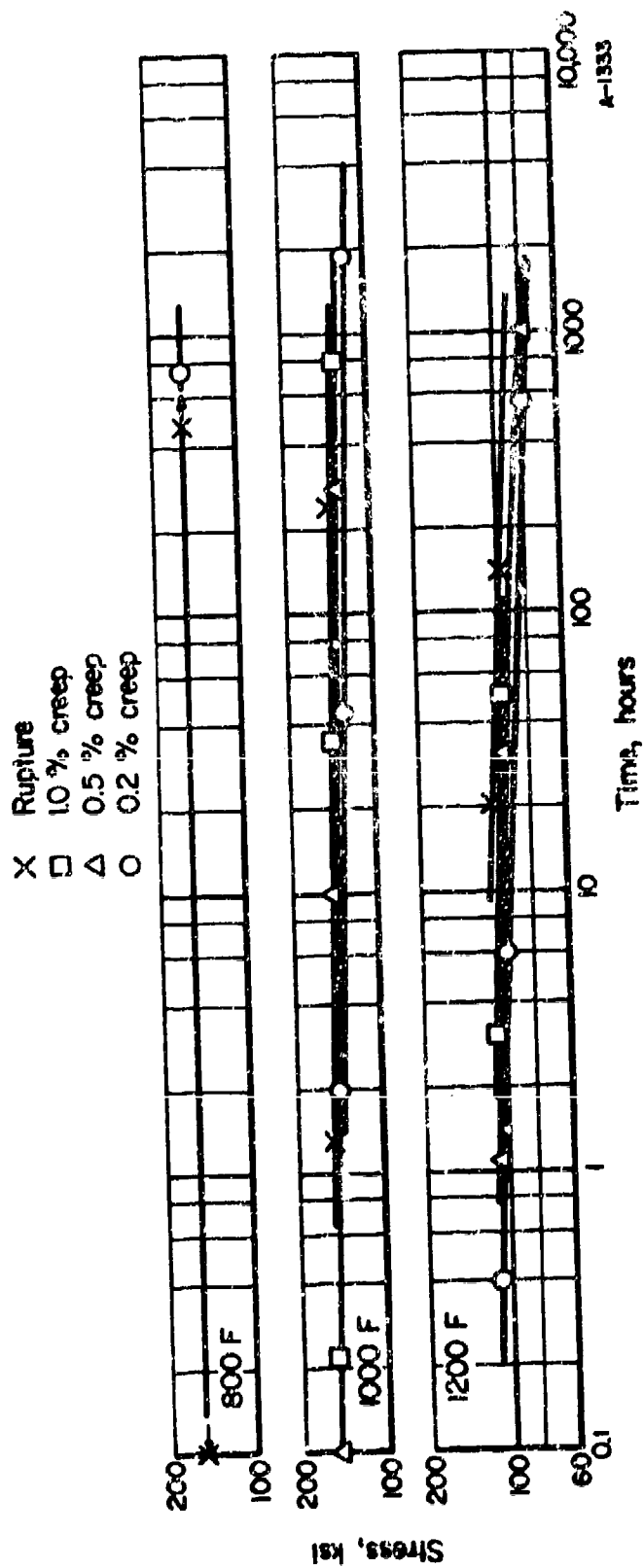


FIGURE 70. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR INCONEL 706 FORGED BAR
(STRESS-RUPTURE HEAT TREATMENT) (TRANSVERSE)

DISCUSSION OF PROGRAM RESULTS

The tendency in an evaluation program of this type is to compare the materials property information obtained with similar data on materials already in use. Whether such a comparison should be the deciding factor for interest in a newer alloy is open to question. Many criteria, such as forming characteristics, weldability, oxidation resistance, etc., can be of particular importance so that strength properties may become secondary. However, since first comparisons are almost always made on the basis of mechanical strength (tensile ultimate and tensile yield) the data generated on this program are compared to information for similar alloys in Figures 71 and 72.

CONCLUSIONS

The objective of this program was the generation of useful engineering data for newly developed materials. During the contract term the following alloys were evaluated:

- (1) 15-5 PH (H1025) stainless steel forged bar
- (2) HP 9Ni-4Co-0.20C steel forged bar
- (3) PH 13-8 Mo (H1000) stainless steel forged bar
- (4) 7049-T76 aluminum extrusion
- (5) 6Al-2Sn-4Zr-6Mo titanium sheet
- (6) Inconel Alloy 702 sheet (Aged)
- (7) Inconel Alloy 706 forged bar (Creep-rupture heat treatment).

A data sheet was issued for each material. As a summary, each of the data sheets is reproduced in Appendix III.

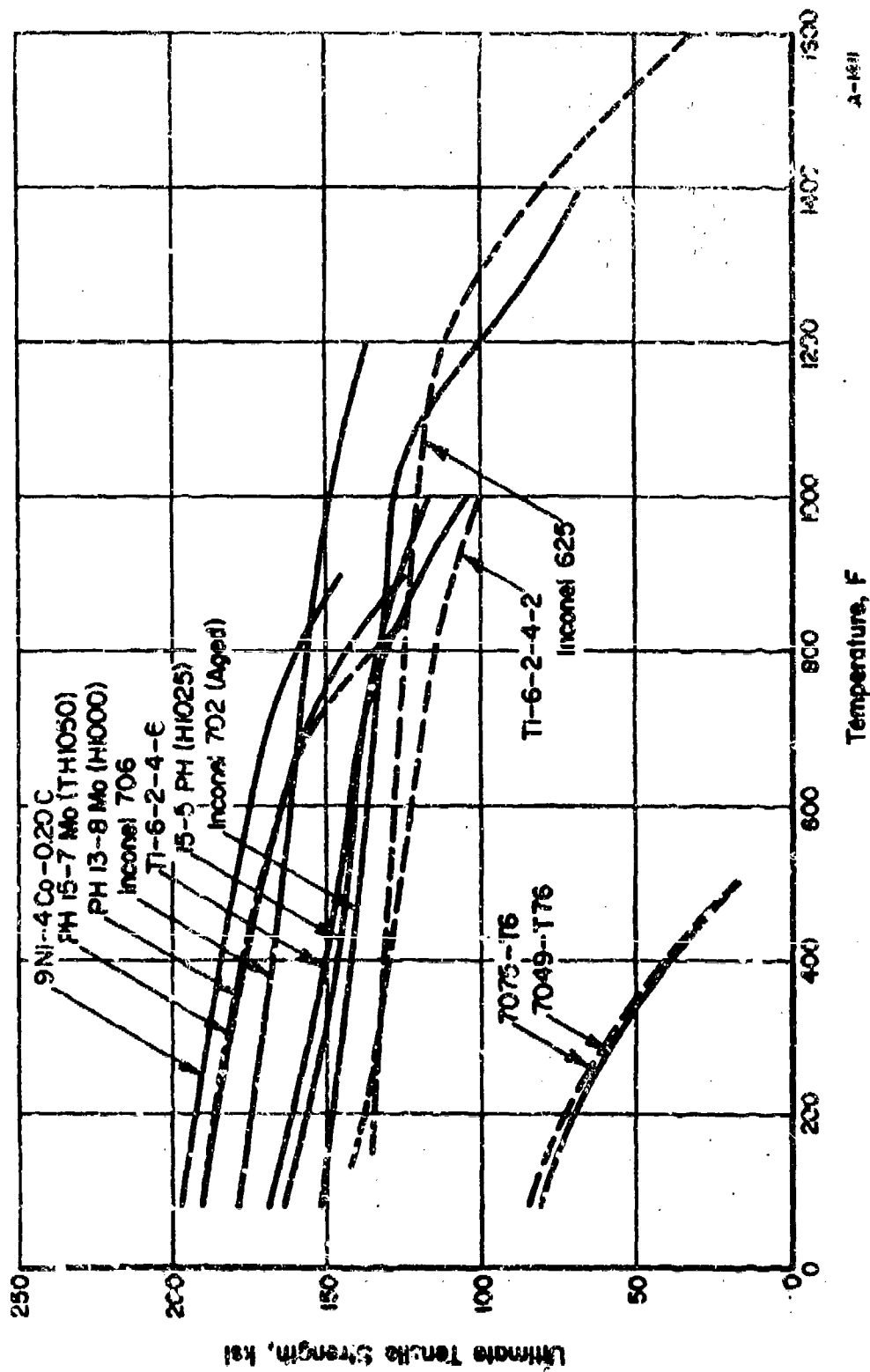
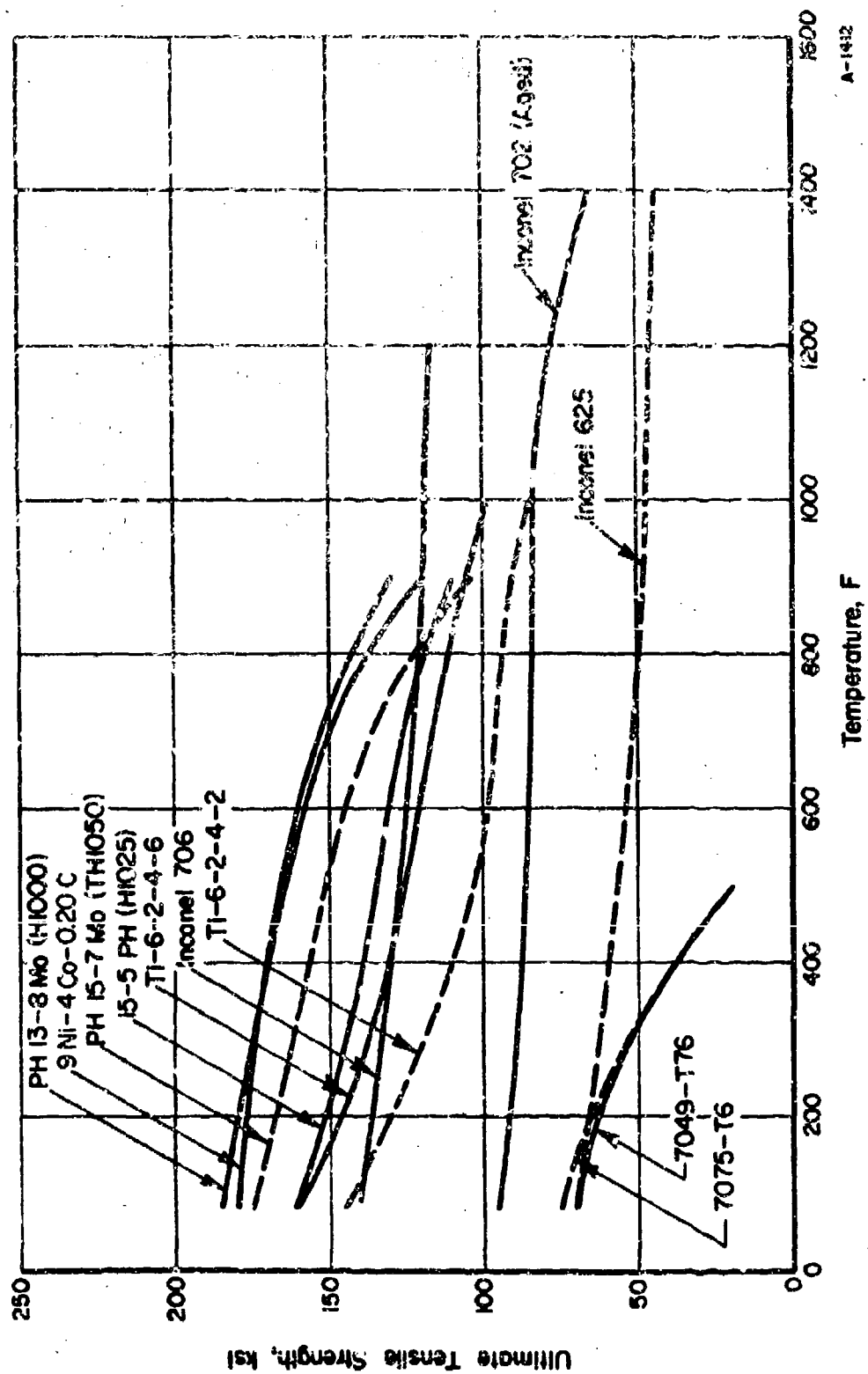


FIGURE 71. TENSILE ULTIMATE STRENGTH AS A FUNCTION OF TEMPERATURE



A-1412

FIGURE 72. TENSILE YIELD STRENGTH AS A FUNCTION OF TEMPERATURE

APPENDIX I
EXPERIMENTAL PROCEDURE

APPENDIX I

EXPERIMENTAL PROCEDURE

Mechanical Properties

The various mechanical properties of interest for each of the materials are as follows:

- (1) Tension
 - (a) Tensile ultimate strength, TUS
 - (b) Tensile yield strength, TYS
 - (c) Elongation, e_t
 - (d) Reduction in area, RA
 - (e) Modulus of elasticity, E_t .
- (2) Compression
 - (a) Compressive yield strength, CYS
 - (b) Modulus of elasticity, E_c .
- (3) Creep and stress-rupture
 - (a) Stress for 0.2 or 0.5 percent deformation in 100 hours and 1000 hours
 - (b) Stress for rupture in 100 hours and 1000 hours.
- (4) Shear
 - (a) Shear ultimate strength, SUS
- (5) Axial fatigue*
 - (a) Unnotched, $R = 0.1$, lifetime: 10^3 through 10^7 cycles

* "R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. " K_t " represents the Neuber-Peterson theoretical stress concentration factor.

- (b) Notched ($K_t = 3.0$), $R = 0.1$, lifetime: 10^3 through 10^7 cycles.
- (6) Fracture toughness, K_{Ic} or K_{IIc}
- (7) Stress corrosion
 - (a) 80 percent TYS for 1000 hours maximum, 3-1/2 percent NaCl solution.
- (8) Thermal expansion.
- (9) Bend
 - (a) Minimum radius.
- (10) Impact
 - (a) Charpy V-notch.
- (11) Density.

Specimen Identification

A simple system of numbers and letters was used for specimen identification. Coding consisted of a number indicating the type of test and also indicating a comparable area on the sheet, plate, or forging. For certain test types, the number was followed by a letter signifying specimen orientation (L for longitudinal, T for transverse, ST for short transverse). The test types where the letter did not appear were creep, fatigue, and bend since, in these cases, only one specimen orientation was used. The next number in the coding specifies the location from which the specimen blank was taken from the original material configuration. Coding was as follows:

<u>Assigned Number</u>	<u>Test Type</u>
1	Tension
2	Compression
3	Creep and stress-rupture
4	Shear
5	Fatigue
6	Fracture toughness

<u>Assigned Number</u>	<u>Test Type</u>
7	Stress corrosion
8	Thermal expansion
9	Bend
10	Impact
11	Density

As an example, a specimen numbered 2-T5 is a compression specimen, transverse orientation, cut from Location 5. Also, a specimen numbered 5-12 is a fatigue specimen cut from Location 12.

Test Description

Tension

Procedures used for tension testing are those recommended in ASTM methods E8-68 and E21-66T as well as in Federal Test Method standard No. 151a (method 211.1). Six specimens (three longitudinal and three transverse) were tested at each temperature to determine ultimate tensile strength, 0.2 percent offset yield strength, elongation, and reduction in area. The modulus of elasticity was obtained from load-strain curves plotted by an autographic recorder during each test.

All tensile tests were carried out in Baldwin Universal testing machines. These machines are calibrated at frequent intervals in accordance with ASTM method E4-64 to assure loading accuracy within 0.2 percent. The machines are equipped with integral automatic strain pacers and autographic strain recorders.

Specimens tested at elevated temperatures were heated in standard wire-wound resistance-type furnaces. Each furnace was equipped with a Foxboro controller capable of maintaining the test temperature to within 5 F of the control temperature over a 2-inch gage length. Chromel-Alumel thermocouples attached to the specimen gage section were used to monitor temperatures. Each specimen was soaked at temperature at least 20 minutes before being tested.

An averaging-type linear differential transformer extensometer was used to measure strain. For elevated temperature testing, the extensometer was equipped with extensions to bring the transformer unit out of the furnace. The extensometer conformed to ASTM E3-64T Classification B1 having a sensitivity of 0.0001 inch/inch. The strain rate in the elastic region was maintained at 0.005 inch/inch/minute. After yielding occurred, the head speed was increased to 0.1 inch/inch/minute until fracture.

Compression

Procedures for conducting compression tests are outlined in ASTM Method E9-67 along with temperature control provisions of E21-66T. All sheet and thin plate tests were carried out in Baldwin Universal testing machines using a North American type compression fixture as shown in Reference 2. Specimen heating was accomplished by a forced-air furnace for temperatures up to 1000 F. Specimen temperature was maintained by means of a Wheelco pyrometer. Three Chromel-Alumel thermocouples attached to the fixture were used to monitor temperatures to within 3 F of the test temperature. For higher temperatures, wire-wound furnaces were used with controls as described in the tensile test section.

The extensometer used for the compression tests was quite similar to that used in the tensile testing. The extension arms were fastened to the specimen at small notches spanning a 2-inch gage length. The output from the micro-former was fed into a load-strain recorder to provide autographic load-strain curves. During testing the strain rate was adjusted to 0.005 inch/inch/minute.

For bar and forging material, cylindrical specimens similar to those described in ASTM E9-67 were used with appropriate temperature control and strain measurement as described above.

Six specimens (three longitudinal and three transverse) were tested at each temperature.

Shear

Single-shear sheet-type specimens were used for sheet and thin-plate material; for bar and forgings, a double-shear pin-type was used. Shear testing was performed at room temperature only. A minimum of six specimens (three longitudinal and three transverse) were used to determine ultimate shear strength.

Bend

The procedures for conducting bend tests are described in Report MAB-192-M. The specimens were placed in a rigid three-point loading fixture and bending tups of various sizes were used to determine the minimum bend radius at room temperature.

Creep and Stress Rupture

Standard dead-weight type creep testing frames were used for the creep and stress-rupture tests. These machines are calibrated to operate well within the accuracy requirements of ASTM method E139-66T.

Specimens similar to those used for tension tests were used for the creep and stress-rupture studies. A platinum strip "slide rule" extensometer is attached for measuring creep strain and three Chromel-Alumel thermocouples are attached to the gage section for temperature measurements. Extensometer measurements were made visually through windows in the furnace by means of a filar micrometer microscope in which the smallest division equals 0.00005 inch.

The furnace was of conventional Chromel A wire-wound design with taps along the side to allow for correcting small temperature differences. Furnace temperature was maintained to within ± 2 F by Foxboro controllers in response to signals from the centrally located thermocouple. The temperature of a specimen under test was stabilized for at least 1/2 hour prior to loading.

For each temperature condition creep and stress-rupture data were obtained to 100 and 1000 hours using as many specimens as necessary to obtain precise information. The percent creep deformation obtained was dependent on the material under test. In most instances stress-time curves were defined for 0.2 and 0.5 percent elongation.

Stress Corrosion

Seven specimens of each alloy were tested for susceptibility to stress-corrosion cracking by alternate immersion in 3-1/2 percent sodium chloride solution at room temperature.

Specimens were prepared for testing by degreasing with acetone. Where a surface film remained from heat treating, it was abraded off one side and the adjacent long edge of five of the specimens, and left intact on the other two.

Each specimen was placed in a four-point loading fixture and deflected to a stress corresponding to 80 percent of the tensile yield strength of the particular material. The specimen was electrically insulated from the fixture by means of glass or sapphire rods. Deflection for a given maximum fiber stress was calculated by the following expression:

$$y = \frac{\sigma(3l^2 - 4a^2)}{12dE}$$

where

y = deflection

σ = maximum fiber stress

l = distance between outer load points

a = distance between outer and inner load points

d = specimen thickness

E = modulus of specimen material.

Each stressed specimen was suspended on an alternate immersion unit. This unit alternately immersed specimens in the 3.5 percent sodium chloride solution for ten minutes and held them above the solution to dry for 50 minutes. Tests were continued to the first sign of cracking or for 1000 hours, whichever occurred first.

Specimens were given frequent low-power microscopic examinations to detect cracks. At the first sign of cracking the specimen was removed. At the conclusion of the test, selected samples were sectioned and examined metallographically for any indication of cracking. Representative samples in which cracks were found were also given a metallographic examination to establish the type and extent of the cracks.

Thermal Expansion

Linear-thermal-expansion measurements were performed in a recording dilatometer with specimens protected by a vacuum of about 2×10^{-6} mm of mercury. In this apparatus a sheet-type specimen is supported between two graphite structures inside a tantalum-tube heater element. On heating, the differential movement of the two structures caused by specimen expansion results in the displacement of the core of a linear-variable differential transformer. The output of the transformer is recorded continuously as a function of specimen temperature. The entire assembly is enclosed in a vacuum chamber.

The furnace is controlled to heat at the desired rate, usually 5 F per minute. Errors associated with measurements in this apparatus are estimated not to exceed ± 2 percent. This is based on calibration with materials of known thermal-expansion characteristics.

Fatigue

Fatigue tests were conducted using MTS electrohydraulic-servocontrolled testing machines. The frequency of cycling of these machines is variable to beyond 2,000 cpm depending on specimen rigidity. These machines operate with closed-loop deflection, strain or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by means of load-cell feedback signals. The calibration and alignment of each machine are checked periodically. In each case, the dynamic load-control accuracy is better than ± 3 percent of the test load.

For elevated temperature studies, an induction heating coil controlled by a Lepel Induction Heater was used. A thermocouple placed on the center of the specimen controlled temperature to ± 5 degrees.

After machining and heat treating (when required), the edges of all sheet and plate specimens were polished according to Battelle-Columbus' standard practice prior to testing. The unnotched specimens were held against a rotating drum covered with emery paper and polished using a kerosene lubricant. Successively finer grits of emery paper were used, as required, to produce a surface

of about 10 RMS. Unnotched round specimens were polished in the Battelle-Columbus polishing apparatus. This machine utilizes a rotating belt sander driven rectilinearly along the specimen test section while the specimen is being rotated. The belt speed and specimen speed are adjusted so that polishing marks on the specimen are in the longitudinal direction. The surface finish is about the same as that on the flat specimens. The notched flat specimens were held in a fixture and polished with a slurry of oil and alundum grit applied liberally to a rotating wire. Notched round specimens are polished in the same manner, except that the specimen is rotated.

A shadowgraph optical comparator was used for measuring the test sections of all polished specimens and for inspection of the root radius in the case of the notched specimens.

The stress ratio for all specimens was $R = 0.1$. Stresses for notched ($K_t = 3.0$) and unnotched specimens were selected so that S-N curves were defined between 10^3 and 10^7 cycles using approximately 10 specimens for each set of fatigue conditions.

Fracture Toughness

Two types of fracture toughness tests were used. For heavy section materials, the chevron-notched, slow bend test specimen of ASTM Method E-399-72 was selected. For thinner section sheet materials, center through-cracked tension panels were used as test specimens. All specimens were precracked in fatigue and subsequently fractured in a servocontrolled electrohydraulic testing system of appropriate load capacity.

The slow-bend type specimens were precracked and tested under 3-point loading. The pop-in load for materials susceptible to brittle fracture was determined from the load-compliance curve. When pop-in was not detectable, the curves were analyzed using the 5 percent secant offset method of the ASTM procedure.

The thin sheet center through-crack tension panels were initially saw-cut and then precracked in constant amplitude fatigue loading. In order to maintain a flat fatigue crack and not plastically strain the uncracked section, the maximum stresses were adjusted to keep the applied stress-intensity factor less than one-third or one-quarter of that anticipated at fracture. This usually involved stepping down the stresses as the cracking proceeded. The crack was extended to approximately one-quarter of the panel width. Buckling guides were attached and a clip-type compliance gage was mounted in the central notch. The panels were fractured in a rising load test at a stress rate in the range

$$.002 \text{ E} < \dot{S} < .005 \text{ E ksi/min} \quad ,$$

which corresponds nominally to the gross strain rate of standard tensile testing.

APPENDIX II
SPECIMEN DRAWINGS

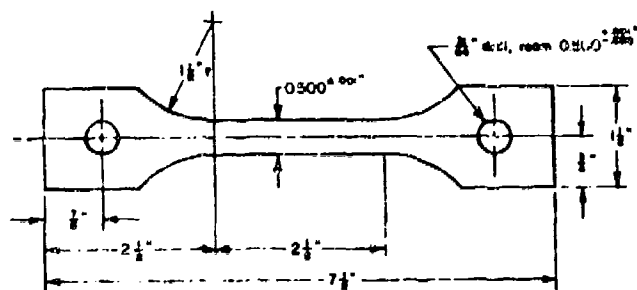


FIGURE 73. SHEET AND THIN-PLATE TENSILE SPECIMEN

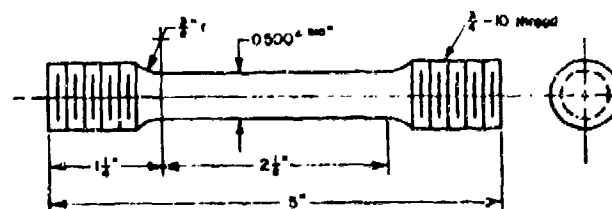
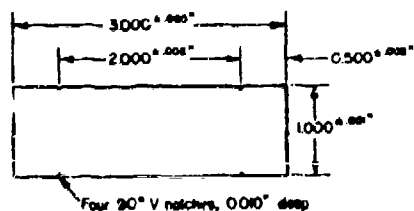


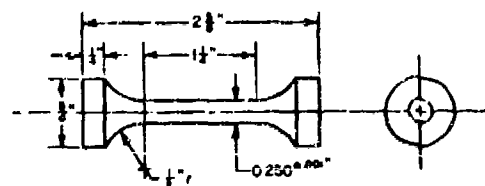
FIGURE 74. ROUND TENSILE SPECIMEN



Notes 1. Ends must be flat and parallel to within 0.0002".

2. Surface must be free from nicks and scratches.

FIGURE 75. SHEET COMPRESSION SPECIMEN



Note. Ends to be flat and parallel to within 0.0002" of ϵ .

FIGURE 76. ROUND COMPRESSION SPECIMEN

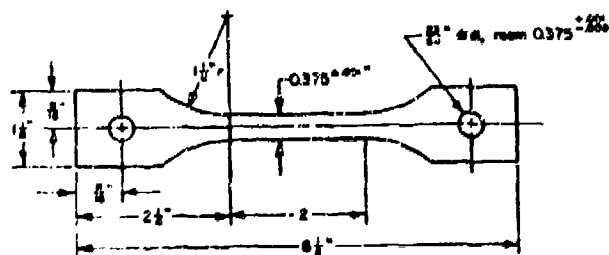
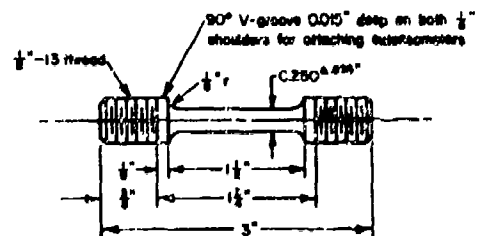


FIGURE 77. SHEET CREEP - AND STRESS-RUPTURE SPECIMEN



A-1363

FIGURE 78. ROUND CREEP - AND STRESS-RUPTURE SPECIMEN

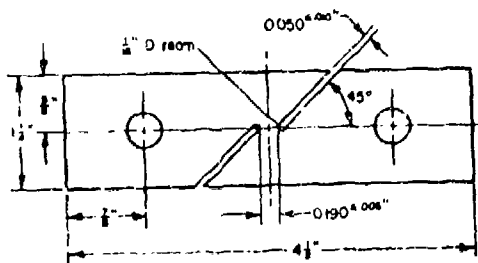


FIGURE 79. SHEET SHEAR TEST SPECIMEN

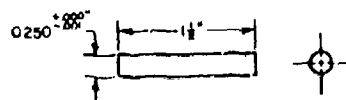


FIGURE 80. PIN SHEAR SPECIMEN

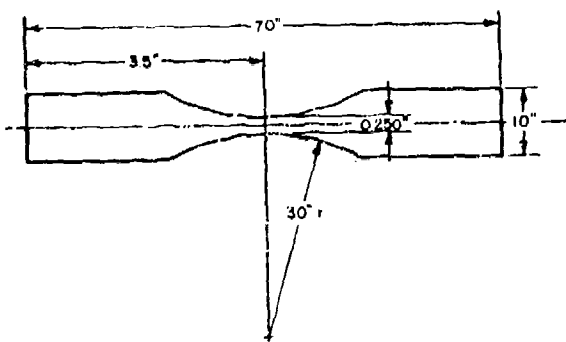


FIGURE 81. UNNOTCHED SHEET FATIGUE SPECIMEN

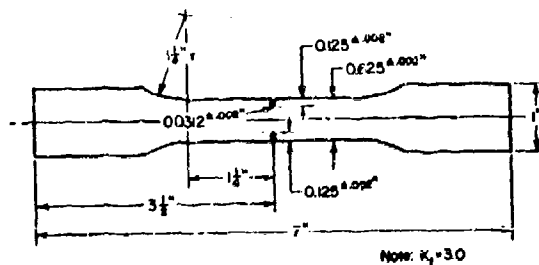


FIGURE 82. NOTCHED SHEET FATIGUE SPECIMEN

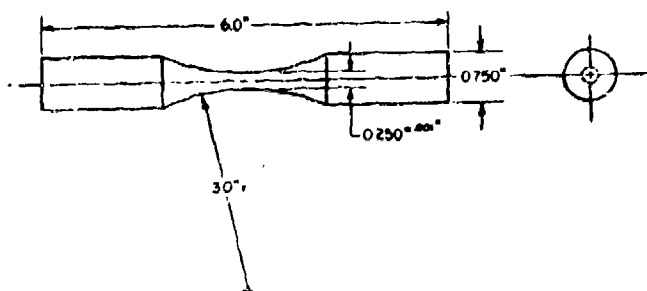


FIGURE 83. UNNOTCHED ROUND FATIGUE SPECIMEN

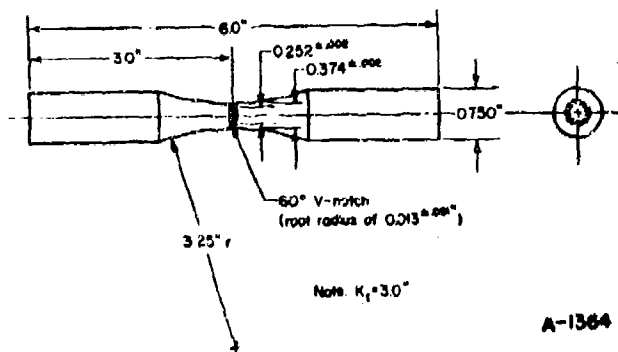


FIGURE 84. NOTCHED ROUND FATIGUE SPECIMEN

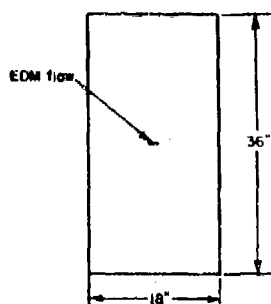


FIGURE 85. SHEET FRACTURE TOUGHNESS SPECIMEN

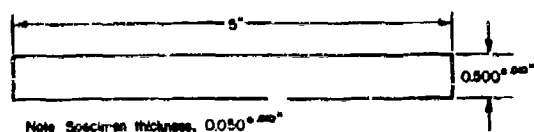


FIGURE 87. STRESS-CORROSION SPECIMEN

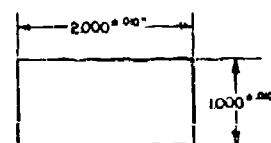


FIGURE 88. THERMAL-EXPANSION SPECIMEN

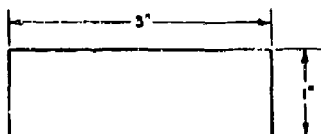


FIGURE 89. SHEET BEND SPECIMEN

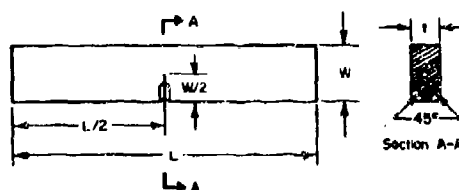


FIGURE 86. SLOW BEND FRACTURE TOUGHNESS SPECIMEN

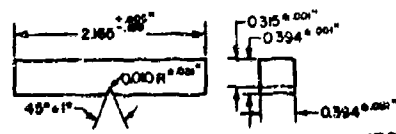


FIGURE 90. NOTCHED IMPACT SPECIMEN

APPENDIX III

DATA SHEETS

15-5 PH Stainless Steel

15-5 PH is a precipitation-hardening stainless steel that offers a combination of high strength and hardness, excellent corrosion resistance plus good transverse toughness and good forgeability. It is produced by consumable vacuum arc remelting and is virtually "ferrite free".

Fabrication practices for 15-5 PH are generally the same as those established for 17-4 PH. Heat techniques are similar to those recommended for the regular grades of stainless steel. Hardening heat treatments require temperatures of only 900 F to 1150 F, depending on the properties desired. Because of the comparatively low hardening temperatures scaling and distortion difficulties are essentially eliminated.

15-5 PH is available in the form of billets, plate, bar, and wire. Typical applications include forgings, pump and valve parts for high pressure systems, aircraft components, and hollow bar parts for hydraulic actuators and controls.

The chemical composition of the forging used for this evaluation is as follows:

Chemical Composition	Percent
Carbon	.037
Manganese	.31
Phosphorus	.018
Sulfur	.010
Silicon	.20
Chromium	15.14
Nickel	4.50
Copper	3.32
Columbium	.24
Tantalum	.01
Iron	Balance

The material tested was obtained from Armco Heat 440370 in the form of 2-1/8 inch x 5-3/4 inch x 8 foot forged bar.

Processing and Heat Treatment

Specimens were machined in the as-received condition & followed by heat treatment for 4 hours at 1025 F to Condition #1025.

15-5 PH Stainless Steel Data (c)

Condition: H 1025

Thickness: 2 inch x 6 inch forged bar

Properties	Temperature, F	
	RT	900
Tension		
T _{TS} (longitudinal), ksi	164.3	137.3
T _{TS} (transverse), ksi	164.0	136.0
T _{YS} (longitudinal), ksi	163.6	128.3
T _{YS} (transverse), ksi	161.6	127.0
a (longitudinal), percent in 2 in.	15.3	10.6
a (transverse), percent in 2 in.	13.0	9.2
RA (longitudinal), percent	63	50
RA (transverse), percent	51	43
R _L (longitudinal), 10 ⁶ psi	30.6	27.7
R _T (transverse), 10 ⁶ psi	28.8	25.1
Compression		
C _{TS} (longitudinal), ksi	163.6	130.0
C _{TS} (transverse), ksi	165.3	130.0
R _C (longitudinal), 10 ⁶ psi	30.2	28.8
R _C (transverse), 10 ⁶ psi	30.3	28.9
Impact (b)		
CVN (longitudinal), ksi	105.5	U
CVN (transverse), ksi	104.3	U
Impact (d)		
V-notch Charpy, ft. lb. (longitudinal)	80.7	U
V-notch Charpy, ft. lb. (transverse)	40.7	U
Fracture Toughness		
K _{IC} , ksi/in	(c)	U
Axial Fatigue (transverse) (f)		
Unnotched, R = 0.1		
10 ⁷ cycles, ksi	172	140
10 ⁶ cycles, ksi	137	113
10 ⁵ cycles, ksi	133	110
Notched, R = 1.0, R = 0.1		
10 ⁷ cycles, ksi	142	113
10 ⁶ cycles, ksi	71	68
10 ⁵ cycles, ksi	50	55

15-5 PH IRONLESS STEEL DATA
(continued)

Temperature	E	Y	TS	Y/T	TS/T
1100					

STRESS RELAXATION

0.2% plastic deformation, 1000 lb, 24 hr, 1000 F, 12, 7.5

STRESS RELAXATION (continued)

0.2% plastic deformation, 1000 lb, 24 hr, 1000 F, 12, 7.5

STRESS RELAXATION (continued)

0.2% plastic deformation, 1000 lb, 24 hr, 1000 F, 12, 7.5

COEFFICIENT OF THERMAL EXPANSION

6.7×10^{-6} in/in/F (20 to 400F)
 5.7×10^{-6} in/in/F (70 to 900F)

RESULTS

0.20 in/in

(a) Values are average of triplicate tests conducted at Institute under the subject conditions unless otherwise indicated. T, TS, Y, and E represent tensile strength and elongation, respectively, using the results of a greater number of tests.

(b) Double-shear pin-type specimens; average of 4 tests.

(c) n, nonavailable; NA, not applicable.

(d) Average of 3 tests.

(e) Six longitudinal shear specimens were tested. Specimen size was 0.190-inch thick by 1.500 inches wide with a gage of 1 inch. The average K₁ obtained was 191.0 ksi/in². Since the size ratio, 2.5 (G₁/G₂), was greater than both the gage size thickness and crack length in all tests, this K₁ value is valid K₁ value by section 4.5.1.1.1.

(f) "n" represents the logarithmic ratio of maximum stress to minimum stress in one cycle; that is, $n = \frac{\log S_{max}}{\log S_{min}}$. "n" represents the higher-frequency theoretical stress concentration factor.

(g) Room-temperature three-point bend test. All test specimens in 3 1/2 in. thick.

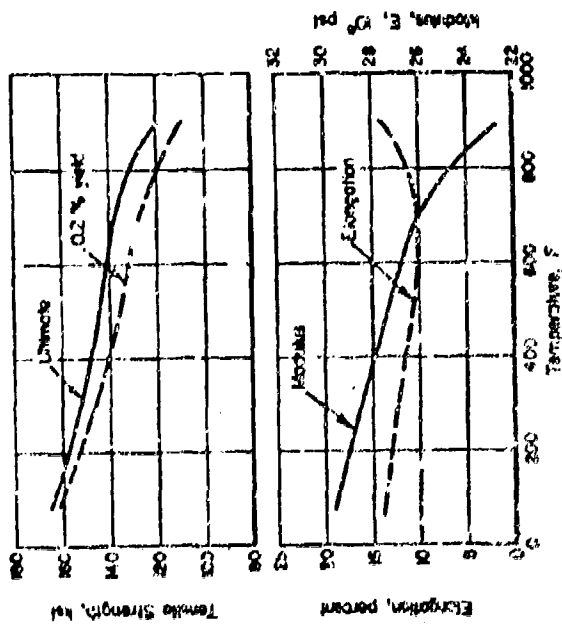


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 15-5 PH (N1025) FORGED BAR

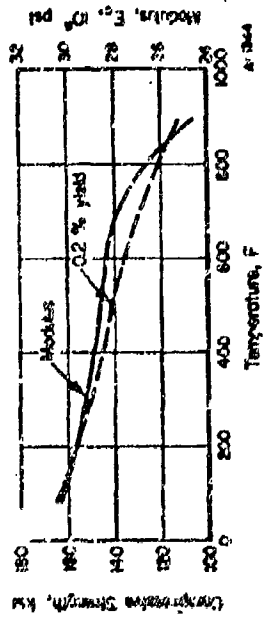


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 15-5 PH (N1025) FORGED BAR

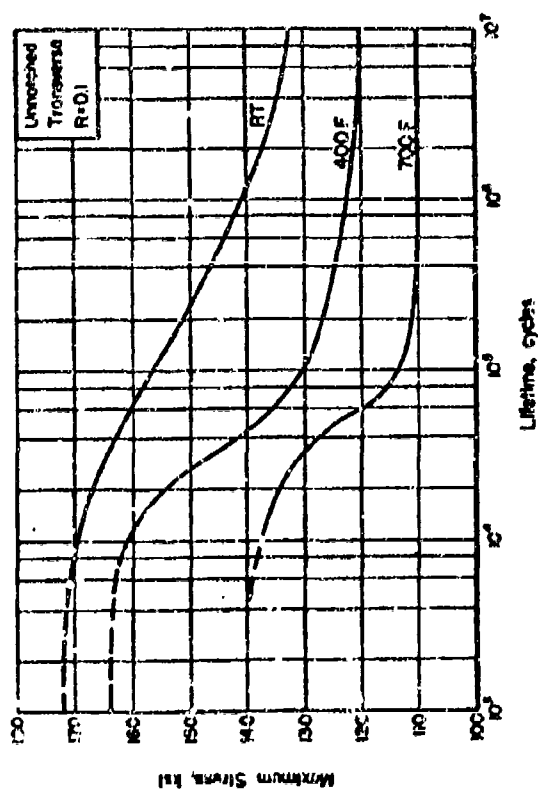


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR FOR UNNOTCHED 13-3 PH (H1025) FORGED BAR

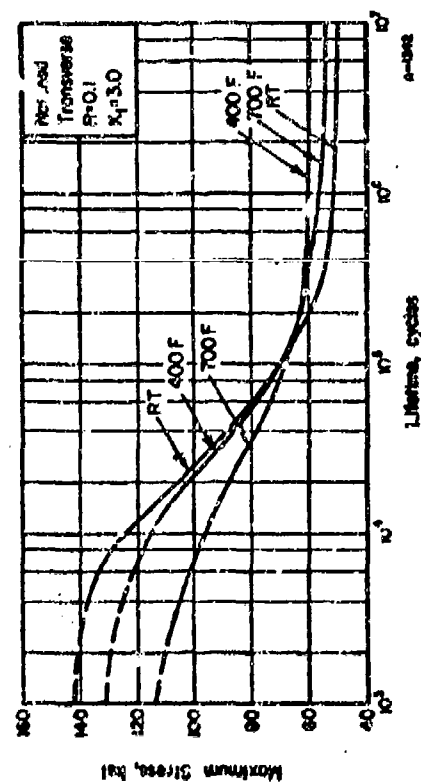


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR FOR NOTCHED ($K_t = 3.0$) 13-3 PH (H1025) FORGED BAR

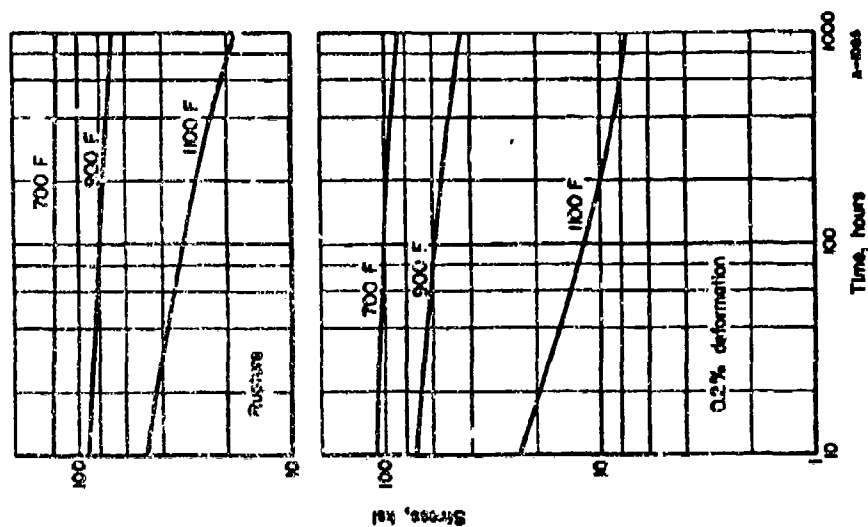


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 13-3 PH (H1025) FORGED BAR (TRANSVERSE)

NP 9M1-4Co-0.20C Data (a)

Condition: Quenched and Tempered
Thickness: 2 inch x 6 inch forging

Material Description

NP 9M1-4Co-0.20C steel was developed specifically to have high hardenability combined with good fracture toughness. It can be welded in the fully heat-treated condition and achieve essentially 100 percent joint efficiency without preheat or postheat treatment. The 0-20C grade is available as sheet, strip, plate, bars, forgings, and tubing.

The material used for this program was consumable electrode vacuum melted and from Republic Steel Heat 3871033. It was obtained as a 2-3/4 inch x 6-inch x 96 inch forged bar and had the following composition:

Chemical Composition	Percent
Carbon	0.19
Manganese	0.36
Phosphorus	0.008
Sulfur	0.007
Silicon	0.04
Nickel	9.30
Chromium	0.80
Molybdenum	1.04
Vanadium	0.08
Cobalt	4.70
Iron	Balance

Processing and Heat Treatment

Specimens were rough machined in the as-received annealed condition, heat treated as follows:

- (1) normalize at 1650 F, 1 hour, air-cool.
- (2) austenitize at 1900 F, 1 hour, oil quench.
- (3) single temper at 1025 F, 6 hours, air cool and then finish machined.

Properties	Temperature, F		
	RT	500	700
Tension			
T _{0S} (longitudinal), ksi	197.0	179.7	170.3
T _{0S} (transverse), ksi	197.0	179.0	167.3
T _{1S} (longitudinal), ksi	180.6	165.0	155.3
T _{1S} (transverse), ksi	180.0	166.0	152.7
σ (longitudinal), percent in 2-in.	17.5	16.0	16.2
σ (transverse), percent in 2 in.	14.6	16.0	14.5
RA (longitudinal), percent	68.0	65.5	66.7
RA (transverse), percent	56.0	55.5	57.8
R (longitudinal), 10 ⁶ psi	27.0	26.0	22.0
R (transverse), 10 ⁶ psi	27.3	25.9	24.7
Compression			
C _{TS} (longitudinal), ksi	196.7	171.6	159.0
C _{TS} (transverse), ksi	194.6	171.3	158.0
R _c (longitudinal), 10 ⁶ psi	27.8	26.4	25.1
R _c (transverse), 10 ⁶ psi	28.0	26.2	25.3
Shear (b)			
S _{0S} (longitudinal), ksi	123.6	U (c)	U
S _{0S} (transverse), ksi	123.3	U	U
Impact (d)			
V-notch Charpy, ft./lb.			
(longitudinal)	42	U	U
(transverse)	53	U	U
Fracture Toughness			
K _{IC} (longitudinal), ksi/in.	(e)	U	U
K _{IC} (transverse), ksi/in.	(e)	U	U
Adial Fatigue (transverse) (f)			
Smoothed, R = 0.1			
10 ⁶ cycles, ksi	170	170	170
10 ⁶ cycles, ksi	73	101	122
10 ⁶ cycles, ksi	57	96	116
Notched, R = 3.0, R = 0.1			
10 ⁶ cycles, ksi	124	114	114
10 ⁶ cycles, ksi	62	42	57
10 ⁶ cycles, ksi	50	30	50

HP 981-4Co-0.20C Data (continued)

Properties	RT	Temperature, F		
		500	700	900
<u>Creep (transverse)</u>				
0.2% plastic deformation, 100 hr, ksi	BA	150	115	60
0.2% plastic deformation, 1000 hr, ksi	BA	149	95	31
<u>Stress Rupture (transverse)</u>				
Rupture, 100 hr, ksi	BA	162	151	95
Rupture, 1000 hr, ksi	BA	159	149	70
<u>Stress Corrosion (a)</u>				
90% TH, 1000 hr maximum	no cracks			
<u>Coefficient of Thermal Expansion</u>				
4.6×10^{-6} in./in./F (80 to 900 F)				

Density

8.224 lb./in.³

(a) Values are average of triplicate tests conducted at lustrate under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 3 tests.

(c) U, unworkable; BA, not applicable.

(d) Average of 5 tests.

(e) Three longitudinal and 3 transverse slow-load specimens were tested. Specimen size was 0.750-inch by 1.250 inches wide with a span of 6 inches. Average K_{IC} obtained was 161.3 ksi/in. is the longitudinal direction and 122.5 ksi/in. in the transverse direction. Since the size ratio, $1/2.5 (K_{IC}/\sigma_{TS})^2$, was greater than both the specimen thickness and crack length in all cases, these values are K_{IC} valid K_{IC} values by existing ASTM criteria.

(f) σ/σ_T represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $\sigma = \sigma_{min}/\sigma_T$. σ_T represents the Rockwell-Carbon concentration stress concentration factor.

(g) Room-temperature three-point bend test. Alternate dimension is 3-1/2 in. σ_{AC} .

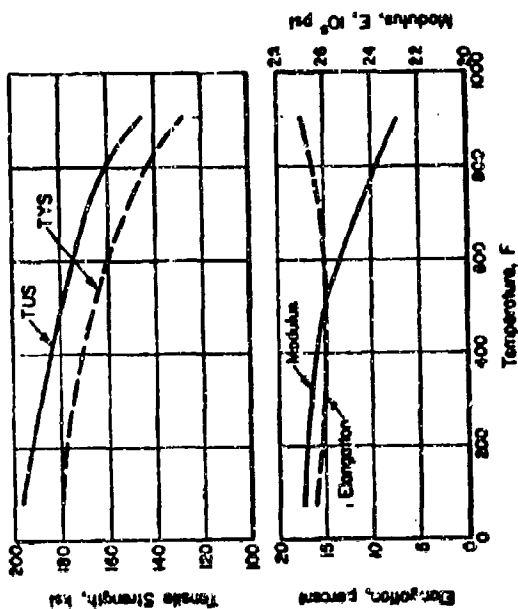


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HP 981-4Co-0.20C FORGED BAR

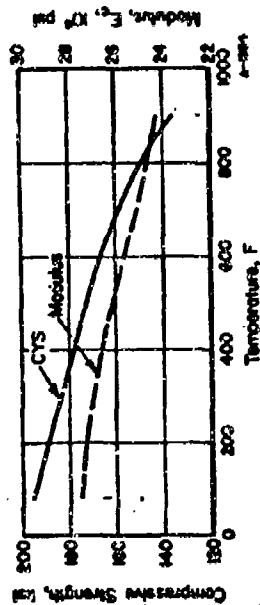


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HP 981-4Co-0.20C FORGED BAR

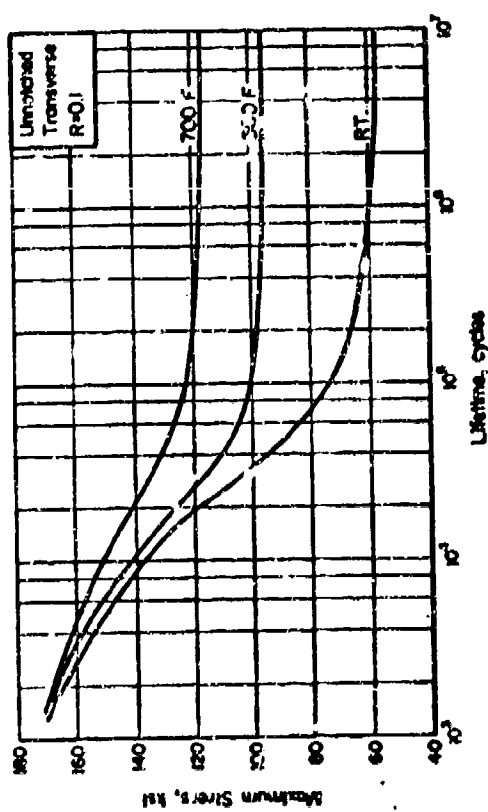


FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED EP 981-A0-0, 20C FORGED BAR

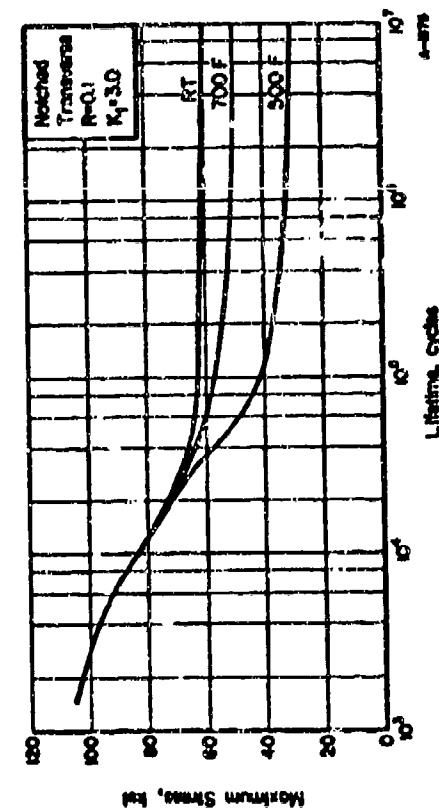


FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED
($K_t = 3.0$) EP 981-A0-0, 20C FORGED BAR

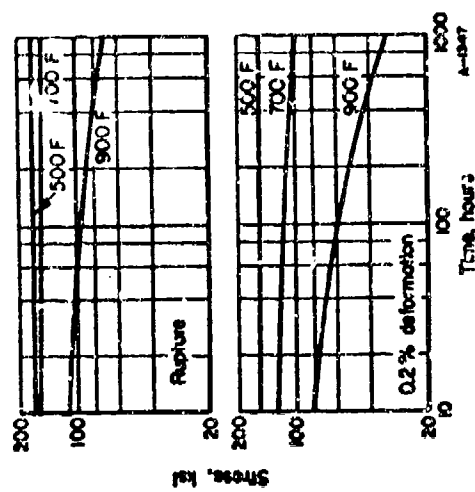


FIGURE 5. STRESS-RUPTURE AND ELASTIC DEFORMATION
CURVES FOR EP 981-A0-0, 20C FORGED BAR
(TRANSVERSE)

PM 13-B No Stainless Steel

Material Description

This alloy is a martensitic precipitation hardenable stainless steel developed by the Ames Steel Corporation. It can be heat treated to high strength levels and exhibits good ductility in the transverse direction. This transverse direction toughness is obtained by composition balance designed to prevent formation of delta ferrite in the structure, low carbon content to minimize grain boundary carbide precipitation, and double vacuum melting to reduce alloy segregation. The alloy reportedly has excellent resistance to stress corrosion cracking in synthetic seawater and excellent resistance to corrosion in a 5 percent salt spray environment.

The material used in this evaluation was obtained as a 4-inch x 5-inch x 5 foot forged bar from Armac Heat 180241. The composition was as follows:

Chemical Composition	Percent
Carbon	0.035
Manganese	0.01
Phosphorus	0.002
Sulfur	0.003
Silicon	0.02
Chromium	12.62
Nickel	8.24
Molybdenum	2.16
Aluminum	1.02
Iron	Balance

Processing and Heat Treatments

Specimens were machined in the as-received Condition A and then heat treated at 1000 F for 4 hours in Condition B 1000.

PM 13-C No Stainless Steel Data (a)

Condition: H1000
Thickness: 4-inch x 6-inch forged bar

Properties	Temperature, F			
	RT	400	500	600
Tension				
TS (longitudinal), ksi	192.7	0	169.0	137.7
TS (transverse), ksi	190.3	0	163.3	137.0
UTS (longitudinal), ksi	187.3	0	164.7	131.3
UTS (transverse), ksi	183.3	0	163.7	118.0
σ (longitudinal), percent in 2 in.	13.3	0	12.5	21.2
σ (transverse), percent in 2 in.	13.8	0	11.5	21.5
RA (longitudinal), percent	51.8	0	56.7	70.5
RA (transverse), percent	54.2	0	51.8	70.5
ϵ (longitudinal), 10 ³ psi	27.7	0	27.1	21.9
ϵ (transverse), 10 ³ psi	20.0	0	25.3	21.4
Compression				
CTS (longitudinal), ksi	187.7	0	158.3	138.3
CTS (transverse), ksi	199.7	0	109.7	121.3
λ (longitudinal), 10 ³ psi	30.0	0	26.2	23.2
λ (transverse), 10 ³ psi	30.0	0	25.7	23.0
Shear				
SUS (longitudinal), ksi	121.3	0	0(a)	0
SUS (transverse), ksi	123.0	0	0	0
Impact (d)				
V-notch Charpy, ft. lb.	34.0	0	0	0
(longitudinal)	27.7	0	0	0
(transverse)				
Fracture Toughness				
K_{IC} (longitudinal), ksi $\sqrt{in.}$	(a)	0	0	0
K_{IC} (transverse), ksi $\sqrt{in.}$	(a)	0	0	0
Axial Fatigue (transverse) (f)				
Smoothed, R = 0.1				
10 ⁶ cycles, ksi	215	200	0	163
10 ⁷ cycles, ksi	187	170	0	153
10 ⁸ cycles, ksi	155	162	0	146
Notched, $R_t = 3.0$, R = 0.1				
10 ⁶ cycles, ksi	183	147	0	141
10 ⁷ cycles, ksi	70	80	0	74
10 ⁸ cycles, ksi	50	70	0	66

PH 13-8 No Stainless Steel Data (continued)

Properties	Temperature, F			
	RT	400	500	900
<u>Crimp (transverse)</u>				
0.2% plastic deformation, 100 hr, ksi	NA	U	150	35
0.2% plastic deformation, 1000 hr, ksi	NA	U	140	25
<u>Stress Rupture (transverse)</u>				
Rupture, 100 hr, ksi	NA	U	161	75
Rupture, 1000 hr, ksi	NA	U	160	60
<u>Stress Corrosion (S)</u>				
20% TWS, 1000 hr minimum	no cracks			
<u>Coefficient of Thermal Expansion</u>				
6.6 ± 10^{-6} in./in./F (80 to 900 F)				
<u>Density</u>				
0.279 lb./in. ³				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 3 specimens.

(c) U, unavailable; NA, not applicable.

(d) Average of 6 tests.

(e) Six longitudinal along-bend specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a span of 6 inches. The average K_{IC} obtained was 19.0 ksi/in. Since the size ratio, $2.5 (W/P)^{1/2}$, was greater than both the specimen thickness and crack length in all tests, this K_{IC} value is not a valid K_{IC} value by existing ASTM criteria.

(f) K_{IC} represents the algebraic ratio of minimum stress to maximum stress in one species; that is, $K_{IC} = \sigma_{min}/\sigma_{max}$. K_{IC} represents the Rubber-Initiation theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

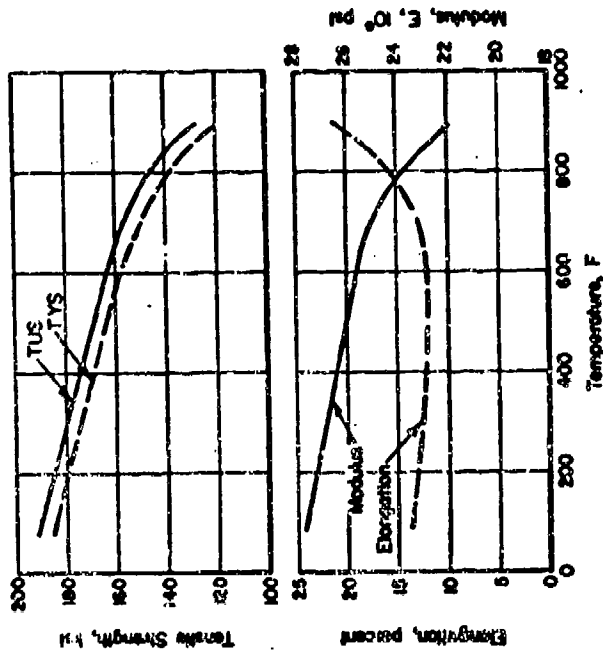


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PH 13-8 No (H1000) FORGED BAR

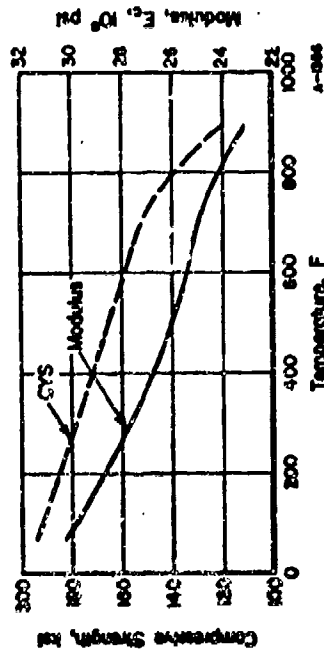


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF PH 13-8 No (H1000) FORGED BAR

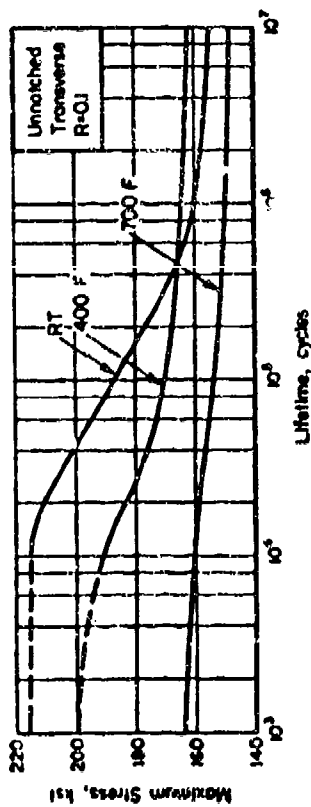


FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED FE 13-8 No (N1000) FORCED MAR

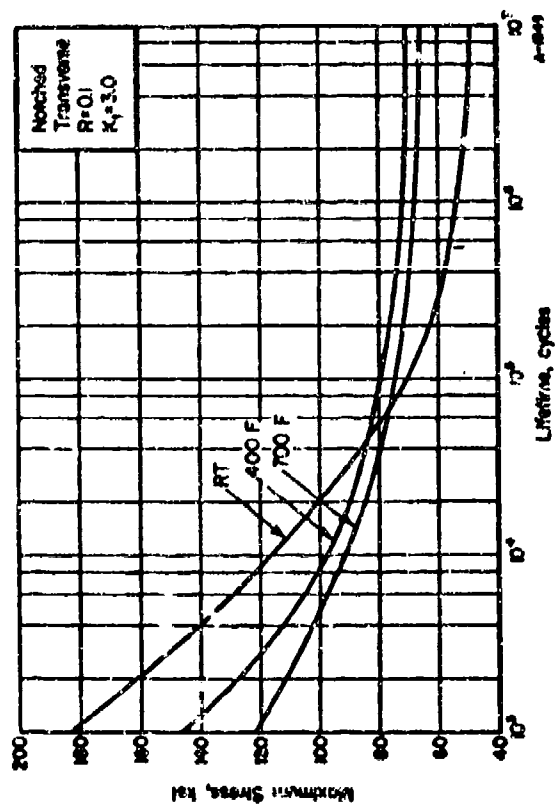


FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) FE 13-8 No (N1000) FORCED MAR

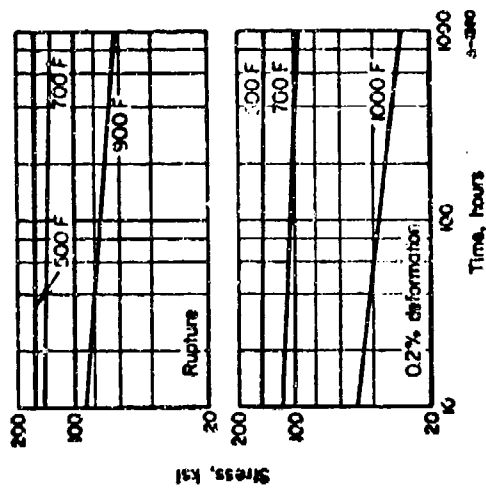


FIGURE 5. STRESS-RUPTURE AND CREEP DEFORMATION CURVES FOR FE 13-8 No (N1000) FORCED MAR (LONGITUDINAL)

7049-T76 Aluminum Extrusions

Material Description

Alloy 7049 was developed by Kaiser Aluminum and Chemical Corporation to have a strength level in the range of 7075-T6 and 7079-T6 coupled with a high resistance to stress corrosion cracking. Initial development and production was in the form of forgings and hand forgings. Further development has been in plates and extrusions.

The material evaluated was a 4-inch x 4-inch extrusion supplied by Kaiser with the following composition:

Chemical Composition	Percent
Zinc	7.6
Magnesium	2.5
Copper	1.5
Chromium	0.15
Silicon	0.25 max
Iron	0.35 max
Titanium	0.10 max
Manganese	0.20 max
Aluminum	Balance

Processing and Heat Treating

Specimens were tested in the as-received -T76 temper.

7049-T76 Aluminum Alloy Data (a) Thickness: 4-inch x 4-inch extrusion

Properties	Temperature, F	
	250	350
Tension		
T _{US} (longitudinal), ksi	83.4	64.4
T _{US} (transverse), ksi	76.2	59.9
T _{US} (short transverse), ksi	75.9	63.2
T _{TS} (longitudinal), ksi	67.4	56.4
T _{TS} (transverse), ksi	67.7	56.4
T _{TS} (short transverse), ksi	12.7	22.2
a (longitudinal), percent in 2 in.	11.2	16.6
a (transverse), percent in 2 in.	11.7	16.6
a (short transverse), percent in 2 in.	35.6	53.1
RA (longitudinal), percent	23.3	34.4
RA (transverse), percent	22.6	34.4
RA (short transverse), percent	10.7	9.3
Z (longitudinal), 10 ⁶ psi	9.9	9.3
Z (transverse), 10 ⁶ psi	10.4	8.6
Z (short transverse), 10 ⁶ psi	10.4	7.3
Compression		
C _{TS} (longitudinal), ksi	78.8	69.8
C _{TS} (transverse), ksi	74.7	63.3
Z _C (longitudinal), 10 ⁶ psi	10.9	9.9
Z _C (transverse), 10 ⁶ psi	10.5	10.2
Shear		
S _{US} (longitudinal), ksi	45.4	37.7
S _{US} (transverse), ksi	42.8	37.7
Impact (d)		
V-notch Charpy, ft. lb. (longitudinal)	5.8	5.8
(transverse)	1.6	1.6
Fracture Toughness		
K _{IC} (longitudinal), ksi √in.	(a)	U
Axial Fatigue (transverse) (f)		
Detached, R = 0.1	70	67
10 ⁶ cycles, ksi	55	51
10 ⁶ cycles, ksi	39	43

7049-T76 Aluminum Alloy Data (continued)

Properties	RT	250	350	500
<u>Axial Fatigue (transverse) (continued)</u>				
Notched, $K_t = 3.0$, $R = 0.1$				
10^5 cycles, ksi	48	45	45	0
10^6 cycles, ksi	19	17	17	0
10^7 cycles, ksi	11	7	7	0
<u>Creep (transverse)</u>				
0.2% plastic deformation, 100 hr, ksi	NA	36	33	2.4
0.2% plastic deformation, 1000 hr, ksi	NA	23	7	1.1
<u>Stress Rupture (transverse)</u>				
Rupture, 100 hr, ksi	NA	44	38	5
Rupture, 1000 hr, ksi	NA	39	32	3.5
<u>Stress Corrosion (S)</u>				
80% TTS, 1000 hr maximum	no cracks			
<u>Coefficient of Thermal Expansion</u>				
12.9 ± 10^{-6} in./in./°F (20 to 212 °F)				
<u>Density</u>				
0.099 lb./in. ³				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract various otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 4 tests.

(c) V. unreliable; NA, not applicable.

(d) Average of 6L and 6T tests.

(e) Six longitudinal slow-bend specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a span of 6 inches. The average K_Q obtained was 54.1 ksi/in. Since the size ratio, $2.5 (K_Q/TTS)^2$, was greater than both the specimen thickness and crack length in all tests, this K_Q value is not a valid K_{Ic} value by existing ASTM criteria.

(f) "n" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $n = S_{min}/S_{max}$. "n" represents the Weber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

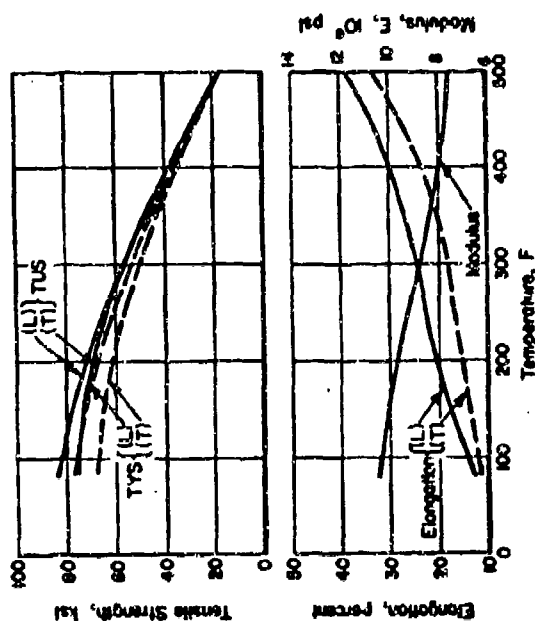


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T76 EXTENSION

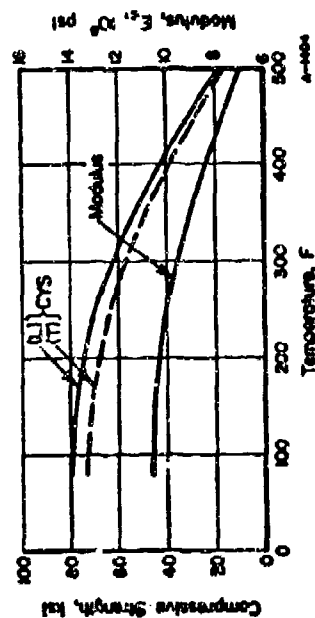


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T76 EXTENSION

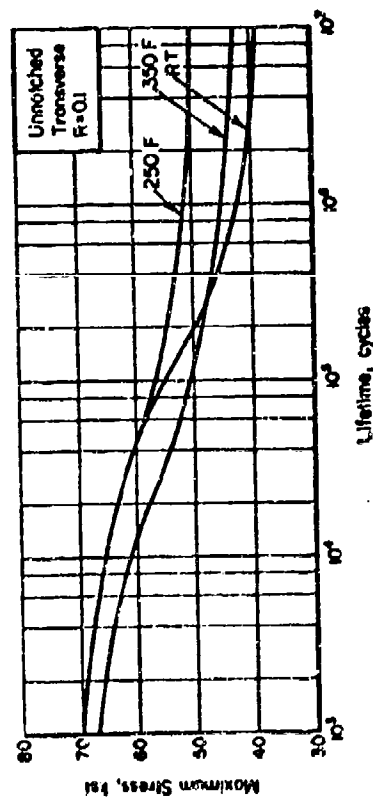


FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 7049-T76 EXTENSIONS

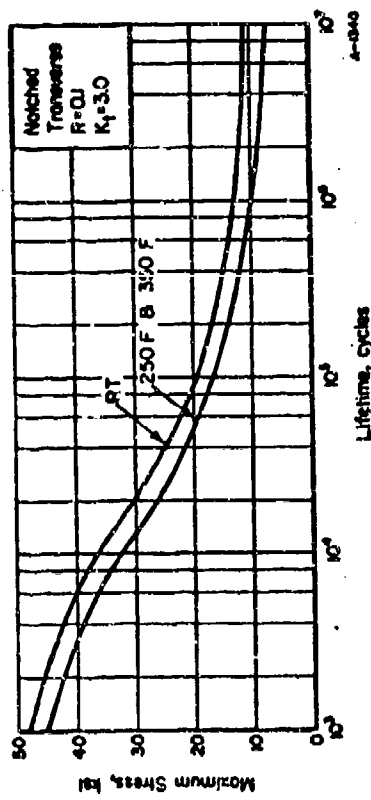


FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) 7049-T76 EXTENSIONS

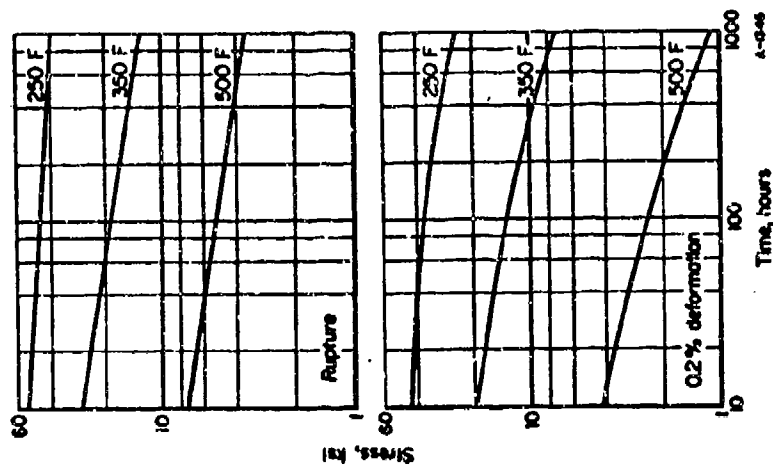


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7049-T76 EXTENSIONS (TRANSVERSE)

TI-6Al-2Sn-4Zr-6Mo Alloy

Material Description

Initially, this alloy was developed by the Titanium Metals Corporation as an off-shoot of the TI-6Al-2Sn-4Zr-2Mo high temperature alloy. Studies had shown that increasing the molybdenum content beyond the 2 percent level resulted in an alloy having improved room and elevated temperature strength with good creep resistance. During early development, investigations were limited to the evaluation of the alloy as a heavy section forging alloy. Promising high temperature properties achieved in heat-treated sections up to 3 inches suggest the alloy might also be useful as a sheet alloy since it should be air hardenable at sheet gages.

The material used in this evaluation was 0.075 inch sheet obtained from INCA. It had the following composition:

Chemical Composition	Percent
Aluminum	5.98
Tin	1.99
Zirconium	3.94
Molybdenum	5.86
Iron	0.057
Oxygen	0.10
Nitrogen	0.004
Titanium	Balance

Processing and Heat Treatment

Spectumens were machined in the as-received condition and heat-treated as follows:

- (1) 1600 F, 75 minutes, air cooled,
- (2) 1315 F, 15 minutes, air cooled,
- (3) 1100 F, 2 hours, air cooled.

TI-6Al-2Sn-4Zr-6Mo Data (a)

Condition: Solution treated and aged
Thickness: 0.080-inch sheet

Properties	Temperature, F	
	RT	700
<u>Tension</u>		
TUS (longitudinal), ksi	168.0	149.3
TUS (transverse), ksi	169.4	150.0
TYS (longitudinal), ksi	160.0	127.3
TYS (transverse), ksi	163.0	130.7
E (longitudinal), percent in 2 in.	12.3	14.8
E (transverse), percent in 2 in.	11.6	14.2
Z (longitudinal), 10 ⁶ psi	17.5	16.3
Z (transverse), 10 ⁶ psi	17.2	15.6
<u>Compression</u>		
CYS (longitudinal), ksi	167.3	133.3
CYS (transverse), ksi	170.6	138.0
E _c (longitudinal), 10 ⁶ psi	19.6	17.9
E _c (transverse), 10 ⁶ psi	18.9	17.6
<u>Shear (b)</u>		
SUS (longitudinal), ksi	96.8	U (c)
SUS (transverse), ksi	98.1	U
<u>Fracture Toughness (d)</u>		
K _{IC} (crack direction LT), ksi √in.	132	U
<u>Axial Fatigue (transverse) (e)</u>		
Unnotched, R = 0.1		
10 ⁶ cycles, ksi	160	140
10 ⁷ cycles, ksi	108	106
10 ⁸ cycles, ksi	100	100
Notched, K _t = 3.0, R = 0.1		
10 ⁶ cycles, ksi	78	85
10 ⁷ cycles, ksi	35	35
10 ⁸ cycles, ksi	30	25

Properties	Temperature			
	RT	700	920 1100	
<u>Creep (transverse)</u>				
0.2% plastic deformation, 100 hr, ksi	MA	113	29	1.9
0.2% plastic deformation, 1000 hr, ksi	MA	90	14	1.2
<u>Stress Rupture (transverse)</u>				
Rupture, 100 hr, ksi	MA	142	101	19
Rupture, 1000 hr, ksi	MA	140	90	7.5
<u>Stress Corrosion (d)</u>				
80% TYS, 1000 hr maximum	no cracks			
<u>Coefficient of Thermal Expansion</u>				
5.5×10^{-6} in./in./°F (80 to 1000 °F)				

Density

0.165 lb./in.³

- Values given are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Values for fatigue, creep, and stress-rupture are from curves generated using a greater number of tests.
- Single-shear sheet-type specimen; average of 3 tests.
- U, unavailable; MA, not applicable.
- Specimens were full sheet thickness, 18 inches x 36 inches with ETW filar in center.
- "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K" represents the Neuber-Peterson theoretical stress concentration factor.
- Room-temperature three-point bend test. Alternate dimension is 3-1/2" x 1/2" x 1/2".

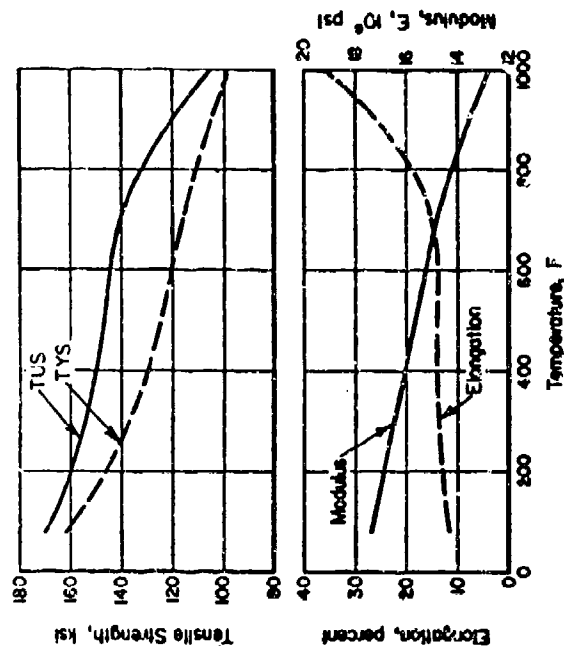


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-6Nb SHEET

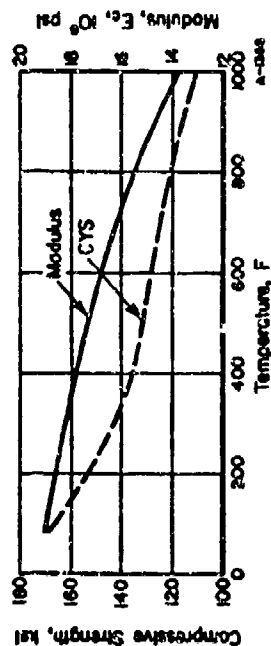


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-2Sn-4Zr-6Nb SHEET

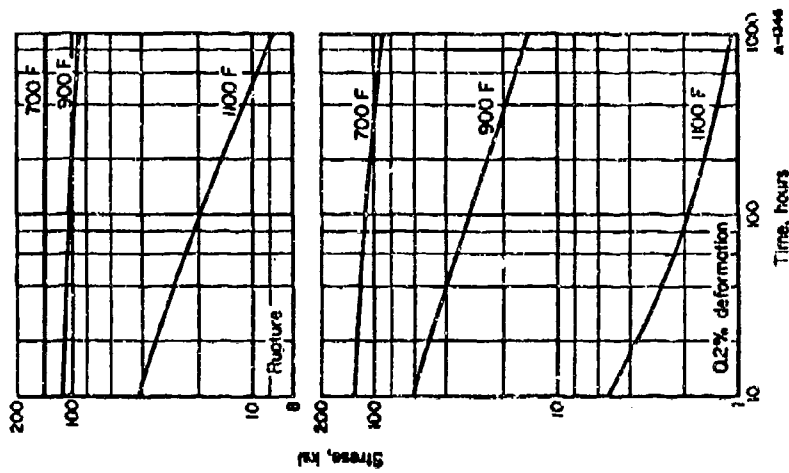


FIGURE 3. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR T1-6Al-25In-4Zr-0.6Mo SHEET (TRANSVERSE)

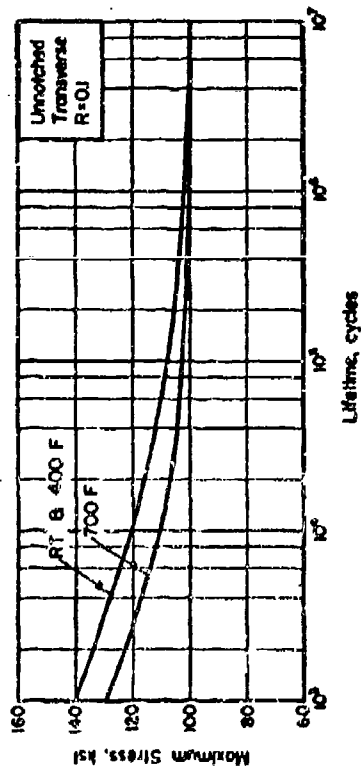


FIGURE 2. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED T1-6Al-25In-4Zr-0.6Mo SHEET

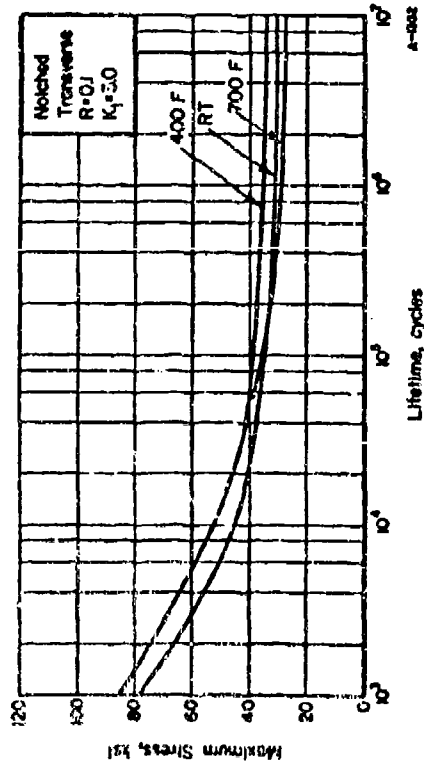


FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) T1-6Al-25In-4Zr-0.6Mo SHEET

Inconel 702 Alloy

Physical Properties

Inconel 702 alloy is a nickel-chromium alloy with excellent resistance to oxidation and corrosion up to 2000 F. It is formed readily in a wide variety of shapes and sizes. The alloy is formed by casting and is then processed by hot rolling, cold rolling, and annealing. The alloy has good mechanical strength and is used in a wide variety of applications.

The composition of Inconel 702 alloy is as follows:

Chemical Element	Percent
Carbon	0.01
Phosphorus	0.01
Sulfur	0.007
Iron	0.11
Chromium	0.01
Aluminum	0.01
Nickel	70.50

Mechanical Properties

The mechanical properties of Inconel 702 alloy are as follows:

Inconel 702 Alloy Data (a)
Condition: Annealed
Thickness: 0.050-inch sheet

Property	Temperature, F	
	75	1000
Tensile		
UTS (longitudinal), ksi	152.7	139.0
UTS (transverse), ksi	151.0	128.3
UTS (longitudinal), ksi	94.8	85.3
UTS (transverse), ksi	94.8	85.3
E (longitudinal), percent in 2 in.	34.2	35.8
E (transverse), percent in 2 in.	34.2	35.8
E (longitudinal), 10 ⁶ psi	34.2	29.6
E (transverse), 10 ⁶ psi	33.7	30.9
Compression		
CRS (longitudinal), ksi	99.4	91.0
CRS (transverse), ksi	101.0	93.6
E _c (longitudinal), 10 ⁶ psi	34.6	35.0
E _c (transverse), 10 ⁶ psi	34.7	33.3
Shear		
SSS (longitudinal), ksi	116.2	90
SSS (transverse), ksi	115.7	90
Fracture Toughness		
K _{IC} , ksi√in.	(4)	0
Axial Fatigue (transverse) (c)		
Unstretched, R = 0.1		
10 ⁶ cycles, ksi	90	77
10 ⁷ cycles, ksi	72	70
10 ⁸ cycles, ksi	31	41
Stretched, R = 3.0, R = 6.1		
10 ⁶ cycles, ksi	72	74
10 ⁷ cycles, ksi	53	51
10 ⁸ cycles, ksi	29	37

second 722 alloy Data (continued)

Temperature	Temperature, F	
	72	1100

Group (Temperature)			
0.1% plastic deformation, 122 hr, 101	115	60	15
0.1% plastic deformation, 122 hr, 101	95	40	4.5

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

Stress (Temperature)			
Stress 1000 lb, 101	122	75	22
Stress 1000 lb, 101	120	55	11

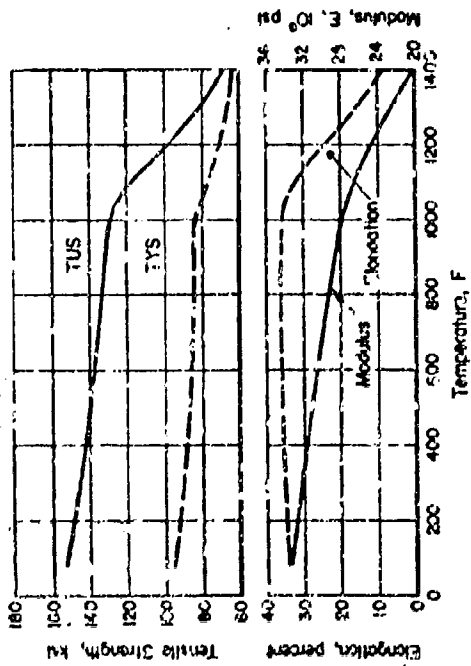


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 702 SHEET (AGED)

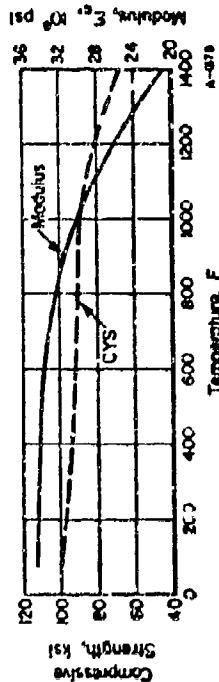


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 702 SHEET (AGED)

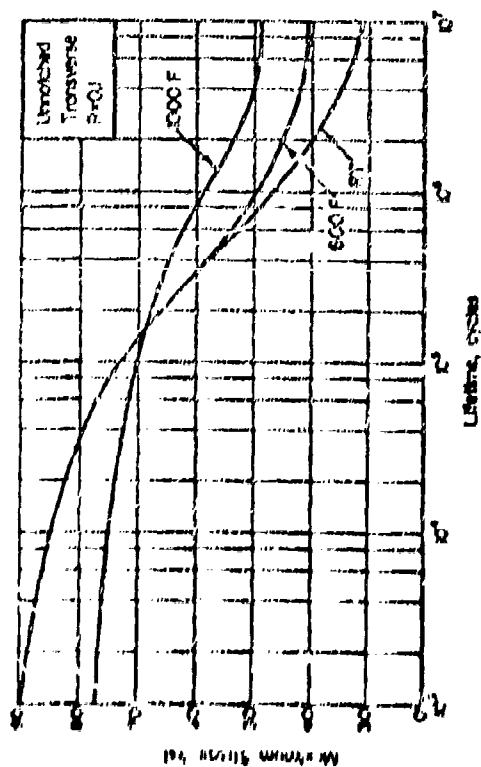


FIGURE 3. MAX. LOAD FACTURE RESULTS FOR ETCHED INCONEL 702 SHEET (AGED)

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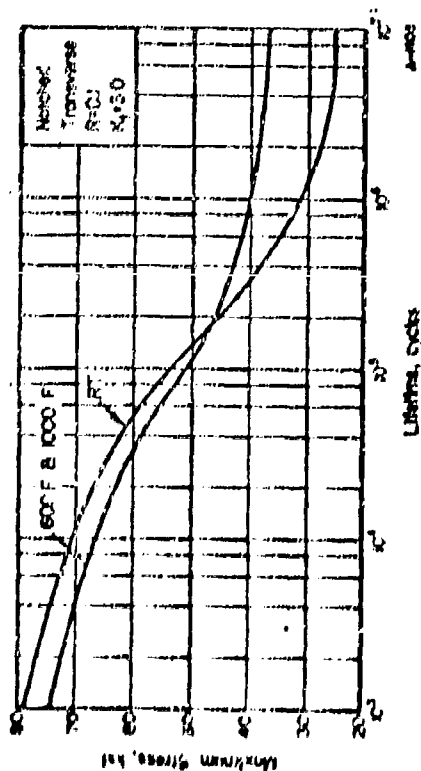


FIGURE 4. MAX. LOAD FACTURE RESULTS FOR ETCHED ($K_t = 3.0$) INCONEL 702 SHEET (AGED)

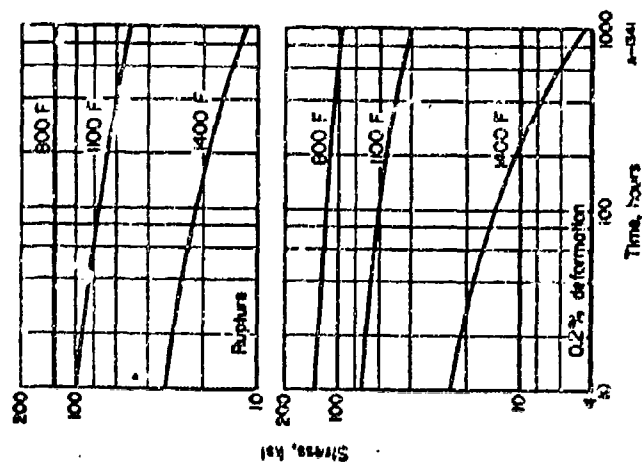


FIGURE 5. STRESS-rupture AND ELASTIC DEFORMATION CURVES F/M INCONEL 702 SHEET (AGED) (TRANSVERSE)

Inconel 706 Alloy

Material Description

Inconel alloy 706 is a precipitation-hardenable, nickel-iron-chromium alloy with characteristics similar to those of Inconel 713, except that 706 has improved machinability. It has high strength at temperatures ranging from cryogenic to 1300 F. It also has good resistance to oxidation and corrosion over a broad range of temperatures and environments.

Fabrication of the alloy is enhanced by its good formability and weldability. Alloy 706 has excellent resistance to postweld strain-ageing.

The material used in this evaluation was obtained as a 6-inch-square forging from INCOMET HX300R. The composition was as follows:

Chemical Conc. in pct	Percent
Carbon	0.03
Manganese	0.12
Iron	34.37
Sulfur	0.007
Silicon	0.13
Copper	0.02
Chromium	16.32
Aluminum	0.28
Titanium	1.62
Columbium plus tantalum	2.96
Nickel	43.12

Processing and Heat Treating

The 6-inch-square material was press forged to a 2 inch x 6 inch forging to make specimen blank easier to obtain. After machining, specimens were heat treated as follows:

- (1) 1800 F, 2 hours, air cool,
- (2) 1550 F, 3 hours, air cool,
- (3) 1325 F, 2 hours, furnace cool to 1150 F, hold for 18 hours, air cool.

Inconel 706 Alloy Data (a)

Condition: Solution treated and aged for optimum stress rupture strength
Thickness: 2-inch x 6-inch forged bar

Properties	Temperature, F		
	RT	600	1000 1200
Tension			
TTS (longitudinal), ksi	177.7	U	156.3 151.7 138.3
TTS (transverse), ksi	176.0	U	157.7 153.0 139.0
TTS (longitudinal), ksi	178.7	U	120.7 119.7 116.0
TTS (transverse), ksi	180.0	U	122.0 121.0 117.0
a (longitudinal), percent in 2 in.	22.2	U	21.7 21.3 23.5
a (transverse), percent in 2 in.	22.0	U	20.2 19.0 23.8
RA (longitudinal), percent	32.8	U	37.5 39.5 40.5
RA (transverse), percent	31.0	U	34.8 34.7 37.8
E (longitudinal), 10 ⁶ psi	29.2	U	29.2 21.2 21.0
E (transverse), 10 ⁶ psi	30.0	U	24.7 21.5 20.6
Compression			
CYS (longitudinal), ksi	149.7	U	126.7 123.3 120.0
CYS (transverse), ksi	149.0	U	129.3 124.7 121.3
E (longitudinal), 10 ⁶ psi	31.1	U	24.3 23.0 22.5
E _c (transverse), 10 ⁶ psi	31.6	U	24.2 24.0 22.2
Shear (b)			
SSS (longitudinal), ksi	117.2	U	U ^(c) U U
SSS (transverse), ksi	117.0	U	U U U
Impact (d)			
V-notch Charpy, ft. lb. (longitudinal) (transverse)	31.8 26.4	U U	U U U
Fracture Toughness			
K _{IC} (longitudinal), ksi/√in.	(e)	U	U U U
K _{IC} (transverse), ksi/√in.	(e)	U	U U U
Axial Fatigue (transverse) (f)			
Directioned, R = 0.1 10 ⁶ cycles, ksi	116	144	U 132 U
10 ⁶ cycles, ksi	121	96	U 90 U
10 ⁷ cycles, ksi	60	60	U 53 U
Directioned, R = 0.1 10 ⁶ cycles, ksi	120	109	U 94 U
10 ⁶ cycles, ksi	52	52	U 49 U
10 ⁷ cycles, ksi	26	30	U 34 U

Inconel 706 Alloy Data (continued)

Property	Temperature, F			
	RT	700	850	1000

Creep (transverse)

0.2% plastic deformation, 100 hr test	MA	U	153	179	85
0.2% plastic deformation, 1000 hr test	MA	U	152	177	76

Stress Rupture (transverse)

Stress, 100 hr test	MA	U	134	145	109
Stress, 1000 hr test	MA	U	133	150	90

Stress Corrosion (a)

RT test, 1000 hr minimum: no cracks

Coefficient of Thermal Expansion

9.8×10^{-6} in./in./F (70 to 1300 F)

Density

0.29 lb./in.³

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; range of 4 tests.

(c) T, unavailable; MA, not applicable.

(d) Average of 4 tests.

(e) Three longitudinal and three transverse slow-bend specimens were tested. Specimen size was 0.750-inch thick by 1.500-inch wide with a span of 6 inches. The average yield strength was 77.1 ksi (538 MPa) in the longitudinal direction and 77.9 ksi (539 MPa) in the transverse direction. Since the elongation ratio $(L_0/L_{0.2})$ was greater than both the specimen thickness and crack length in all tests, these K_{IC} values are per valid K_{IC} values by existing ASTM criteria.

(f) η_T represents the average ratio of minimum stress to maximum stress in one cycle; that is, $\eta_T = \frac{\sigma_{min}}{\sigma_{max}}$. η_{TC} represents the Wohler-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate temperature is 2-1/2% NaCl.

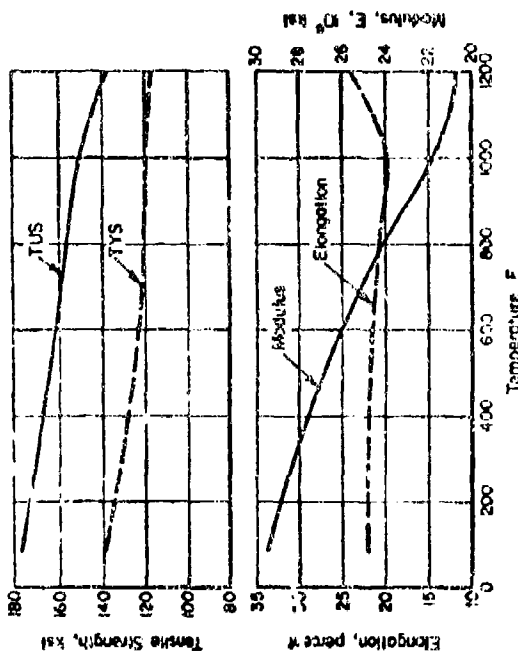


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

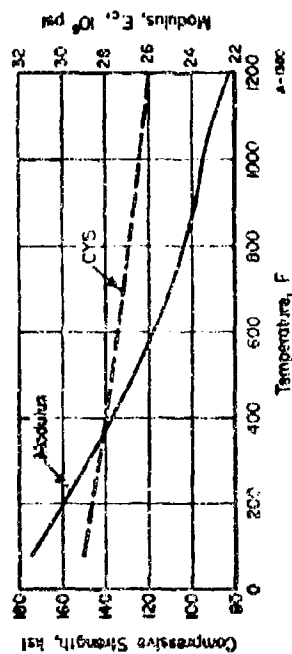


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

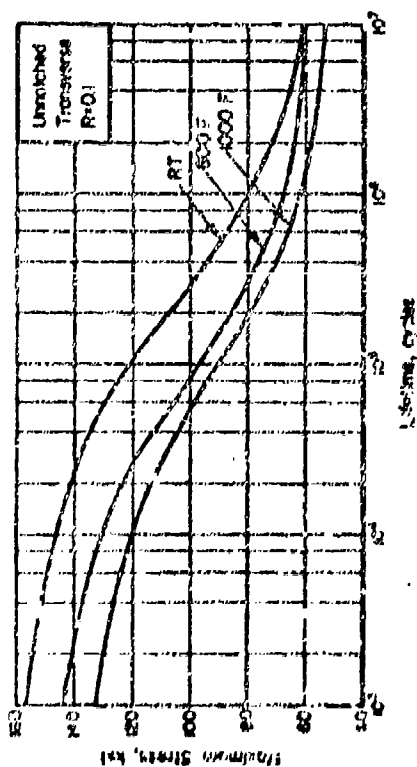


FIGURE 3. MAXIMUM STRESS RESULTS FOR NOTCHED TRANSVERSE FORCED BAR (STRESS-RUPTURE TEST TREATMENT)

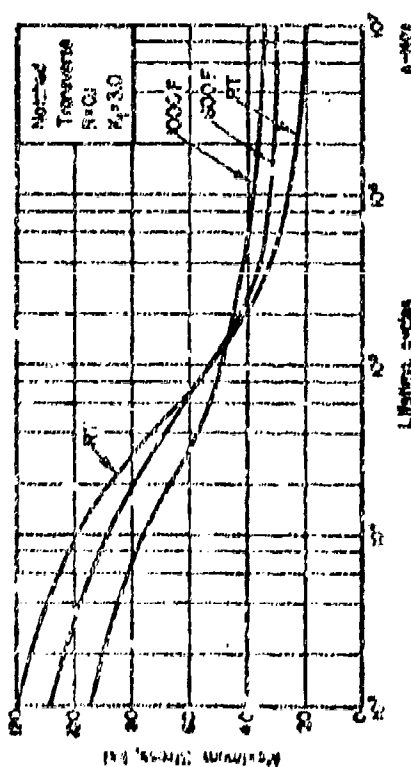


FIGURE 4. MAXIMUM STRESS RESULTS FOR NOTCHED TRANSVERSE FORCED BAR (STRESS-RUPTURE TEST TREATMENT)

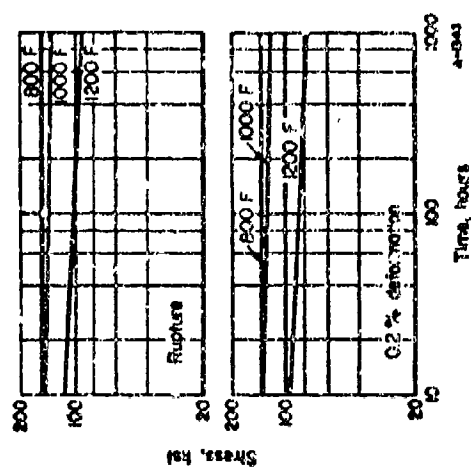


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR NOTCHED TRANSVERSE FORCED BAR (STRESS-RUPTURE TEST TREATMENT) (TRANSVERSE)