FATIGUE RESISTANCE OF ALLOY 625 SHEET

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Abstract

Alloy 625 has been used often in applications which take advantage of its fatigue resistance. The factors which influence fatigue resistance of alloy 625 sheet material at room temperature including composition, cold-work, and grain size have been examined. In particular, the properties of the UNS N06626 alloy (restricted composition for bellows applications per AMS 5879) will be compared to UNS N06625 (AMS 5599) and to material produced according to US Patent 4,765,956[1]. Data show that UNS N06626 alloy sheet exhibits similar performance to that of UNS N06625 alloy sheet. Either of these materials can be at least as fatigue resistant as material produced with the patent teachings.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

The precipitation hardening of nickel base superalloys with gamma-prime phases has produced alloys having outstanding strength and creep resistance. Unfortunately, these gamma-prime precipitates have been less successful in raising the resistance of the superalloys to fatigue crack initiation or propagation. Solid solution strengthening has proven to be more successful in providing improved fatigue resistance in nickel-base alloys. The solid solution alloy 625 is especially notable in this respect since it also exhibits good corrosion resistance, good elevated temperature strength, good weldability, excellent formability, and strength.

This combination of properties makes alloy 625 a natural choice for the manufacture of metal bellows. Recent changes in air pollution regulations are driving automobile manufacturers away from the old ball and socket connector flanges and toward flex connectors for joining automobile exhaust system components. These flex connectors are built around a flexible metal bellows. This bellows absorbs the displacements caused by differential thermal expansions as well as the mechanical loads imposed by road shocks. At the same time, this metal bellows must resist oxidation and corrosion by the hot exhaust gasses flowing through it. In many instances, it must also resist external corrosion induced by environmental factors, such as road salt deposition.

In recent years, design using fatigue "S/N" curves has been largely superseded by "damage tolerant" design using an assumed pre-existing flaw and fatigue crack growth data, but such an approach is not always valid. In particular, parts made from very thin materials, such as flex connector bellows which may be made from sheet as thin as 0.1 mm thick, would be completely penetrated by the commonly-assumed flaw sizes. Therefore, this study focuses on conventional fatigue testing.

This study is an examination of the factors which control the fatigue strength of alloy 625. Bending tests were used both for experimental convenience and because bending is the loading mode experienced by the parts of greatest interest.

Materials and Procedure

The materials used in this study all were commercially-produced alloy 625 sheet. The materials studied included hard cold rolled ALTEMP® 625 alloy sheet and mill annealed sheet from the same coil. This annealed material meets the requirements of AMS 5599. Laboratory annealed sheet which received special processing to provide a softer product and which does not fully satisfy the requirements of AMS 5599 was also studied. This will be referred to as "soft forming temper" material. Annealed INCO* 625LCF* and annealed AL 625HP™ sheets were also tested. Both satisfy the composition requirements of the AMS 5879 specification, but only the 625LCF material is produced in accordance with US Patent 4,765,956, and only it satisfies the minimum yield strength requirement of the specification. Although often produced to meet the AMS requirements, this particular lot of AL 625HP material received special processing to provide a softer product with maximum ductility. In order to facilitate both testing and comparisons between materials, material of about 0.9 mm thick was chosen for

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testing. Further details of the properties of these materials are listed in Table I. Compositions of these are shown in Table II.

Table I - Materials Property Summary

Material	ALTEMP® 625 (cold worked)	ALTEMP® 625 (annealed)	Soft Forming Temper (annealed)	INCO* 625LCF* (annealed)	AL 625HP™ (annealed)	Specification Requirements	Specification Requirements
Specification	---	AMS 5599	---	AMS 5879	AMS 5879	AMS 5599	AMS 5879
Heat	054157	054157	054170	VX2047AK	054600	---	---
Thickness	0.91 mm	0.91 mm	1.14 mm	0.81 mm	0.89 mm	---	---
Anneal	---	mill	2150°F / 5 min.	mill	mill	---	---
Grain Size #	---	9.0	4.0	8.0	7.5	8.0‡	6.0‡
Hardness	44.5 Rc	97.5 Rb	97.5 Rb	96.2 Rb	89.2 Rb		
YS (MPa)	1400	538	531	494	370§	414†	414†
UTS (MPa)	1576	974	980	940	860	827†	827†
Elong. (%)	4.0	45.0	43.0	46.9	52.8	30.0†	40.0†

Table II - Heat Analyses

Heat\ Element	054157	054170	054600	VX2047AK (INCO analysis)	VX2047AK (A-L analysis)	AMS 5599 (Rev. E) (max. or range)	AMS 5879 (Rev. B) (max. or range)
Mn	0.02	0.02	0.01	0.05	0.068	0.50	0.50
P	0.012	0.009	0.008	0.006	0.007	0.015	0.015
Si	0.20	0.22	0.13	0.06	0.076	0.50	0.15
Cr	20.60	20.30	20.59	21.84	21.70	20.00-23.00	20.00-23.00
Ni	61.04	62.15	61.27	60.59	60.10	remainder	remainder
Al	0.20	0.20	0.21	0.25	0.24	0.40	0.40
Mo	8.95	8.37	8.94	9.01	8.74	8.00-10.00	8.00-10.00
Cb+Ta	3.36	3.33	3.38	3.47	3.46	3.15-4.15	3.15-4.15
Ti	0.17	0.15	0.16	0.06	0.018	0.40	0.40
Co	0.01	0.01	0.01	0.26	0.19	1.00	1.00
C	0.027	0.025	0.025	0.01	0.012	0.10	0.03
S	0.0010	0.0012	0.0035	<.001	0.0003	0.015	0.015
N2	0.0077	0.0068	0.0150	0.02	0.015	---	0.02
Fe	4.82	4.87	4.81	4.37	4.14	5.00	5.00
C+N+ Si/10	0.0547	0.0538	0.0530	0.036	0.0346	---	---

‡ Maximum

§ Does not satisfy AMS 5879 minimum requirement.

† Minimum.

Fatigue testing was performed at room temperature in flexural loading mode using Sonntag Model SF-2U test equipment. This equipment uses cantilever loading of tapered specimens. This produces a constant alternating stress over the gauge sections of the test specimens. A photograph of the test specimen is shown in Figure 1. Specimens were prepared and tested using the mill-supplied surface, or for laboratory processed materials either the as-rolled or annealed and pickled surfaces. Specimens exhibiting scratches or other obvious defects were discarded before testing. Tests were conducted with zero mean load at a frequency of 30 Hertz.

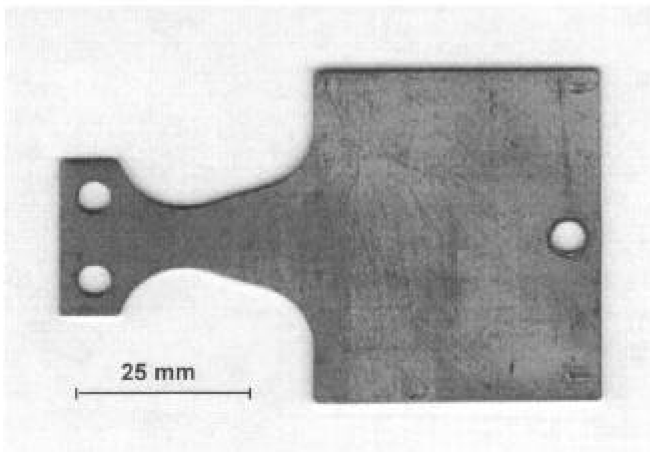

Figure 1. Photograph of fatigue test specimen.

Results

The results of the bending fatigue tests are summarized in the following graphs: (arrows denote "runouts")

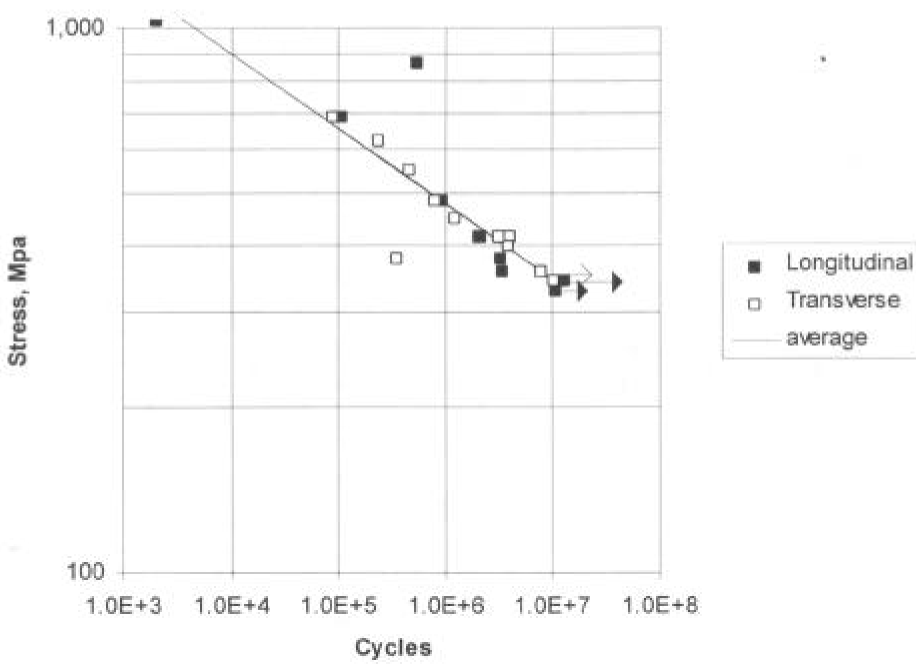

Figure 2. Bending fatigue results for annealed ALTEMP® 625 sheet material.

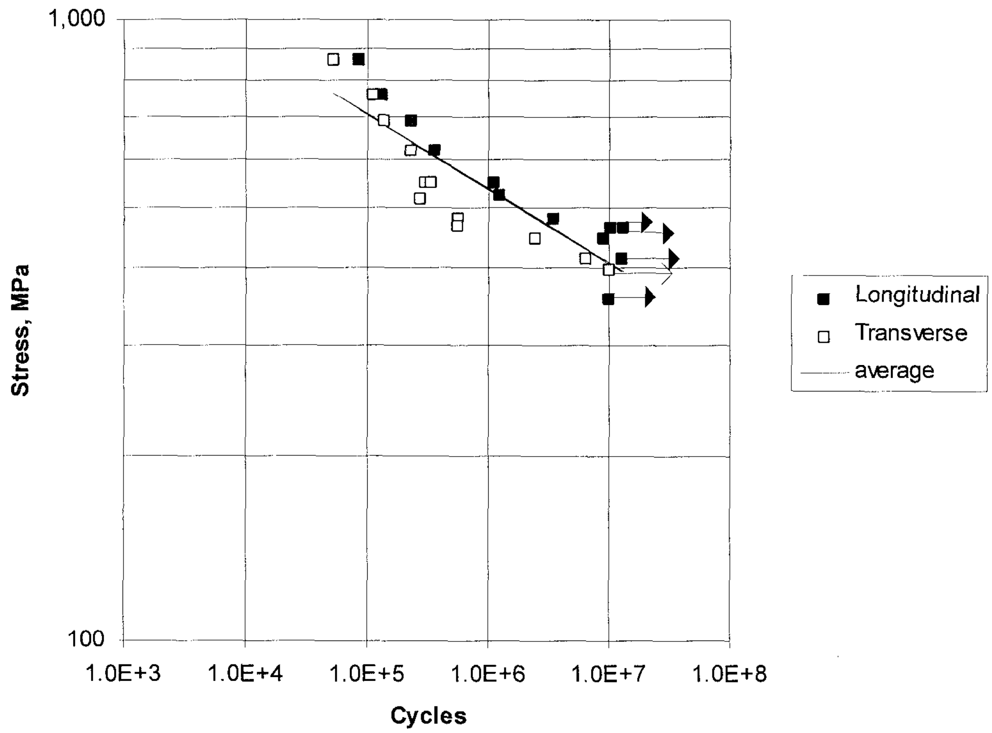

Figure 3. Bending fatigue results for hard cold rolled ALTEMP® 625 sheet material.

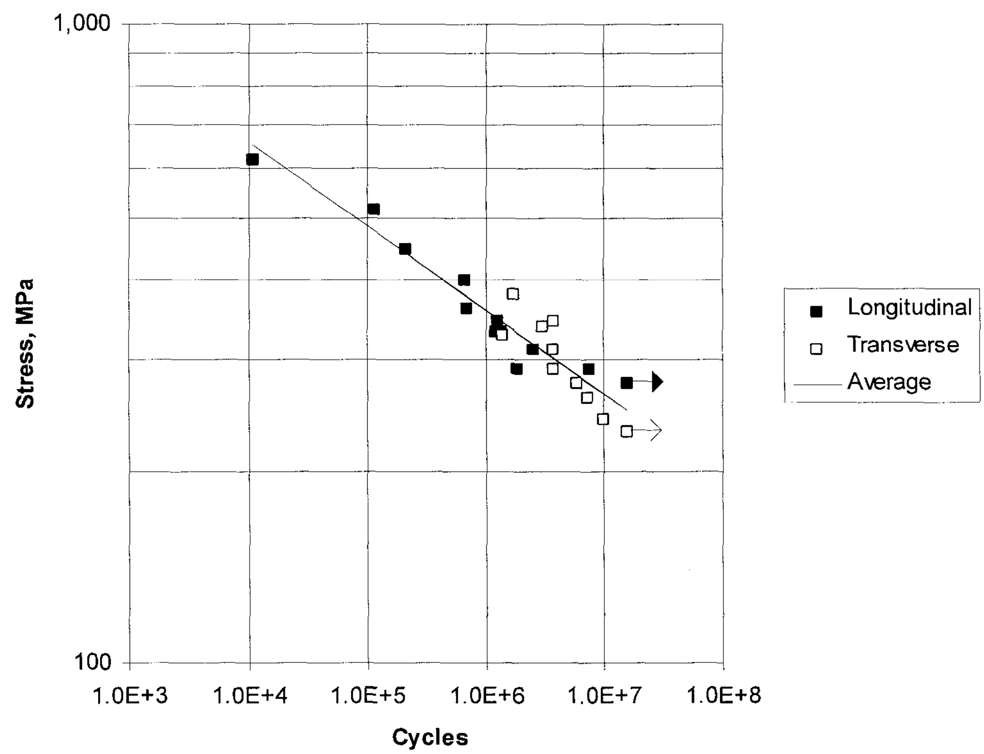

Figure 4. Bending fatigue results for "Soft forming temper" alloy 625 sheet material.

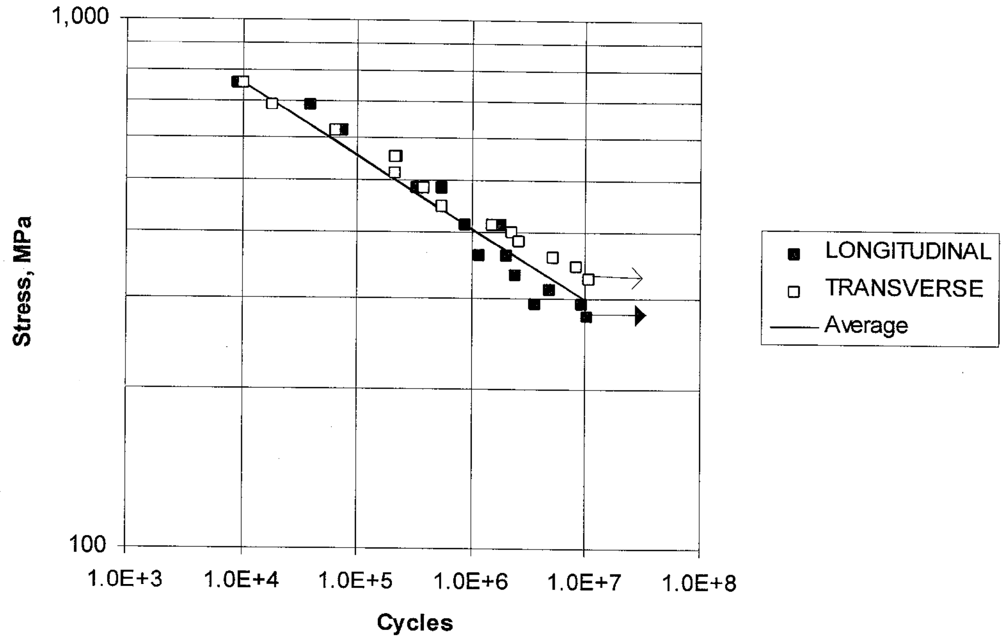

Figure 5. Bending fatigue results for annealed AL 625HP™ sheet material.

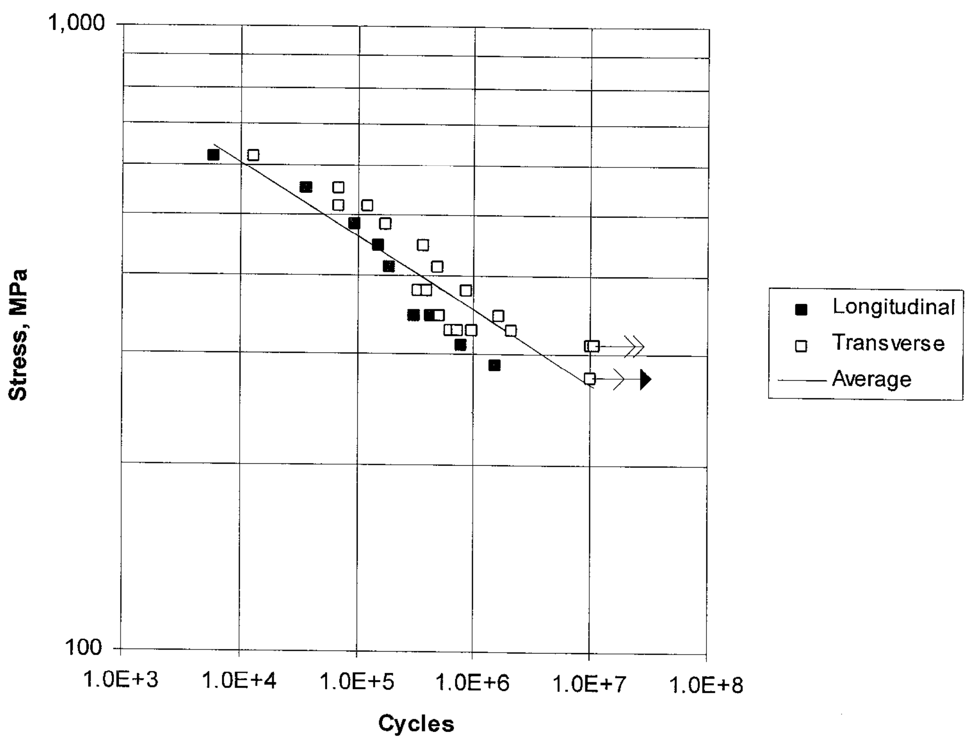

Figure 6. Bending fatigue results for annealed INCO* 625LCF* sheet material.

Regression analyses have shown that differences in fatigue resistance between the longitudinal (rolling direction) and transverse directions are not significant. These same regression analyses [using a linear log (stress) vs. Log (cycles) model] have yielded the following endurance limits (average stress for 10^7 cycle life):

ALTEMP 625 (HCR)	Endurance Limit = 408 MPa
ALTEMP 625 (Annealed)	Endurance Limit = 347 MPa
AL625HP	Endurance Limit = 298 MPa
INCO 625LCF	Endurance Limit = 269 MPa
Soft Forming Temper	Endurance Limit = 264 Mpa

These results demonstrate that the work hardening induced by cold rolling raises the endurance limit for the alloy 625 material tested, although by less than the increase in tensile strength and by far less than the increase in yield strength.

Discussion

Wright[2] has shown that a wide variety of austenitic stainless steels exhibit a common ratio of endurance limit (EL) to tensile strength (UTS) of approximately 0.36. These endurance limit ratios (EL/UTS) for the alloys of this study are:

ALTEMP 625 (Annealed)	EL/UTS =	0.357
Soft Forming Temper	EL/UTS =	0.350
AL 625HP	EL/UTS =	0.346
INCO 625LCF	EL/UTS =	0.286
ALTEMP 625 (HCR)	EL/UTS =	0.259

The annealed A-L products all approximate Wright's ratio. The lower ratio for the hard cold rolled product is also consistent with Wright's observations on stainless steel. He attributed such an endurance ratio reduction to surface damage caused by cold rolling and showed that electropolished samples of cold rolled stainless steel materials exhibited the 0.36 ratio. Since none of the samples in this study received any special surface finishing treatment, that explanation might be valid in this case also.

Grain size has a profound effect upon the endurance limit strength of nickel-base alloys. This has been demonstrated in alloy 625[6] as well as in other nickel alloys[7,8]. While coarse grains have been shown to slow fatigue crack propagation, they seem to promote fatigue crack initiation in smooth specimens[3]. Miller interprets this as indicating that fatigue cracks are easily nucleated but are blocked by grain boundaries and therefore usually do not grow large enough to propagate. An alternative explanation could be made based upon the Hall-Petch dislocation pileup model. In the first case the fatigue endurance limit should vary with $1/d^{1/2}$ where d is the grain diameter, and in the second case, the fatigue endurance limit should vary with $1/d^2$. In principle, it should be possible by careful experiments to differentiate between these two explanations, but in practice such experiments are not likely to yield unambiguous results. In either case however, grain size may explain the low fatigue resistance exhibited by the "soft forming temper" material, since it had the coarsest grain size, ASTM #4 versus ASTM #7.5-9 for the other materials tested.

The type, size, and density of inclusions are critically dependent upon the melting process used. It may be notable that all of the materials used in this study were vacuum melted. This typically produces material having lower nitrogen and oxygen contents. This limits the contents of nitrides (mainly TiN) and oxides (titania, alumina, or silicates), and may result in improved fatigue crack initiation resistance. Reductions in carbon contents may similarly reduce the number and size of carbides (TiC or NbC).

It is also notable that this study focuses on high cycle rather than low cycle fatigue. This is because in considering the service life expected for the flex connector bellows (10 years or 100,000 miles), it is obvious that the connector experiences many cycles of varying intensity. These include the trip thermal cycle (start-up, drive, park; ~5,000), road bumps (~500,000), and engine exhaust valve operation (~1,000,000,000) cycles.

U. S. Patent Number 4,765,956[1] places a number of restrictions upon the composition of what would otherwise be ordinary alloy 625 material. Most noteworthy of these are that carbon and nitrogen both be less than or equal to 0.03 weight percent, silicon should be below 0.35 weight percent, and the inequality $C+N+(Si/10) < 0.035$ (weight percent) must be satisfied. The INCO 625LCF product tested just satisfies this last requirement, while none of the other materials tested come close to meeting the inequality formula. Essential equivalence of fatigue properties was achieved without satisfying this requirement.

Another factor which influences fatigue resistance is loading mode. Rotating beam bending fatigue tests typically show higher stresses for similar cycles to fail than are seen in the same material tested in axial fatigue[4]. Alternating (flexural) bending, as employed in this study, exhibits fatigue strengths (including endurance limit) higher than axial fatigue loading, but below rotating beam results[5]. While the conclusions cited above were based upon work on carbon steels, previous tests of alloy 625[6] have shown the same effect.

Future Work/Open Issues

This work examined only room temperature fatigue. Although the results of elevated temperature tests would be expected to produce similar rankings for these materials, that remains to be proven. The effects of oxidation and hot corrosion could produce further reduction of fatigue resistance beyond that produced by elevated temperature alone. Much more involved testing would be required to examine such effects. The effects of welding upon fatigue resistance were not examined either.

Conclusions

1. Alloy 625 material produced to the requirements of AMS 5599 may exhibit high cycle fatigue resistance at least as good as exhibited by material produced to the AMS 5879 specification.
2. Alloy 625 material produced to the composition requirements of AMS 5879, but outside the composition limits of US Patent 4,765,956 may exhibit high cycle fatigue resistance at least as good as exhibited by material produced within the composition range described in the patent.
3. The high cycle fatigue endurance limit of AMS 5599 alloy 625 material is not reduced by prior cold deformation.
4. Grain size is an important variable influencing fatigue resistance of alloy 625.

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