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Mechanical Properties of Aluminium Alloy DS-Al-550 at low Temperatures

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Abstract

A dispersion strengthened aluminium alloy, RAUFOSS DS-Al-550, has been considered as a possible material for high energy physics applications. Tensile tests were performed on cold rolled sheets of DS-Al-550 at 293 K, 77 K, and 4.2 K, both on transverse and longitudinal samples. The tests were carried out on a special cryogenic tensile machine developed at CERN. The mechanical tensile properties of DS-Al-550 at low temperatures are high compared to pure Aluminium and close to Al-2219-T851.

1. INTRODUCTION

The Dispersion Strengthened Aluminium DS-Al-550, developed by Raufoss Technology, is a mechanical alloy obtained by powder metallurgy in a high energy ball mill in a liquid nitrogen bath [1]. It consists of an aluminium matrix reinforced with small particles (2-10 nm) of AlN. The estimated volume fraction of the reinforcement phase is 0.15-0.2% and the spacing between the particles is about 80 nm [1].

Its weldability by friction stir welding has been demonstrated by tests performed by the International Institute of Welding (IIW). The material has been used in various applications, in particular for components of aerospace engines ([1]-Annexes 2, 3, 5).

The high strength characteristics of DS-Al-550, its excellent creep properties and thermal resistance ([1]-Annexe 1) makes it interesting for low temperatures applications. The material could be applied for the production of high energy physics components working at cryogenic temperature.

Tensile test measurements have been performed at 293 K, 77 K and 4.2 K to determine the behaviour at cryogenic temperatures. The present paper will show that the material keeps its ductility at very low temperatures (4.2 K). Its characteristics will be compared to those of both commercially pure aluminium (Al-1100-O) and Al-2219-T851.

2. EXPERIMENTAL SET-UP

Sheets 1.1 mm thick of DS-Al-550 were supplied by Raufoss. Specimens of 23 mm calibrated length and 2.3 mm^2 cross-section have been machined by spark erosion with their axis parallel and perpendicular to the rolling direction.

Specimens have been measured in a liquid Helium or Nitrogen bath. Two Linear Variable Differential Transformer (LVDT) sensors fixed on the calibrated length of the specimen allow high precision measurements of strain in the early stage of deformation (up to 10%), while in the fully plastic regime the deformation is measured by a carbon potentiometer. The analogue signals of the sensors and the potentiometer are converted by a 16 bit ADC (Analog Digital Converter) and treated by the software LabVIEW from National Instruments on a micro-computer. The high displacement resolution obtained after conversion of the LVDT signals (about 0.5 µm) permits a precise evaluation of the Young's modulus and the yield stress at low temperatures. The effects of possible misalignments of the specimen are corrected by averaging the two LVDT signals. [2]

For each test, the Young's modulus E, the yield strength $R_{p0.2}$, the total elongation ε_{tot}, and the Ultimate Tensile Strength (UTS) are determined. The Young's modulus E is determined by unloading/loading loop evaluated at $\varepsilon = 0.2$ %. This method of E-modulus determination was chosen because DS-Al-550 as well as pure Aluminium show microplasticity in the early stage of deformation.

3. EXPERIMENTAL RESULTS

In figure 1, an example of stress-strain curves for longitudinal specimens measured at 293K, 77K and 4.2K, is shown. The results are summarised in table 1 and figure 2.

The curves show that:

- The UTS increases significantly as the temperature decreases.
- The yield stress increases with the decrease of temperature, as the UTS and E.
- The highest tensile/yield stress ratio is obtained for the lowest temperature.
- The total elongation first increases as the temperature decreases. A reversal of this trend is observed between 77 K and 4.2 K. The final failure is always ductile.

At 4.2K, serrated yield (i.e. instabilities in the stress / strain curve) occurs.

Apart from a low difference in elongation, the mechanical characteristics show a good reproducibility and no significant difference between longitudinal and transverse specimens.

The mechanical properties of commercially pure aluminium Al-1100-O (purity of 99%), taken as a standard of comparison, are given in table 2 for 293 K, 77 K and 4.2 K. Those for Al-2219-T851 are summarised in table 3.

Apart from a higher ductility, the mechanical properties of pure Aluminium are poor compared to DS-Al-550[1] and Al-2219-T851 (See tables 1, 2, 3 and figure 3). The effect of temperature on the ductility of DS-Al-550 and Al-2219-T851 is relevant for low temperatures applications. For both of them, the temperature has less effect on the elongation compared to commercially pure Al-1100-O.

Further insight into the behaviour of DS-Al-550 can be obtained by comparing the $R_{p0.2}$ and the UTS. DS-Al-550 has a yield strength of 490 MPa at 4.2 K, which is eight times higher than commercially pure aluminium and approximately the same as Al-2219-T851 (Figure 3a). The yield strength of Al-1100-O weakly depends on temperature while its UTS has a strong temperature dependence. This is typical for face-centered-cubic (f.c.c.) materials. In contrast for both DS-Al-550 and Al-2219-T851, the ratio of UTS / $R_{p0.2}$ slightly increases with decreasing of temperature, although its value, which is the same for both, is lower than that for the Al-1100-O (figure 4). Below ambient temperature, Al-2219-T851 has a higher rigidity. Nethertheless, the difference in E at 4.2 K is less pronounced than at 293 K (tables 1 and 3). As a final remark, the properties of DS-Al-550 at room temperature are half those of Al-2219-T851, except for the elongation which is similar.

The DS-Al-550 properties are isotropic and significantly improved over the pure aluminium. Its mechanical behaviour as a function of temperature is comparable to Al-2219-T851.

4. DISCUSSION

The mechanical properties of DS-Al-550, considered as a MMC (Metal Matrix Composite), depend on the amount, size, shape and distribution of the dispersed phase (reinforcement), and on the mechanical properties of the matrix material. By definition, a composite material generally implies an amount of dispersed phase >1 vol.% and a particle size >1 µm. According to this definition the DS-Al-550 cannot be considered as a MMC because the reinforcing particles reinforcing have a size of 2-10 nm. Such a size will then merely control the dislocation movement (as the precipitates do in precipitation strengthened Al-alloy) and will not act as a load bearer. However, this pinning of dislocations results in an improvement of the mechanical properties compared to pure Aluminium [3], and in an increase of the work-hardening coefficient ($d\sigma/d\varepsilon$) while the temperature decreases.

5. CONCLUSION

DS-Al-550 shows high mechanical properties at cryogenic temperatures compared to Al-1100-O. Mechanical alloying results in the formation of a reinforced aluminium, initially foreseen for applications at higher temperatures, with good mechanical characteristics in a large temperature range. The DS-Al-550 alloy is comparable to the Al-2219-T851, which is reliable for use at low temperatures since all the important engineering parameters improve as the temperature decreases.

[1] Part of the difference could arise from the difference in amount cold-work between the two alloys.

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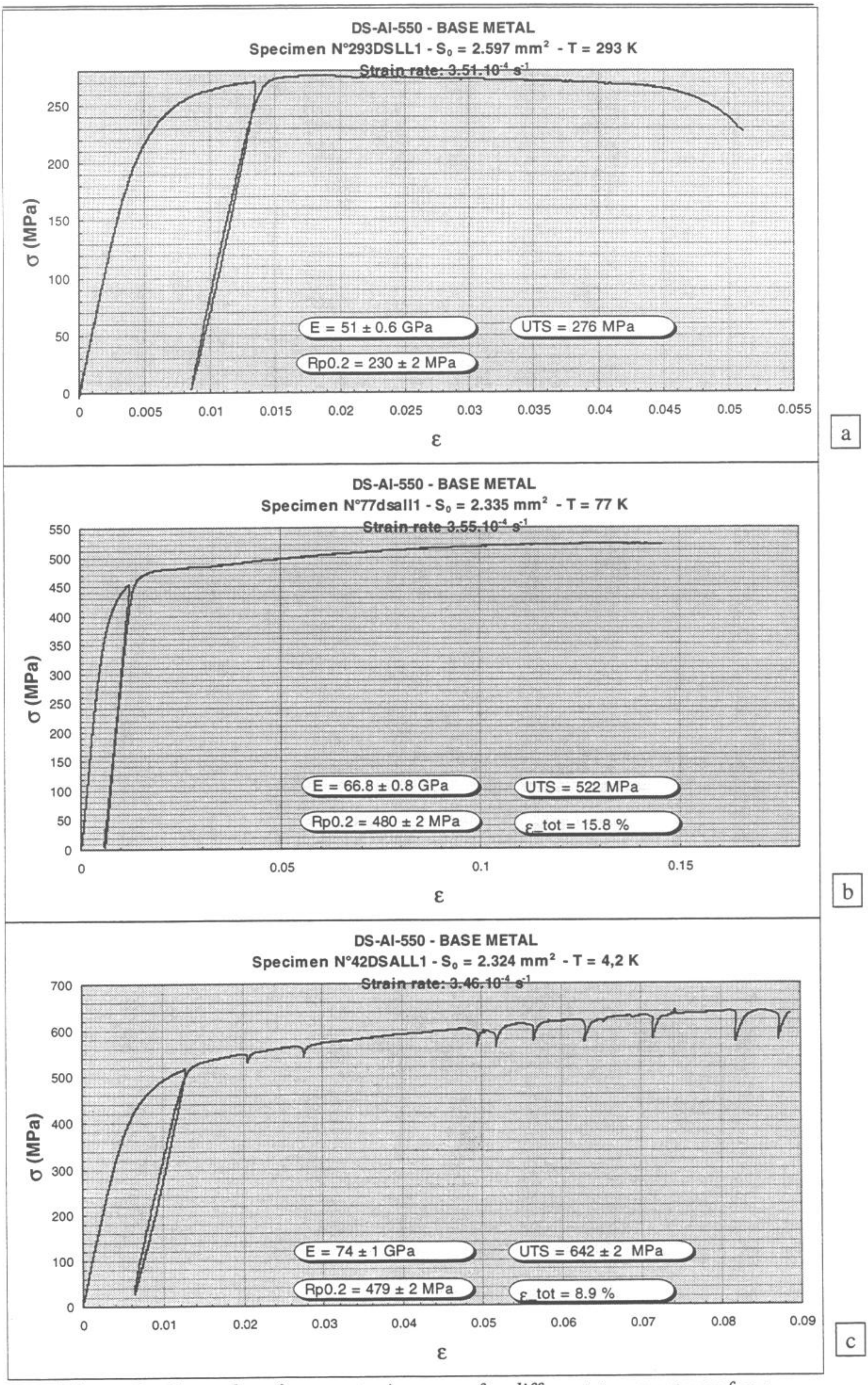

Figure 1 - *Examples of stress-strain curves for different temperatures for a longitudinal sample*

T (K)		Samples	E (GPa)	$R_{p0.2}$ (MPa)	UTS (MPa)	$\varepsilon_{tot.}$ (%)	UTS/$R_{p0.2}$
293K		Transverse	51 [2]	236	270	6	1.1
		Longitudinal	51 [2]	212	276	/	/
	Tests performed by CERN (UTS-200kN-Machine)	*Transverse*	*58*	*286*	*310*	*11*	*1.1*
		Longitudinal	*/*	*282*	*309*	*9*	*1.1*
	Tests performed by QUALIMATEST[3]	*Transverse*	*64*	*278*	*312*	*13.4*	*1.1*
		Longitudinal	*65*	*271*	*310.7*	*/*	*1.1*
77K		Transverse	66.7	411	519	14.4	1.2
		Longitudinal	69.5	415	533	12.5	1.2
4.2K		Transverse	76	481	627	9	1.3
		Longitudinal	75	502	655	10.6	1.3

Table 1 - *Characteristics of DS-Al-550 as a function of temperature*

T (K)	E (GPa)	$R_{p0.2}$ (MPa)	UTS (MPa)	$\varepsilon_{tot.}$ (%)	UTS/$R_{p0.2}$
Test at 293 K	/	41	90	29	2.6
Test at 77 K	/	59	190	42	3.4
Test at 4.2 K	/	59	270	47	4.5

Table 2 - *Characteristics of annealed commercially pure Aluminium 1100-0 as a function of temperature* [5], [6]

T (K)	E (GPa)	$R_{p0.2}$ (MPa)	UTS (MPa)	$\varepsilon_{tot.}$ (%)	UTS/$R_{p0.2}$
Test at 293 K	77.4	367	461	11	1.25
Test at 77 K	85.1	441	571	14	1.3
Test at 4.2 K	85.7	490	666	15	1.36

Table 3 - *Characteristics of Aluminium 2219-T851 as a function of temperature* [4], [6]

2 Approximate values

3 Because of the E-modulus determined with our equipment at 293 K, which was not expected to be so slow, other tests were performed by the company QUALIMATEST [7]

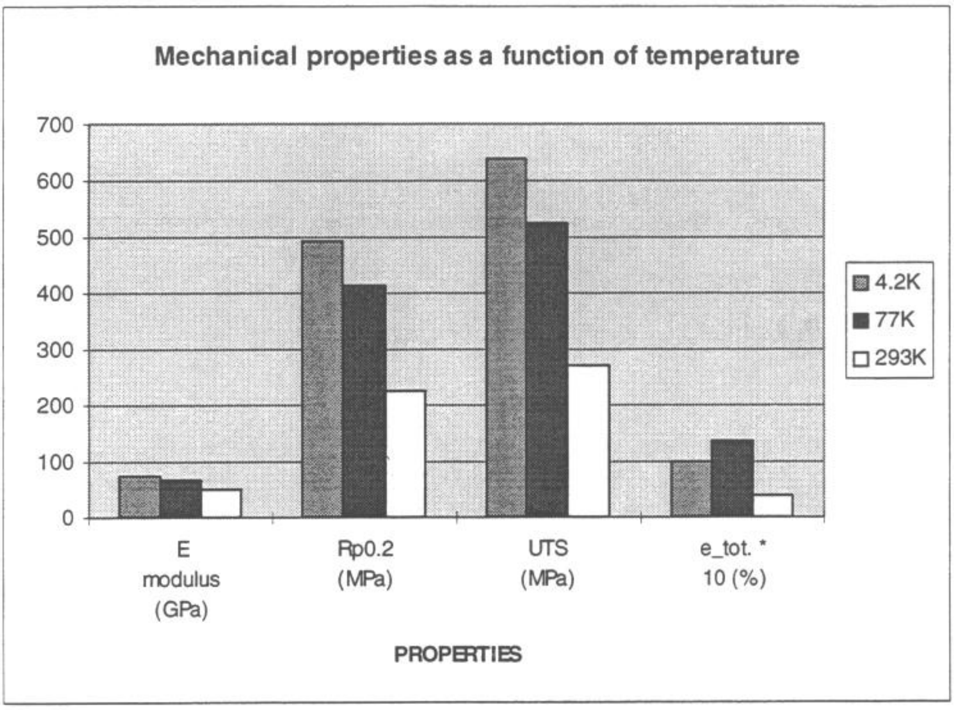

Figure 2 - *Summary of temperature dependence of the mechanical properties of DS-Al-550*

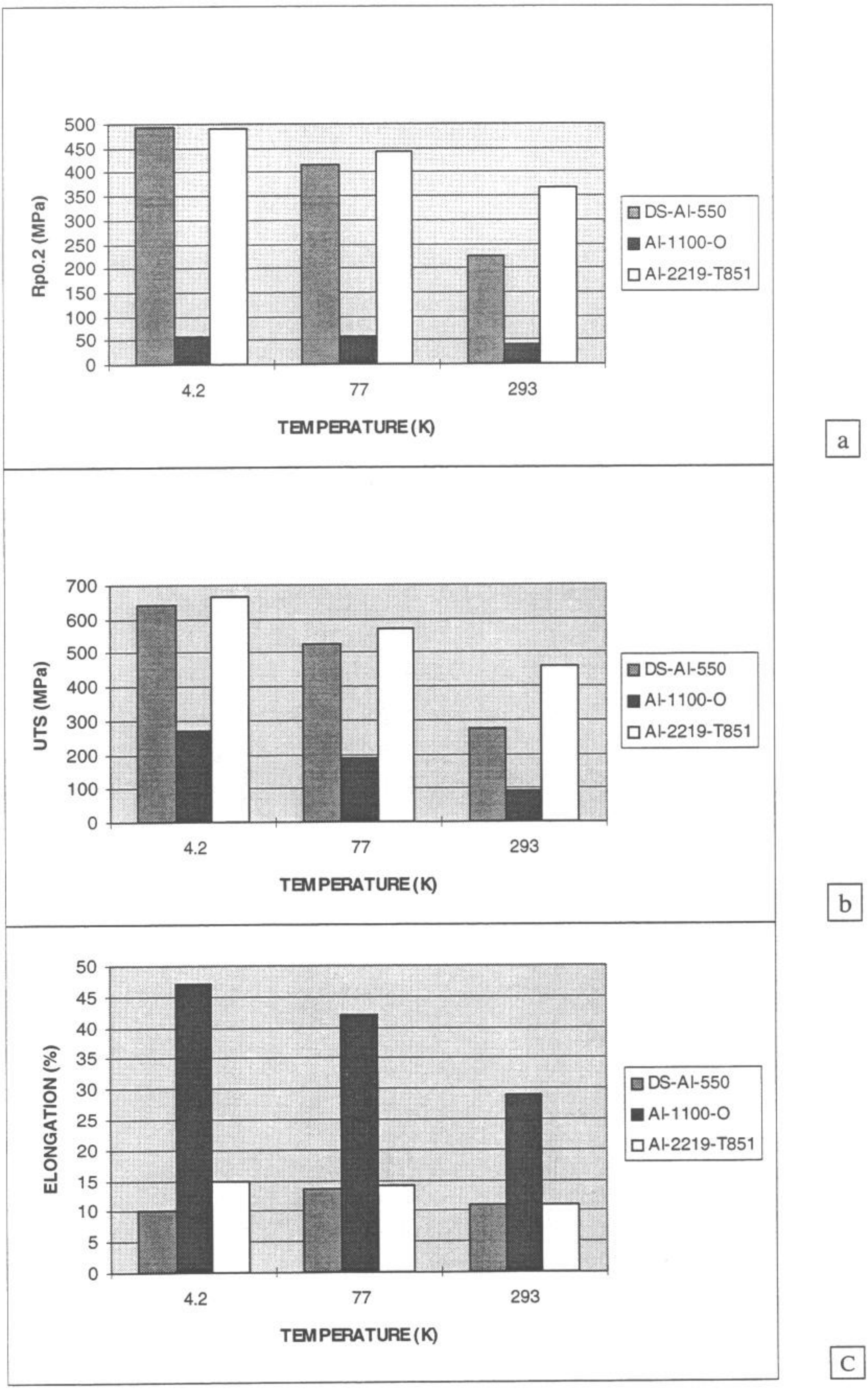

Figure 3 - Compared mechanical properties of DS-Al-550, Al-1100-O, Al-2219-T851

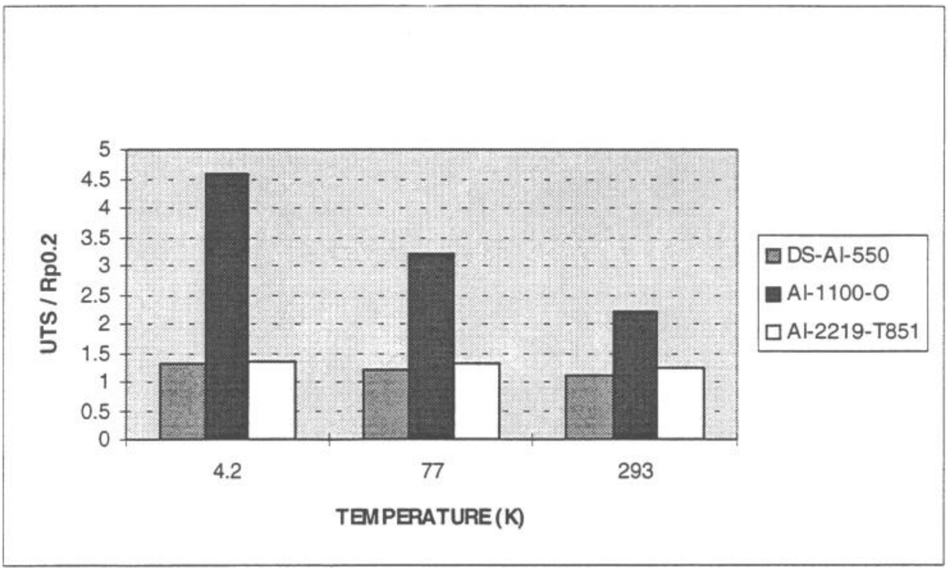

Figure 4 - *UTS / $Rp_{0.2}$ as a function of temperature for DS-Al-550, Al-1100-O, Al-2219-T851*