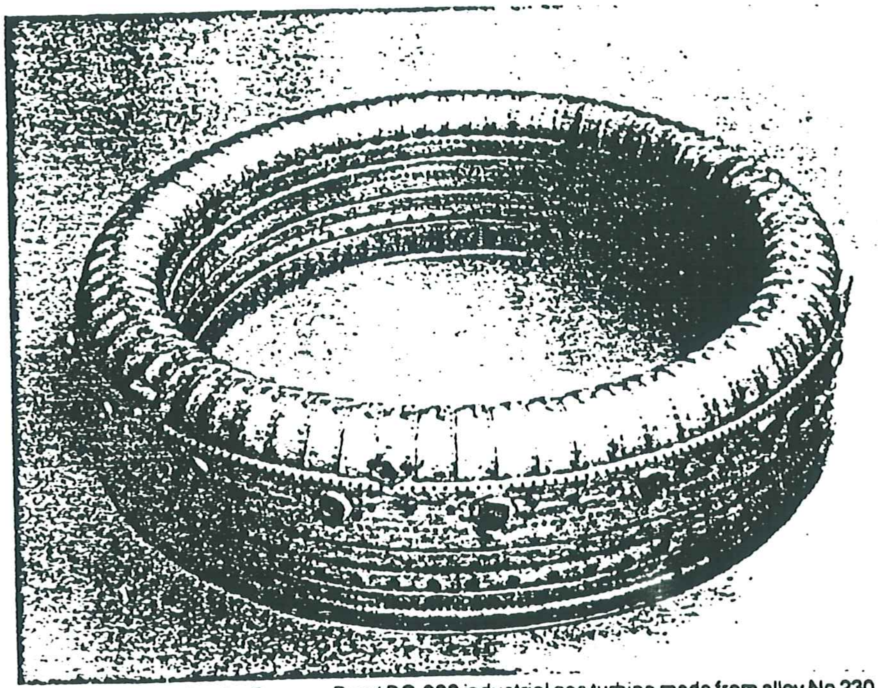
Modern alloys in gas turbines

Michael F Rothman
Haynes International, Inc

The evolution of the modern class of readily-fabricated, high-temperature alloys, commonly known as solid-solution-strengthened superalloys, and the history of their use in gas turbine engines can rightfully be traced back to the late 1930s. HASTELLOY® alloy B (Ni-28Mo-5.5Fe-.12C) and HASTELLOY® alloy C (Ni16.5Cr-17Mo-4.5W-6Fe-.15C) were used in various aircraft applications. Originally developed as corrosion-resistant materials for the chemical industry, these alloys were found to combine excellent high-temperature strength with ease of fabrication and, in the case of alloy C, superior oxidation-resistance compared to stainless steels. Early applications included forged turbine buckets for the I-16 and I-40 engines for alloy B, and exhaust cowlings, tailpipes, and cabin heaters for alloy C.



Combustion chamber for Dresser-Rand DC-990 industrial gas turbine made from alloy No 230 sheet.

These initial successful uses of adapted alloys, and the growing need for even stronger and more oxidation-resistant materials to match the demands of developing gas turbine technology, ultimately led to the development of alloys such as the cobalt-base HAYNES® alloy No 25 (Co-20Cr-10Ni-15W-3Fe-.15C). Also known by the development designation L-605, this alloy was designed specifically to meet the requirements of the United States Air Force for a material that could resist oxidation and high stress at temperatures up to 1800°F (980°C) and still be fabricated into complex components, such as gas turbine combustor cans.

As the acceptance of gas turbine engines grew rapidly during the late 1940s, fear arose that the then known worldwide supplies of such critical metals as cobalt and tungsten would soon be depleted. This gave rise to the development of an iron-base material with lower levels of strategic metals and which could be made using large quantities of scrap, thus reducing dependence on virgin raw materials. MULTIMET® alloy (Fe-20Ni-20Co-21Cr-3Mo-3W-.2N-1.0 (Cb+Ta)-1.OC) was also known as N-155 alloy. This material had strength capabilities and oxidation-resistance closely matching that of alloy No 25, and was somewhat easier to fabricate.

Even though the advent of N-155 alloy reduced strategic dependence upon cobalt and tungsten, with the onset of the Korean War in the early 1950s, renewed emphasis was placed upon reducing the use of these particular elements by engine builders. The result of this continued concern was the development of HASTELLOY alloy X (Ni-22Cr-18Fe-9Mo-.10C), perhaps one of the most widely used gas turbine alloys ever. Alloy X contains none of the elements commonly considered to be strategic (save chromium), and although it was not as strong as either alloy No 25 or N-155, it was far more oxidation-resistant and easier to fabricate.

Rapid growth for alloy X usage

Following the failure of an alloy No X-750 combustor on the test stand for the JT3D engine being developed by Pratt & Whitney Aircraft in the early to mid-1950s, alloy X was quickly adopted as the specified combustor material for the Boeing 707. The proliferation of use experienced for alloy X in commercial aircraft engines which followed on this initial application was dramatic. Indeed, 30 years later this material is still the most widely used combustor can material for commercial aircraft engines.

During the late 1950s and the 1960s, less emphasis was placed upon the strategic element content of this type of material, as such considerations were subordinated to the demands for higher temperature capability in military aircraft engines. In the late 1960s, HAYNES alloy No 188 (Co-20Ni-22Cr-14W-.10C) was developed to meet these demands. Superior to alloy No 25 in both oxidation-resistance and thermal stability, by a wide margin, alloy No 188 afforded engine designers a 300°F (165°C) performance advantage over alloy X in combustor and afterburner section applications. It was a key ingredient in the success of modern military aircraft, such as the F-15 and F-16.

With cobalt crisis of 1979–1980, renewed attention upon this strategic element lead to the development of the latest generation of solid-solution-strengthened superalloy, HAYNES alloy No 230 (Ni-22Cr-14W-2Mo). Introduced in 1981, alloy No 230 can trace its roots back through all of the previously mentioned materials, and perhaps represents the quintessential example of the balance of properties and design concerns that so typify this alloy class.

Although they are called solid-solution-strengthened alloys, materials such as alloys X, No 188 and No 230 really depend upon two important strengthening mechanisms — solid-solution-strengthening and in-service carbide precipitation strengthening. The use of these particular strengthening mechanisms tends to orient the alloys toward components which are subjected to low stress and high-temperatures for prolonged periods. These typically include complex fabrications where strengthening by means of an age-harden-

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ing heat tre sion of gamma prime prec engthened super-alloys is imp The alloys must meet the constra . the manufacturing processes used to make components such as combustors, transition liners, afterburner flameholders, and other complex assemblies, and still provide the strength required in service. To do this they must essentially be both strength- and fabrication-capable, as-supplied.

The concept of solid-solution-strengthening is well known from the literature[1,2]. The solid-solution-strengthening aspect of these alloys is self-evident from their telltale refractory element content. It is also readily apparent from an inspection of the various alloy compositions that the generally accepted range for the most effective level of refractory element content is the equivalent (on an atomic per cent basis) of seven to ten per cent by weight of molybdenum (2%W=1%Mo). Materials consistent with this range include alloys X, No 25, No 188, No 230, No 625 (Ni-22Cr-9Mo-5Cb-5Fe), No 617 (Ni-22Cr-12Co-9Mo-1Al) and N-86 (Ni-25Cr-9Mo), or virtually the entire alloy family.

Carbon's vital role

Carbon also can play the role of solid-solution-strengthened as an interstitial atom in these alloys; however, its more important role in strengthening involves the precipitation of carbides from solution on dislocations moving through the alloy while in service at elevated temperature[3]. This in-service strengthening by precipitation of carbides is perhaps more important than solid-solution-strengthening. Indeed, alloys which contain relatively low carbon, such as alloy No 625 (less than 0.03C) and HASTELLOY alloy S (Ni-16Cr-15Mo-less than 0.02C), are markedly inferior in rupture strength at high-temperatures to alloys with similar refractory element content but 0.05 per cent to 0.15 per cent carbon content. This is clear from 1600°F (870°C) rupture strength data presented in Table 1.

In designing alloys to resist the combustion environments associated with gas turbine and aerospace applications, the key elements required are either chromium, or possibly aluminium in combination with chromium. In order to provide for the formation of protective aluminium oxide scales in nickel-, iron-, or cobalt-base alloys, upwards of about 4 per cent aluminium is required. This poses significant fabrication problems for most of the types of components usually addressed with solid-solution-strengthened alloys, particularly in terms of welding and severe forming operations. It is, therefore, not surprising that all principal solid-solution-strengthened superalloys depend upon chromium for environment-resistance at elevated temperature.

The normal range of chromium content in these alloys is from about 16 to 25 per cent by weight, although most materials contain 20 to 22 per cent. Most often these alloys do not form pure chromium oxide scales in service, but rather typically they will form complex Ni-Cr, Fe-Ni-Cr, or Co-Ni-Cr containing spinel-type oxide scales which are quite protective. The addition of up to 2 per cent manganese, silicon or aluminium can facilitate the formation of these scales and their adherence to the alloy; however, silicon and aluminium contents over 1 per cent can also foster internal attack along grain boundaries[4].

The major design development in improving the oxidation-resistance of these alloys beyond the standard set by alloy X over 30 years ago has been the incorporation of rare earth metals in very small amounts into the composition. Beginning with alloy No 188 in the late 1960s, many of today's modern alloys have been developed with contents of from about 0.01 to 0.10 per cent lanthanum or cerium. The effects of such seemingly insignificant amounts of these elements are quite dramatic. Recently developed materials, such as alloy No 230, exhibit oxidation-resistance two to three times that of alloy X, and are usable at temperature as high as 2100°F (1050°C).

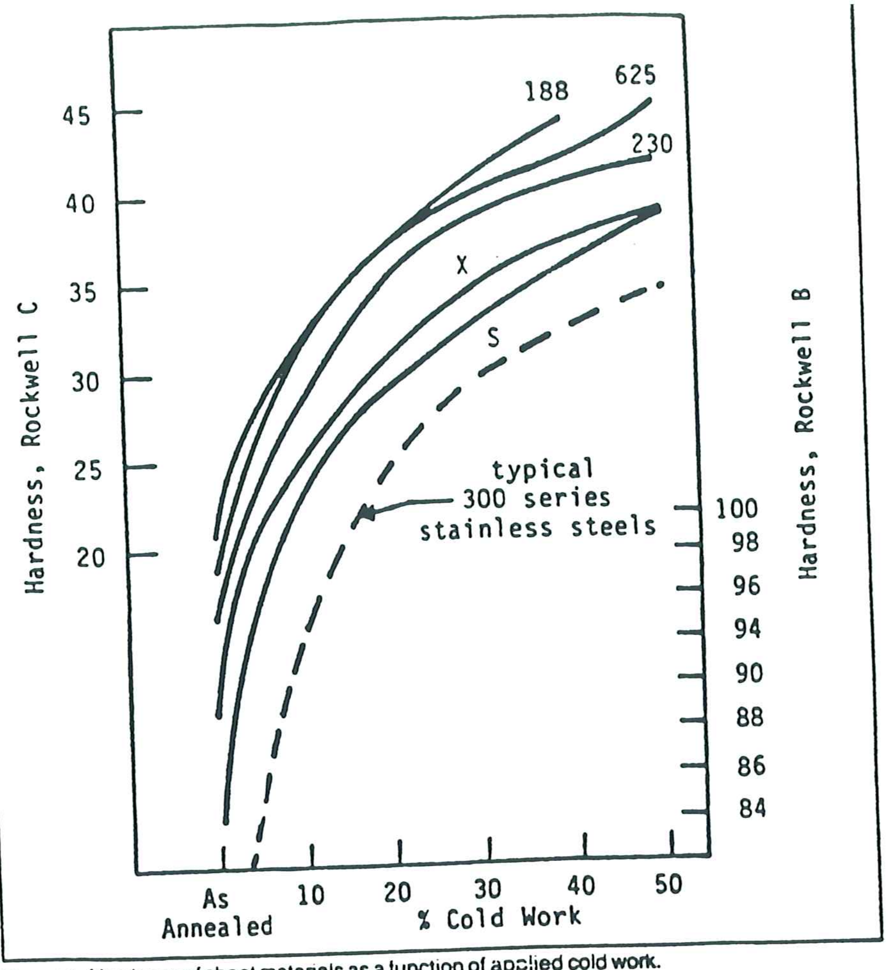

Figure 1. Hardness of sheet materials as a function of applied cold work.

Many properties necessary

To be useful over the range of applications required, these solid-solution-strengthened alloys must not only possess excellent high-temperature strength and environment-resistance, but must also be capable of being manufactured into a variety of forms for fabrication into complex components by many techniques. Other materials can match the strength and resistance to oxidation, but not with the inherent forming and joining advantages enjoyed with these alloys.

The work hardening characteristics of solid-solution-strengthened alloys are somewhat more pronounced than those for stainless steels, as shown in Figure 1[5]. The excellent ductility and relatively low room-temperature strength of these materials, however, allows for the most severe type of cold forming operations. Hot fabrication processes, such as spin forming and ring rolling are facilitated by the excellent elevated temperature ductility of the

Alloy	Weight Per cent Mo	 W	 C	Stress Rupture Life (hours)
230	2	14	0.10	51 000
X	9	0.6	0.10	5900
S	15	—	0.02*	2500

Table 1. Stress rupture life for various alloy plate samples tested at 1600°F/4.5ksi (870°C/31MPa). *Burner-rig oxidation test results.

alloys, and the absence of precipitation hardening with very short thermal exposures. Unlike gamma-prime-strengthened superalloys, with their inherently higher strengths and lower ductilities (even in the annealed condition), and high-carbon alloys (over 0.20 per cent) with their much lower ductility, solid-solution-strengthened alloys can be put through repetitive forming and stress-relief cycles without significant cracking or distortion.

Superalloy welding problems

The same considerations apply to joining technology. The gamma-prime-strengthened superalloys and high-carbon alloys both are susceptible to welding difficulties. These take the form of weld metal cracking, at least partially associated with the low cast ductility of these materials, and base-metal cracking. Cracking in the base metal can be related to heat-affected-zone precipitation causing ductility loss, or the more complex phenomenon, strain-age cracking, which is common in gamma prima alloys. The absence of the precipitation strengthening, and the high ductility of [illegible] solid-solution-strengthened in cast [illegible] set these alloys well above the others in joinability.

Progress during the last 30 years in solid-solution-strengthened superalloy strength development is illustrated by Figure 2. Half of the 300°F (165°C) operating temperature advance of alloy No 188 over alloy X was in creep strength. As can be seen from Figure 2, the temperature advantage of alloy No 188 over alloy X in creep is about 150°F (83°C) over the range of operating temperatures from 1400°F to 1800°F (760°C to 980°C). The newer material, alloy No 230, represents a compromise in creep strength made to help optimise other key properties, as will be discussed. Still, as operating temperatures exceed about 1650°F (900°C), the strength capabilities of alloy No 230 approach those of alloy No 188. This is particularly significant, since advances in gas turbine combustor wall temperatures are pushing well into this range.

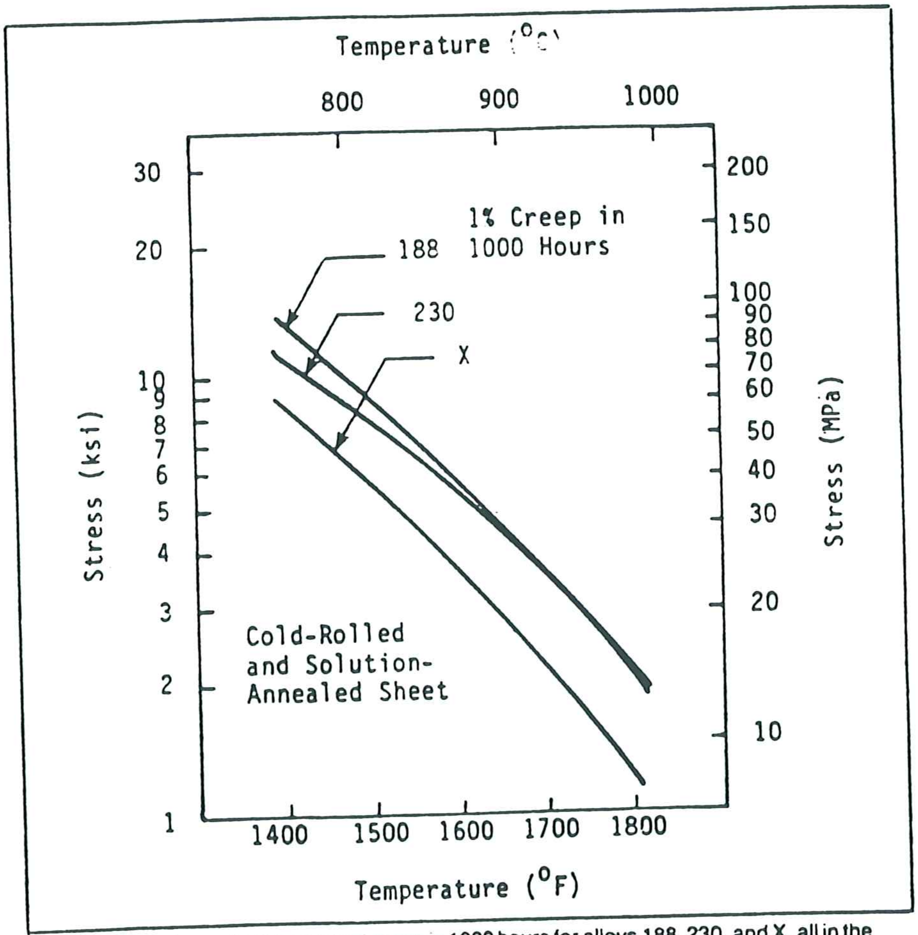

Figure 2. Stress to produce 1 per cent creep in 1000 hours for alloys 188, 230, and X, all in the solution annealed condition.

One of the areas of major progress in the newer alloys, such as alloy No 230 and somewhat older materials such as alloy No 617 and alloy N-86, is improved thermal stability. While alloy No 188 was an advance in strength over alloy X, there was little improvement in the resistance of the materials to loss of ductility from long-term ageing. Alloy X is embrittled in service after long-term exposure from the precipitation of both sigma phase and mu phase. Alloy No 188, although it does not form sigma phase, does become embrittled from the formation of a Co$_2$W laves phase[6]. These effects are completely avoided in alloy No 230, as shown in Figure 3[5]. An improvement is also observed for alloys No 617 and N-86.

This improvement in thermal stability has important implications for the long-term service potential of these alloys in applications such as combustor cans. Loss of ductility in service will often lead to the life limiting factor being thermomechanical fatigue rather than creep damage. The relationship between thermal stability and fatigue performance is illustrated in Figure 4. Note that the loss of fatigue life for alloy X and alloy No 188 upon prior exposure for 1000 hours at 1400°F (760°C) is much greater than that for alloy No 230. Longer exposure time might be expected to yield even greater differences.

The other half of the 300°F (165°C) improvement in performance for alloy No 188 over alloy X was due to its improved oxidation resistance. Comparative properties in burner rig tests, simulating gas turbine cycles, are presented in Table 2 for both 1800°F (980°C) and 2000°F (1095°C) tests. As may be seen, the significant advance of alloy No 188 over alloy X at 1800°F (980°C) has been marginally improved with alloy No 230. At 2000°F (1095°C), alloy No 230 represents a significant advance over both other materials.

Alloy	1800°F/(980°C)/1000 hours	2000°F(1095°C)/500 hours
230	2.8 (.071)	5.2 (.132)
188	3.5 (.089)	9.8 (.249)
X	5.6 (.142)	12.9 (.328)

Table 2.

Numerous components fabricated

Various sophisticated turbine components have been fabricated from all of the materials discussed here. An excellent example of the complexity of component fabrication capabilities available with solid-solution-strengthened alloys is shown in the photograph. This combustor for the Dresser-Rand DC990 industrial gas turbine was fabricated from alloy No 230 sheet employing extensive roll forming, metal spinning, TIG welding and brazing techniques, among others.

This typical response to the demands of manufacturing technology for the utmost versatility in material fabrication capability points to the flexibility that this type of alloy can afford designers. Today's combustor designs, for example, require that a single alloy must be capable of being used in several distinctly different ways. These include welded and brazed sheet metal construction, a stack of welded contour rolled rings, a series of shingles riveted or welded to a sheet metal liner, or even a forged/rolled cylinder precision machined into a one-piece can. Add other related components that also require similar performance characteristics, and the ability to do it all with one material becomes quite a testimonial to this class of alloys.

This kind of flexibility is being utilised to full advantage in the planned component design and manufacturing for some of the latest and future gen[illegible]rbine engines. Novel combustor constructions under evaluation include honeycomb wall concepts and ultra-thin wall, one-piece castings, both in existing solid-solution-strengthened materials such as alloy No 230. New manufacturing technology for these alloys includes precision cold-forming of rings and combustor liners from wide rectangular cross-section feedstock.

New application areas for the solid-solution-strengthened alloy family will include various recuperator and heat exchanger constructions for vehicular and industrial gas turbines. There will also be usage in advanced air frames and outer surface construction for high-speed and transatmospheric vehicles, where density penalties will be offset by design flexibility in the fabrication of light-weight honeycomb or laminated structures. On-going alloy development efforts in both industry and the public sector will bring additional refinement to this family of materials. □

Michael F Rothman is product applications manager for high-temperature alloys with Haynes International, Inc, Kokomo, Indiana. He is chairman of the ASM Heat-Resistant Material Properties Committee, secretary of the Joint ASM/TMS Corrosion and Environmental Effects Committee, a former chairman of the TMS High-Temperature Alloys Committee, and a member of the NACE T5B Committee on High-Temperature Corrosion.

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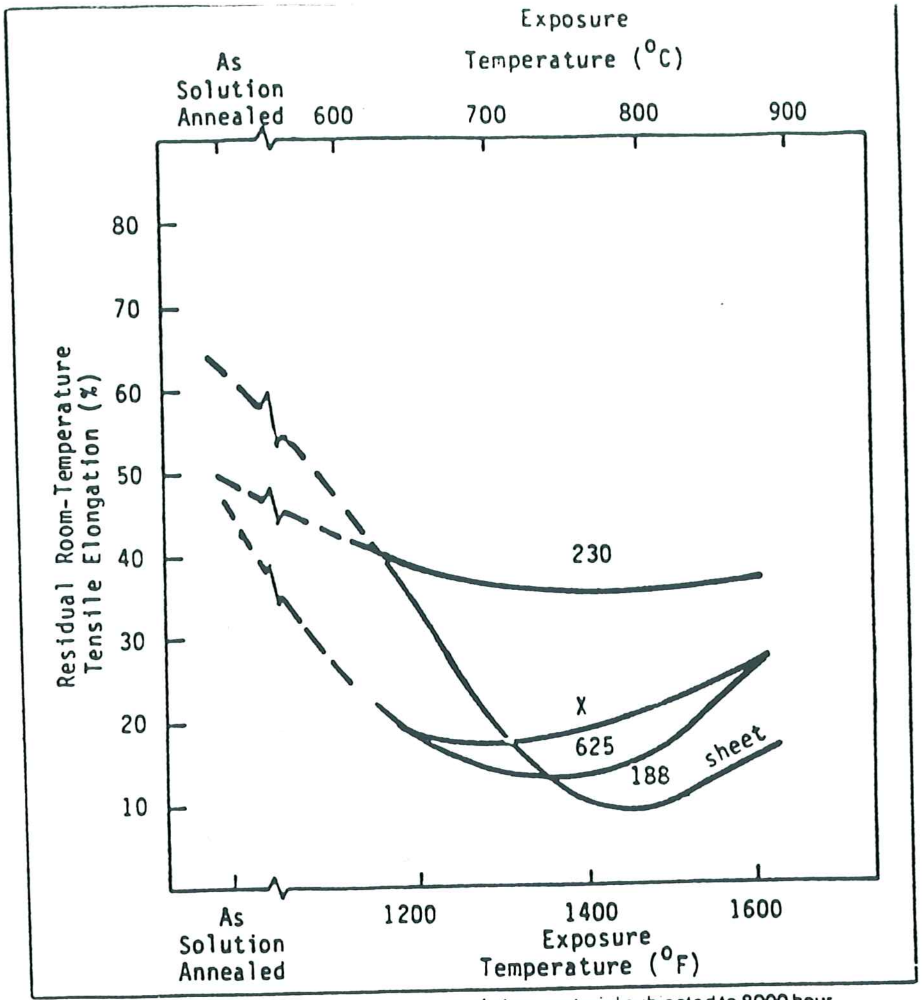

Figure 3. Room-temperature tensile elongation of plate material subjected to 8000 hour exposure at elevated temperature.

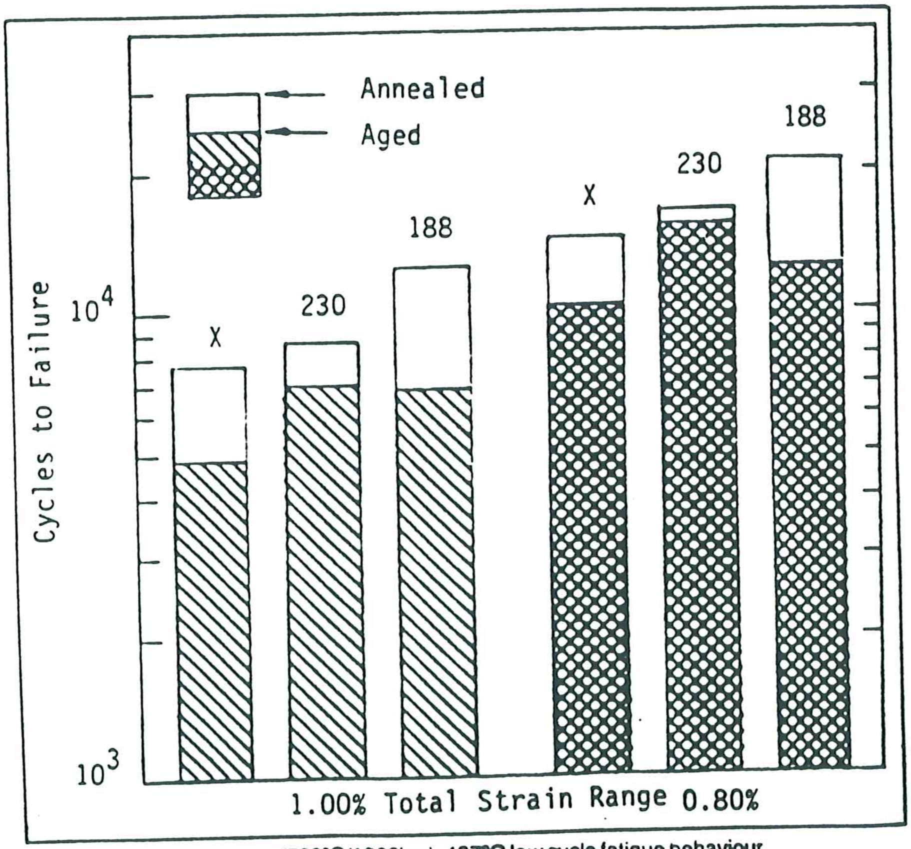

Figure 4. Annealed vs aged (760°C/1000hrs). 427°C low cycle fatigue behaviour.