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## LOW CYCLE FATIGUE CHARACTERISTICS OF A LOW-THERMAL EXPANSION, HIGH STRENGTH ALLOY (HAYNES 242 ALLOY)

**L. M. Pike and S. K. Srivastava**
Research and Technology
Haynes International, Inc.
1020 West Park Ave.
Kokomo, IN 46904-9013
Email: lpike@haynesintl.com,
ksrivastava@haynesintl.com

## ABSTRACT

HAYNES® 242® alloy, based primarily on the Ni-25Mo-8Cr system, derives its low thermal expansion characteristics from its composition and its high strength concomitant with high ductility from a long-range ordering reaction upon an aging heat treatment. This combination has enabled the alloy continually to find a challenging range of applications in the aerospace industry at up to 1300°F (704°C). These include seal rings, containment rings, duct segments, casings, rocket nozzles, etc. In conjunction with the creep strength and environmental resistance, the low cycle fatigue (LCF) behavior is an important material property affecting the service life of 242 alloy components. The low cycle fatigue behavior of 242 alloy was studied under fully reversed strain-controlled mode at 800°F (427°C), 1000°F (538°C), 1200°F (649°C) and 1400°F (760°C) using a triangular wave form with a frequency of 0.33 Hz. Results are presented in terms of cycles to crack initiation and failure. The magnitudes of fatigue lives at total strain range ≤ 0.7% at 800, 1000 and 1200°F are significantly greater than those of solid solution strengthened alloys. Additionally, stress-controlled LCF tests were performed at 1200°F (649°C) on 242 alloy as well as 909 alloy (for comparison). The paper will discuss the results of these two test programs.



## INTRODUCTION

Introduced in 1989 [1], HAYNES 242 alloy is used in aircraft gas turbines for high temperature sealing and containment rings and high strength fasteners. During the last 20 years, the alloy has been specified and retrofitted into several gas turbine engines. Based on such prolonged service experience, the alloy was very recently specified for use in an advanced flying gas turbine. In land based gas turbines, the alloy finds use in turbine nozzle cases. The 242 alloy is used in fluoroelastomer processing equipment and semiconductor processing equipment due to its resistance to corrosion. The alloy's cryogenic properties enabled the use of 242 alloy as conduit for superconducting cables in magnet systems.

HAYNES 242 alloy was the first commercial alloy designed to be intentionally strengthened by long range ordered (LRO) domains of $Ni_2(Mo,Cr)$. These domains, which have the $Pt_2Mo$ crystal structure, are formed upon a 24h or longer heat treatment at 1200°F (649°C) and provide effective strengthening while leaving the alloy with excellent ductility and toughness, a combination well suited for applications requiring outstanding containment capabilities. With a high Mo content of 25 wt.% (see Table 1 for full composition), 242 alloy has a low coefficient of thermal expansion (CTE) compared to other high-strength Ni-base alloys. Moreover, the formation of the LRO domains provides an additional reduction in the CTE. The oxidation resistance of 242 alloy is very good when compared to other low CTE Ni-base alloys, such as 909 alloy [2]. This can be attributed to the presence of 8 wt.% Cr which provides sufficient oxidation resistance at the intermediate temperatures where 242 alloy is used in service. A big advantage of 242 alloy compared to other low CTE alloys is that it can often be used in the uncoated condition. The strengthening imparted by the LRO domains provides 242 alloy with high tensile yield, ultimate tensile, and creep-rupture strength along with excellent ductility [3]. A number of technical papers have been published detailing the physical metallurgy, ordering transformation, and other aspects of 242 alloy [4-7]. One key property for gas turbine applications for which 242 alloy is a candidate is the LCF strength. The purpose of this paper will be to discuss the LCF properties of 242 alloy through the results of two different test programs (strain-control and stress-control).

## EXPERIMENTAL PROCEDURE

### Materials

For the strain-controlled LCF test program, the material used was 0.625" (16 mm) hot rolled plate produced from a commercial heat of 242 alloy (heat #8422-8-7340). The as-rolled plate had been mill-annealed at 1950°F (1066°C). Specimen blanks were cut from the plate and heat treated at 1200°F (649°C) for 24 hours followed by air cooling. This is consistent with standard 242 alloy practice which calls for a minimum of 24 hours at 1200°F (649°C), but in many cases it is more common to extend the heat treat duration to 48 hours. The as-heat treated specimen blanks were machined into button-head smooth bar specimens using a low-stress grinding and polishing technique. To establish baseline mechanical properties, tensile tests were first conducted at temperatures from RT to 1400°F (760°C). The results are shown in Table 2. The strength of 242 alloy is seen to be very high at temperatures up to 1200°F (649°C), with a sharp drop at 1400°F (760°C). At all temperatures the alloy was found to have excellent ductility.

For the stress-controlled LCF test program, specimen blanks were electric discharge machined (EDM) from a 242 alloy ring produced at Schlosser Forge. The approximate ring dimensions were 26" (660 mm) O.D. x 0.875" (22 mm) wall. The 242 alloy sample blanks were heat treated as above. For this program, 909 alloy was also tested for comparison. Specimen blanks of 909 alloy were taken from an uncoated, heat-treated ring of the following approximate dimensions: 24" (610 mm) O.D. x 1.875" (48 mm) wall. The heat treatment was standard for 909 alloy: 1800°F (982°C)/1h followed by 1325°F (718°C)/8h FC (furnace cool) to 1150°F (621°C)/8h. For both alloys, blanks were machined into double-notch bar specimens ($K_t$ = 2.18). The specimens were low-stress ground and polished.

### Strain-Controlled LCF Testing

Fully reversed, strain-controlled LCF testing was performed at Metcut Research Associates, Cincinnati, OH with the following test conditions:

| | |
|---|---|
| Mode: | Longitudinal Strain Control |
| Temperature: | 800, 1000, 1200, and 1400°F (427, 538, 649, and 760°C) |
| R: | -1 |
| Frequency: | 0.33 Hz |
| Waveform: | Triangular |
| Machine: | Closed-loop Servo-Cont. Hydraulic |
| Heat Source: | High Freq. Induction Generator |

The number of cycles to failure ($N_f$) and the number of cycles to crack initiation ($N_i$) were recorded. Failure was defined as either complete fracture of the specimen, or as the point at which the maximum stress had dropped to 75% of its stabilized value. The point of crack initiation was determined by means of a continuous load monitor and represents a discernable deviation from the mean after the stabilized portion of the trace. Also recorded was the variation of the stress amplitude with increasing cycles.

### Stress-Controlled LCF Testing

Stress-controlled LCF testing was performed at Metcut Research Associates, Cincinnati, OH with the following test conditions:

| | |
|---|---|
| Mode: | Axial Load Control |
| Temperature: | 1200°F (649°C) |
| R: | 0.05 |
| A: | 0.90 |
| Frequency: | 0.33 Hz |
| Waveform: | Triangular |
| Machine: | Closed-loop Servo-Cont. Hydraulic |
| Heat Source: | High Freq. Induction Generator |

The number of cycles to failure ($N_f$) was recorded as well as the cycle number of the last inspection prior to crack observation ($N_{pc}$).

## RESULTS AND DISCUSSION

### Strain-Controlled LCF Behavior

**Fatigue Life.** The results ($N_f$ and $N_i$ values) of the strain-controlled LCF testing of 242 alloy are given in Table 3. One observation when comparing the $N_f$ and $N_i$ values was that, for each test condition, the major portion of the fatigue life consisted of cycles to crack initiation. The fatigue lives are graphically presented in Fig. 1 where for each test temperature the total strain range ($\Delta\varepsilon_t$) is plotted against the fatigue life (as characterized by the number of cycles to failure, $N_f$). Not unexpectedly, the fatigue life was found to decrease with increasing total strain range. Of more interest was the temperature dependence of the fatigue life. This discussion is best divided into two parts: 1) 800 to 1200°F (427 to 649°C) where the $Ni_2(Mo,Cr)$ domains are stable, and 2) 1400°F (760°C) where the $Ni_2(Mo,Cr)$ domains are unstable.

In the 800 to 1200°F (427 to 649°C) temperature range, the effect of temperature on the fatigue life was dependent on the total strain range. At higher levels of strain, the fatigue life decreased with increasing temperature as would normally be expected. However, at lower strain levels the fatigue life at 800°F (427°C) crossed over the 1000 and 1200°F (538 and 649°C) life. That is, in this lower strain range the fatigue life of 242 alloy at 800°F (427°C) was less than those at the higher temperatures. This can possibly be rationalized by considering that at the higher temperatures of 1000 and 1200°F (538 and 649°C) there is likely strain-assisted ordering transformation continuing to occur with a resultant increase in fatigue life. This continued transformation would be expected to be greater for lower strain levels where the time at temperature would be longer. The 800°F temperature is likely too low to result in further ordering. Between the temperatures of 1000 and 1200°F (538 and 649°C) the fatigue life decreased with increasing temperature across the full total strain range regime.

At 1400°F (760°C), fatigue lives were significantly reduced in comparison to the lower temperatures. This was true across the full total strain range regime tested in this program. The lower fatigue lives are not surprising when it is considered that at this temperature the LRO $Ni_2(Mo,Cr)$ domains, responsible for the high strength, are not stable.

Low cycle fatigue life is affected by the ductility of an alloy at higher strain ranges, but more by the strength at lower strain ranges. Among age-hardened alloys, 242 alloy retains both strength and ductility in prolonged service as microstructural changes (such as overaging) are not expected to detrimentally affect the LCF life at temperatures up to around 1300°F (704C°). The magnitude of the fatigue life of 242 alloy at 800 to 1200°F (427 to 649°C) is considered excellent in comparison to high-temperature solid solution strengthened alloys such as 230®, 617, and 625 alloys and HASTELLOY X alloy. The fatigue life of 242 alloy is shown in Fig. 2 along with the other alloys where available data was found in the literature [8-13]. At 800°F (427°C), the LCF life of 242 alloy was comparable to 230, 617, 625, and X alloys at higher strain ranges, but a clear advantage of 242 alloy was seen at the lower strain ranges (where the high strength of 242 alloy provides the improvement). At 1000°F (538°C) the LCF life of 242 was considerably greater than X or 617 alloy, particularly at lower strains. This trend was continued at 1200°F (649°C), where at total strains below 1% the LCF life of 242 alloy was much greater than X alloy. Even at 1400°F (760°C), where the LRO strengthening effect has dissipated, the fatigue life of 242 alloy compared favorably to 230, X, and 617 alloys.

**Stress vs. Cycles.** The stress amplitude as a function of the cycle number, N, is shown in Fig. 3 for all four test temperatures. For a given test temperature, the stress amplitude typically increased with increasing total strain. Generally, it was observed that the stress amplitude increased with increasing number of cycles (cyclic hardening). Also, for test temperatures of 800 to 1200°F (427 to 649°C), the slopes of the strengthening curves were generally observed to increase with increasing strain. In many cases the change in slope took place beyond a certain number of cycles and, for a given temperature, this number appeared to decrease with increasing total strain. An interesting observation was made concerning the tests (discussed in the previous section) at 1000 and 1200°F (538 and 649°C) which had greater fatigue life than tests at equivalent total strain at 800°F (427°C). In these cases, the stress amplitude was observed to be very flat or even slightly decrease (cyclic softening) with increasing cycle number for the first several hundred cycles. After that, the slope of the stress amplitude curve began to increase. The explanation for this behavior is not clear, but it was apparently associated with the low-strain (primarily elastic) tests at 1000 and 1200°F (538 and 649°C) which had greater fatigue life than observed for equivalent total strain tests at 800°F (427°C).

At 1400°F (760°C), where the LRO strengthening was not present, the stress amplitudes were significantly lower than for the other three temperatures. Strong cyclic hardening behavior was observed even at low a number of cycles. This was particularly true for higher total strain tests.

## Stress-Controlled LCF Behavior

The results of the stress-controlled LCF program are given in Table 4. It is important to note that all of the tests were run at a maximum stress at or above the 1200°F (649°C) yield strength of 242 alloy (~80 ksi/552 MPa), while all tests were well below that of 909 alloy (~125 ksi/862 MPa). It was observed that crack initiation in 909 alloy occurred fairly early during the test. For example, for tests with a maximum stress of 80 ksi (552 MPa) no cracking was observed for 242 alloy up to 198,030 cycles (65% of $N_f$), where for 909 alloy the equivalent number was only 45,800 cycles (35% of $N_f$).

The 1200°F (649°C) fatigue life of both 242 alloy and 909 alloy is plotted as a function of the maximum stress in Fig. 4. There appeared to be more scatter in the 909 alloy data than for 242 alloy. The fatigue life curves in Fig. 4 crossover at a maximum stress of 98 ksi (676 MPa). Above this stress the higher strength of 909 alloy provides an advantage in LCF life. However, when the maximum stress is below 98 ksi the 242 alloy exhibits longer fatigue life. The relatively poor LCF life of 909 alloy in this regime has been attributed to its poor oxidation resistance relative to 242 alloy [2]. The heavy oxidation of 909 alloy, particularly during the lower stress tests (where the test duration and hence oxidation exposure is greater), leads to increased tendency of scale cracking and consequent reduction of fatigue life. Thus, the excellent oxidation resistance of 242 alloy provides a significant advantage in LCF life.

## SUMMARY

The LCF behavior of the high-strength, low thermal expansion HAYNES 242 alloy has been investigated. Programs involving both strain-controlled and stress-controlled testing were conducted and the results reported. The strain-controlled testing was conducted at temperatures ranging from 800 to 1400°F (427 to 760°C). The LCF life of samples tested from 800 to 1200°F (427 to 649°C) was very high, being considerably greater than high-performance solid-solution strengthened alloys, such as 230, X, and 617 alloys, at total strain ranges ≤ 0.7%. For tests at lower total strain levels at 1000 and 1200°F (538 and 649°C), the LCF life of 242 alloy was greater than for equivalent strains at 800°F (427°C), suggesting that at the higher temperatures a strain-assisted ordering trans-formation contributed to improved LCF resistance. At 1400°F (760°C), the LCF life was considerably shorter as a result of the loss of LRO $Ni_2$(Mo,Cr) strengthening.

Comparative stress-controlled LCF testing at 1200°F (649°C) between 242 alloy and 909 alloy (another low-thermal expansion alloy) revealed that for maximum stress levels below 98 ksi (676 MPa), 242 alloy had superior LCF life. The superior LCF behavior of 242 alloy relative to 909 alloy can be attributed in part to its improved oxidation resistance.

## NOMENCLATURE

| | |
|---|---|
| $\Delta\varepsilon_t$ | total strain range |
| A | ratio of alt. stress/mean stress (stress-control) |
| $K_t$ | stress intensity factor |
| $N_f$ | number of cycles to failure |
| $N_i$ | number of cycles to crack initiation |
| $N_{pc}$ | cycle number of last inspection prior to crack observation |
| R | ratio of min. stress/max. stress (stress-control) |
| R | ratio of min. strain/max. strain (strain-control) |

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**Table 1   Nominal Composition of 242 Alloy**

| Ni | Mo | Cr | Fe | Co | Mn | Si | Cu | Al | C | B |
|---|---|---|---|---|---|---|---|---|---|---|
| 65[a] | 25 | 8 | 2* | 1* | 0.8* | 0.8* | 0.5* | 0.5* | 0.03* | 0.006* |

[a]As Balance *Maximum

**Table 2  Tensile Properties of 242 alloy (0.625"/16mm Plate)**

| Temperature | | 0.2%  Yield Strength | | Ultimate Tensile Strength | | Elongation | R.A. |
|---|---|---|---|---|---|---|---|
| °F | °C | ksi | MPa | ksi | MPa | % | % |
| RT | RT | 109.9 | 758 | 179.3 | 1236 | 39.3 | 43.7 |
| 200 | 93 | 105.5 | 727 | 173.6 | 1197 | 39.8 | 48.1 |
| 400 | 204 | 91.3 | 630 | 161.0 | 1110 | 42.3 | 43.1 |
| 600 | 316 | 86.7 | 598 | 155.8 | 1074 | 42.7 | 41.5 |
| 800 | 427 | 80.2 | 553 | 153.6 | 1059 | 44.0 | 39.7 |
| 1000 | 538 | 69.8 | 481 | 144.9 | 999 | 46.6 | 41.4 |
| 1200 | 649 | 76.0 | 524 | 142.2 | 980 | 43.1 | 36.0 |
| 1400 | 760 | 41.7 | 288 | 105.9 | 730 | 66.3 | 45.0 |

**Table 3  Strain-controlled LCF Test results**

| Total Strain Range, % | 800°F (427°C) | | 1000°F (538°C) | | 1200°F (649°C) | | 1400°F (760°C) | |
|---|---|---|---|---|---|---|---|---|
| | $N_i$ | $N_f$ | $N_i$ | $N_f$ | $N_i$ | $N_f$ | $N_i$ | $N_f$ |
| 1.25 | 3,754 | 4,681 | 2,261 | 2,700 | 430 | 459 | | |
| 1.0 | 6,478 | 7,482 | 4,737 | 5,237 | 1,272 | 1,455 | 709 | 735 |
| 0.8 | 13,531 | 14,540 | 32,432 | 36,490 | 10,776 | 10,837 | 2,204 | 2,281 |
| 0.75 | | | -- | 200,000* | 36,754 | 36,922 | | |
| 0.7 | 22,187 | 31,037 | -- | 208,300* | 109,628 | 109,695 | | |
| 0.65 | -- | 200,000* | | | | | | |
| 0.6 | -- | 200,000* | | | | | 8,736 | 8,793 |
| 0.5 | | | | | | | 27,980 | 28,021 |
| 0.4 | | | | | | | 151,149 | 151,614 |

*Sample removed prior to failure

**Table 4  Stress-controlled LCF Test results**

| Max. Stress | | Min. Stress | | 242 alloy | | 909 alloy | |
|---|---|---|---|---|---|---|---|
| ksi | MPa | ksi | MPa | $N_{pc}$ | $N_f$ | $N_{pc}$ | $N_f$ |
| 110 | 758 | 5.5 | 37.9 | 340 | 845 | 250 | 2,835 |
| 100 | 690 | 5.0 | 34.5 | 11,100 | 12,220 | 20,230 | 22,568 |
| 95 | 655 | 4.75 | 32.8 | 30,920 | 32,587 | 4,500 | 13,796 |
| 90 | 621 | 4.5 | 31.0 | 60,400 | 76,763 | 20,160<br>32,025 | 40,525<br>59,679 |
| 85 | 586 | 4.25 | 29.3 | 184,290 | 297,848 | 19,480<br>43,701 | 22,400<br>47,707 |
| 80 | 552 | 4.0 | 27.6 | 198,030 | 304,116 | 45,800 | 129,573 |

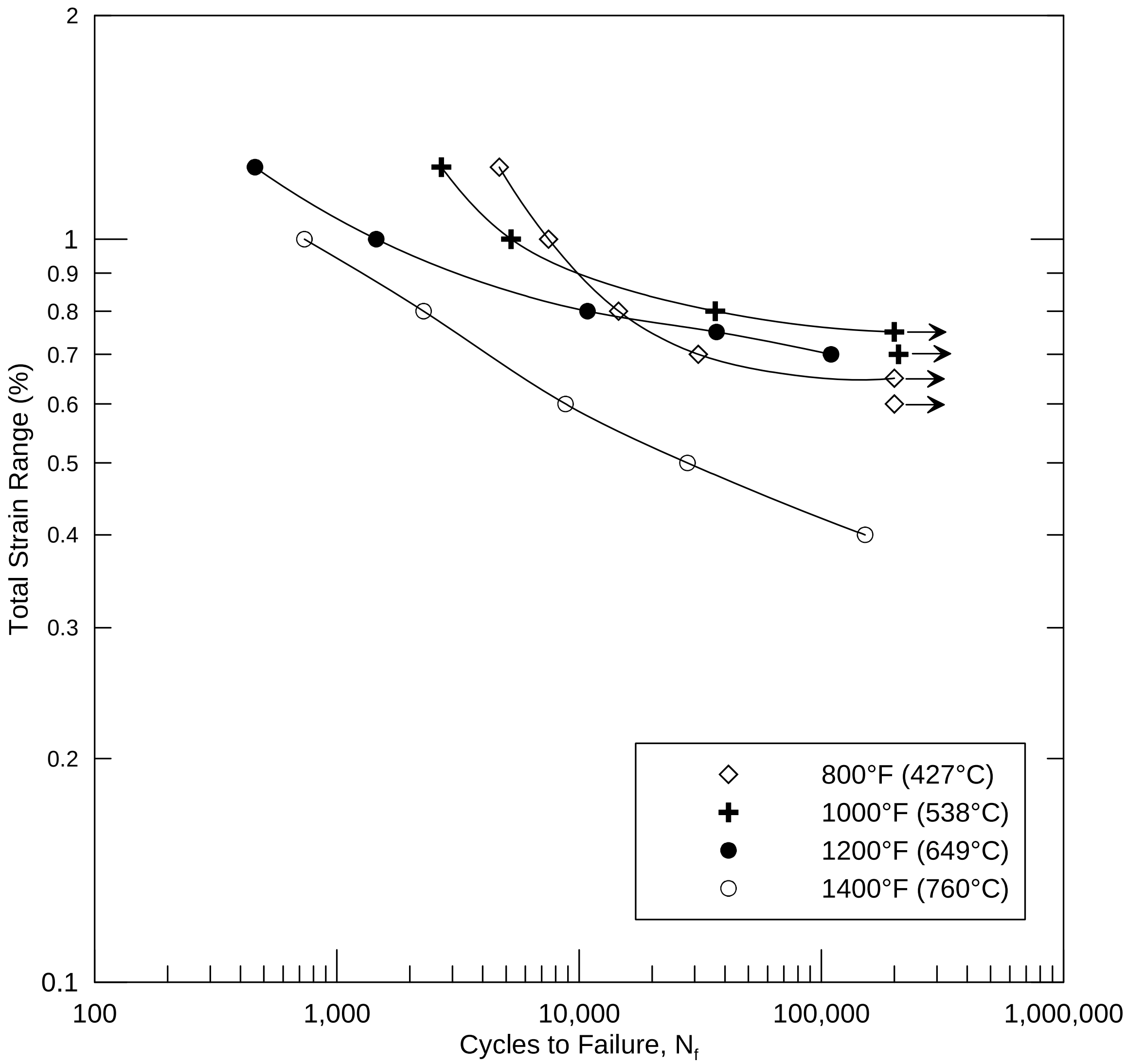


**Fig. 1  HAYNES 242 alloy: Strain-controlled LCF life vs. total strain range.**

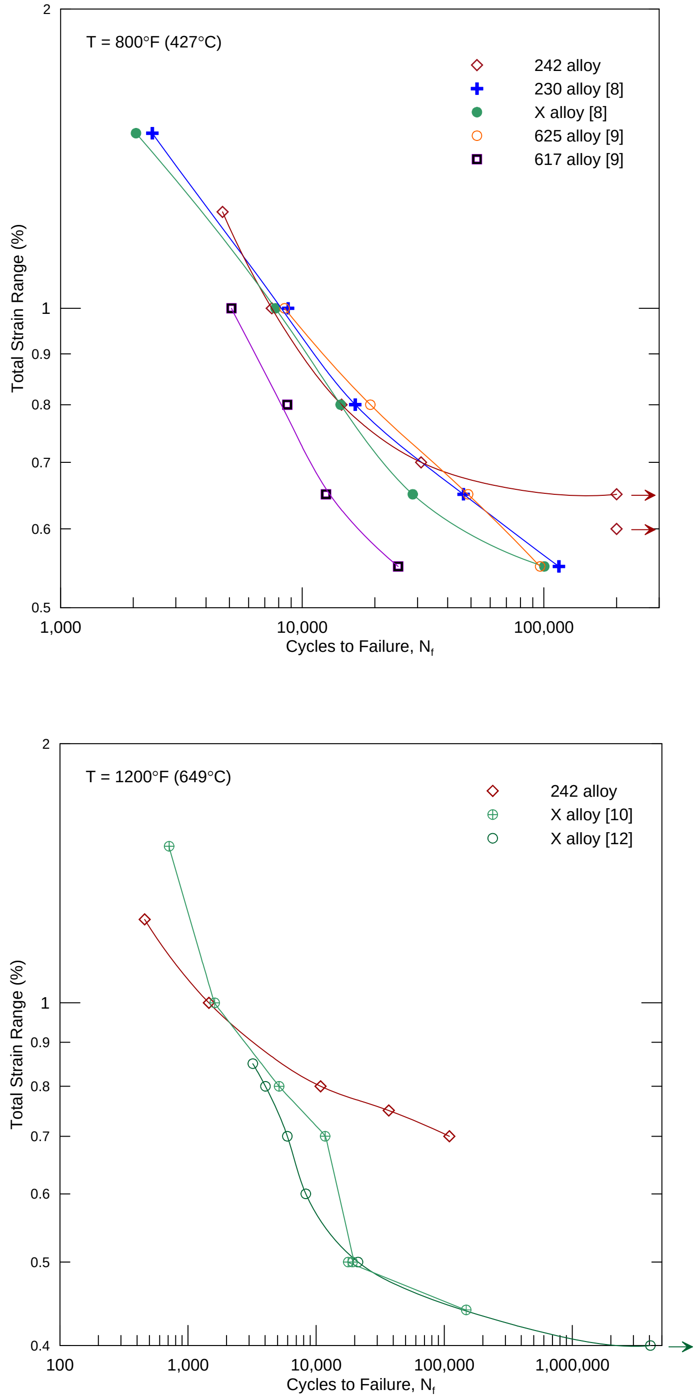


**Fig. 2 Comparative LCF life of several high-temperature alloys at 800 to 1400°F (427 to 760°C).**

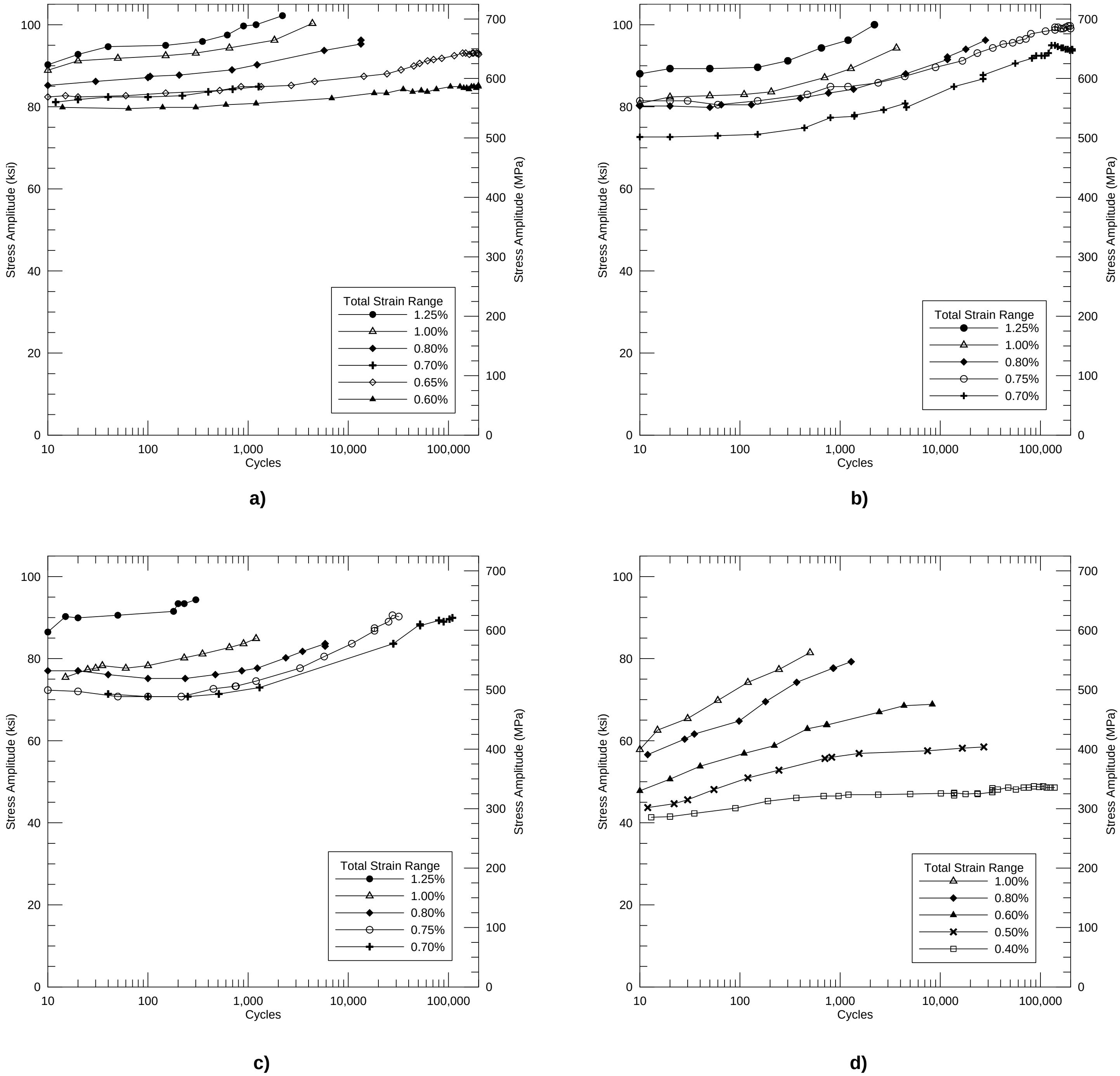


**Fig. 3 Stress amplitude vs. cycles: a) 800°F (427°C), b) 1000°F (538°C), c) 1200°F (649°C), and d) 1400°F (760°C).**

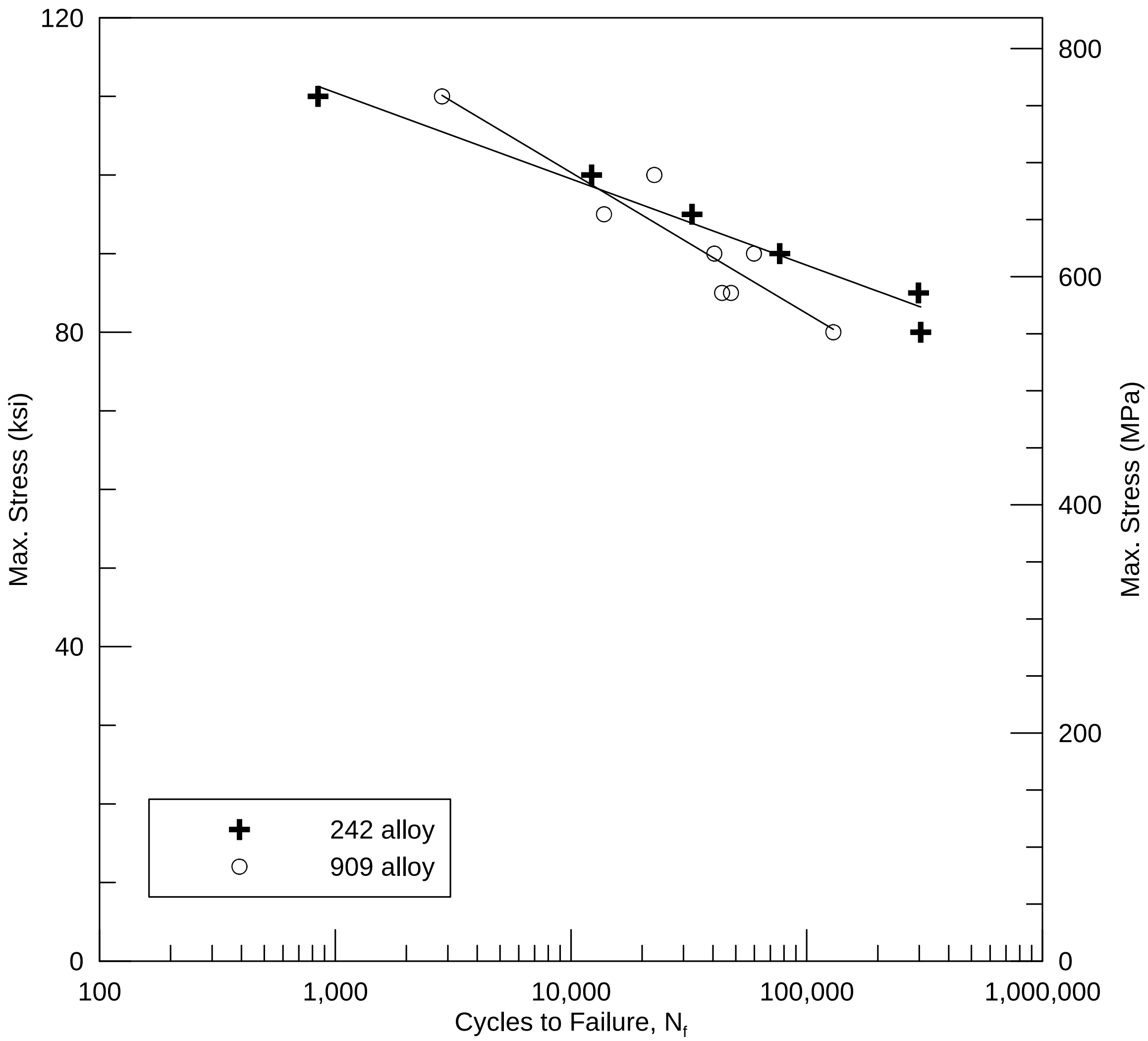


**Fig. 4 Stress-controlled LCF life vs. max. stress at 1200°F (649°C).**