CHAPTER SIX

Physical Interpretation of the Yield Strength of Mechanically Alloyed ODS Iron Alloys

6.1 Introduction

In Chapter four, an empirical neural network analysis of the mechanical properties of mechanically alloyed iron–base ODS alloys was presented as a function of a large number of variables. The neural network analysis produced models which are non–linear and incorporate interactions between variables. Such models are extremely useful in alloy design and data interpretation, but any model which includes a large number of interacting variables becomes difficult to interpret using the principles of physical metallurgy. This is because the latter are simple in the context of sophisticated industrial alloys, but in some circumstances can nevertheless give great insight and understanding on a level which is easier to picture.

The neural network analysis dealt with the yield and ultimate tensile strength and the elongation. Of these, the yield strength should be the best behaved mechanical property given that the other two rely on complex phenomena related to large degrees of homogeneous and inhomogeneous deformation. The purpose of the work reported in this Chapter was, therefore, to attempt a better *physical* understanding of the yield strength of the mechanically alloyed ODS materials.

MA 956, which is the focus of the present work, is a ferritic MA–ODS steel with the nominal composition Fe–20Cr–4.5Al–0.5Ti–0.5Y_2O_3 wt.%. It is strengthened against creep by a highly stable fine dispersion

of yttrium oxide [Benjamin, 1970; Benjamin and Cairns, 1971]. By conventional standards, this dispersion changes little even as the melting temperature is approached. In the as-extruded condition, the alloy has a microstructure with less than one micrometre grain size and a grain aspect ratio of about 30, while in the recrystallized condition the grain size is about 10–50 μ m and the aspect ratio is about 10 [Alamo *etal.*, 1992]. The yttria particles added to the starting powders react with aluminium and oxygen from the solid solution to form very fine dispersions of mixed (Y, Al) oxides [Cama and Hughes, 1994]. The average dispersoid diameter in the as–extruded condition is about 11 nm [Regle, 1994].

The essential problem which is addressed in this Chapter is the results of neural network analysis, summarised in Figure 6.1 which shows the variation in the yield strength of recrystallised and unrecrystallised MA956 as a function of the temperature. The curves represent a best–fit empirical interpretation of a large quantity of experimental data with the caveat that overfitting has been avoided as explained in Chapter 4. The error bars correspond to $\pm 1\sigma$ and give an indication of the uncertainty in the experimental data as well as the uncertainty in interpretating those data. The major aim of the work presented here is to explain the curves in Figure 6.1 on the basis of strengthening theories.

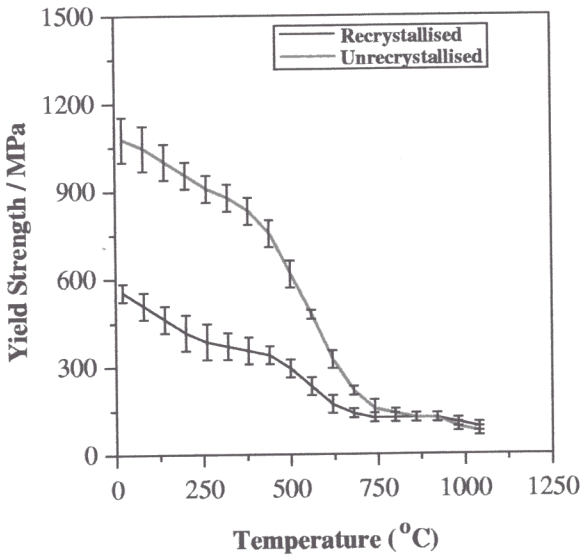

Figure 6.1 : Neural network predictions for the yield strength of the recrystallized and unrecrystallized MA956 [Chapter 4].

6.2 Strength of Recrystallized MA956

It is usual to express the yield strength as a linear combination of contributions from a number of mechanisms using the approximation that these mechanisms are essentially non–interacting:

$$\sigma_y = \sigma_{Fe} + \sigma_s + \sigma_p + \sigma_g + \sigma_d \tag{6.1}$$

where

σ_{Fe}	is the strength of the pure, annealed matrix,
σ_s	is solid solution strengthening,
σ_p	is the particle strengthening,
σ_g	is the grain boundary strengthening,
σ_d	is the dislocation strengthening.

The yield strength σ_{Fe} of pure, annealed iron at room temperature was calculated as in [Young and Bhadeshia, 1994] with the temperature dependence according to the experimental results by Leslie (1972) who studied interstitial–free Ti-gettered iron. Leslie also reported the temperature dependence of solid solution strenghtening by a number of solutes in iron. Although the concentrations he studied did not achieve the levels of interest in the present work, his data for 6 at.% solute were used to obtain the temperature dependence of solution strengthening for each solute. The absolute values of the room temperature solid solution strengthening were obtained from an empirical expression for fully recrystallised ferritic stainless steels (17–25 wt.% Cr) by Lewis and Pickering (1983):

$$\sigma_y = 36 + 8.5(\text{wt.\% Cr}) + 58(\text{wt.\% Mo}) - 107(\text{wt.\% Ti}) + 15.9d^{-\frac{1}{2}} \quad \text{MPa} \tag{6.2}$$

so that $\sigma_s = 8.5(\text{wt.\% Cr}) + 58(\text{wt.\% Mo}) - 107(\text{wt.\% Ti})$ MPa

The negative coefficient for Ti shows some effect of interstitial solutes [Lewis and Pickering, 1983]. Ti removes interstitial solutes as TiC or TiN.

Shewfelt and Brown (1977) modelled dispersion strengthening as a function of temperature assuming that the dislocations remain on their slip planes except when they are able to overcome the obstacles by

climb. Whether or not climb occurs depends on the strain rate and temperature. By comparing theory against experimental data (1974) they obtained

$$\sigma_p = \frac{Gb}{\lambda}\left[(0.51 \pm 0.01) + (0.12 \pm 0.02)\log\left\{\frac{\dot{\epsilon} k T R^2}{4\pi\rho b^2 a_v G\lambda D_o}\right\} + (0.052 \pm 0.009)\left(\frac{Q}{kT}\right)\right] \quad \text{MPa} \tag{6.3}$$

where G is the shear modulus, b is the Burgers vector, D_o is the pre–exponential component of the self–diffusion coefficient of ferritic iron, Q is the activation energy for this self–diffusion coefficient, k is the Boltzmann constant, ρ is the dislocation density, $\dot{\epsilon}$ is the shear strain rate, R is the particle radius, λ is the square lattice spacing of the particles and a_v is the area associated with a vacancy. Table 6.1 shows the values of these parameters for MA 956 and the references where the information is from literature. The value for the particle spacing, λ, has been calculated using an expression by Kelly and Nicholson (1963):

$$\lambda = \sqrt{\frac{2\pi}{3}}\left(\frac{R^2}{f}\right)^{\frac{1}{2}} \tag{6.4}$$

where R is the particle radius, and f is the volume fraction of particles. The area associated with a vacancy was calculated using $a_v = \pi(b/2)^2$.

Table 6.1 : Parameters for the particle strengthening calculation. a is the lattice parameter of ferrite, taken as 2.87 Å

Parameter	Value	Reference
Shear modulus, G^*	80 GPa	Ubhi *et al.*, 1981
Burgers vector, b	$a\sqrt{\frac{3}{4}} = 2.485$ Å	-
Particle radius, R	5.695 nm	Regle, 1994
Dislocation density, ρ	10^{15} m^{-2}	Little *et al.*, 1991
D_o of α–Fe	5×10^{-5} m^2 s^{-1}	Honeycombe and Bhadeshia, 1995
Activation energy, Q	240000 J mol^{-1}	Honeycombe and Bhadeshia, 1995

The calculated components of strength are given in Table 6.2 and are illustrated as functions of temperature in Figure 6.2a for recrystallised MA956. It is seen that the major contribution is from the

to float off. The remaining particles coagulate and segregate making them ineffective as strengthening dispersoids†. At the same time, the other strengthening terms are unaffected by this procedure when the comparison is with a recrystallised MA956 sample.

Arc melting might seem a drastic method to eliminate dispersoid strengthening. It is nevertheless necessary because the yttria is added because of its stability in iron. Attempts to coarsen the dispersion would not only be ineffective but also unconvincing in the present context.

Figure 6.3 shows the optical microstructures and TEM of the replicas of the samples before melting and after melting. The optical micrographs show that the grain sizes of the two samples are comparable whereas the replica images show that the experiment has been successful in removing fine dispersoids from the melted sample. This is reflected in the measured hardness values which were found to be in the range 248–253 HV (mean 251 HV) and 188–196 HV (mean 192 HV) for the unmelted and melted samples.

† This is why yttria is not incorporated into the alloy by melting, but by mechanical alloying.

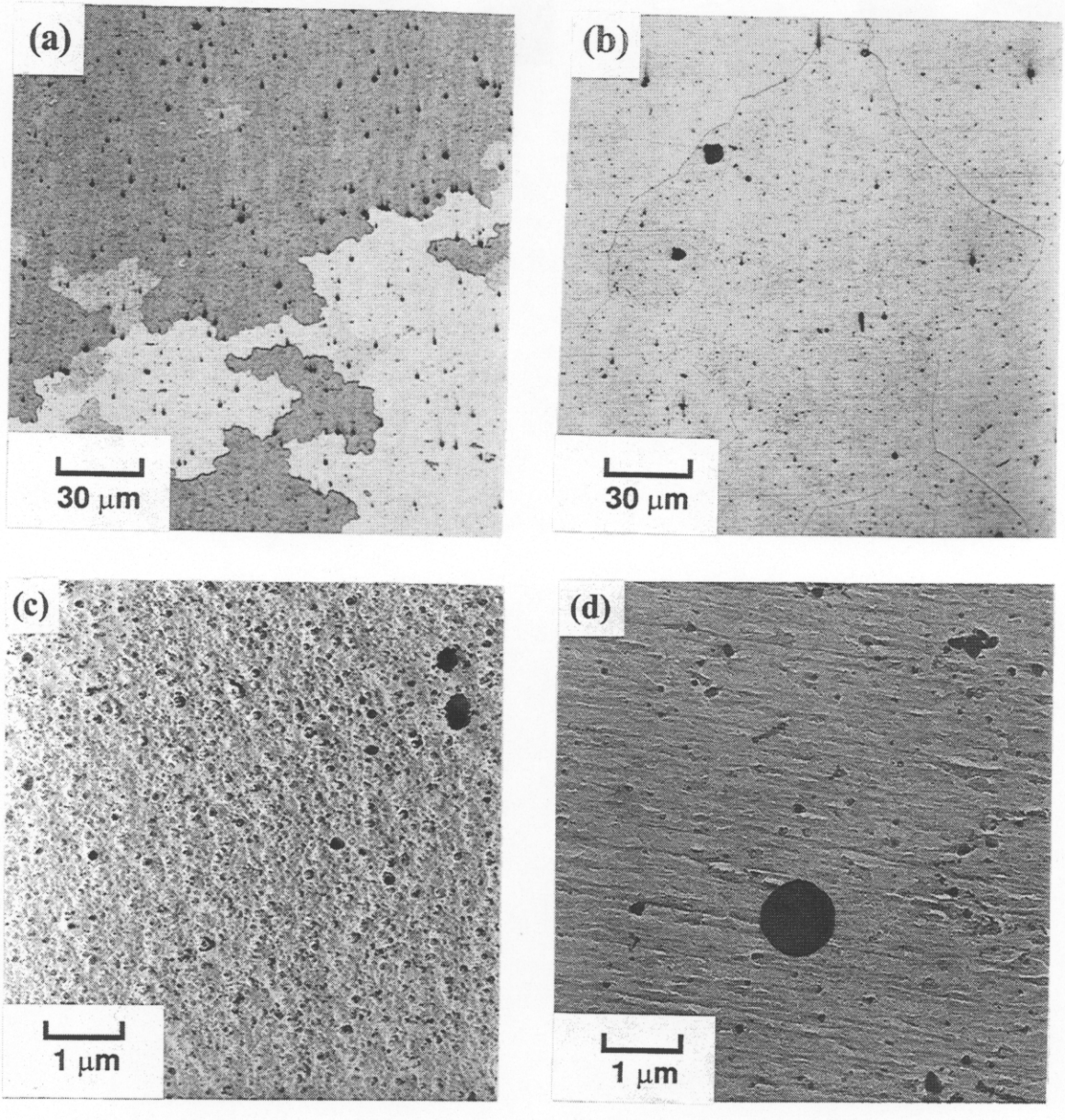

Figure 6.3: Optical micrographs of the samples of MA956 (a) before and (b) after melting. Corresponding TEM replica images of the samples of MA956 (c) before and (d) after melting.

Nominal stress/nominal strain curves are presented in Figure 6.4 which show that there is a reduction of 250 MPa in the yield strength for the melted sample. This is in remarkable agreement with the calculated room temperature particle strengthening of 248 MPa, giving confidence in the model†

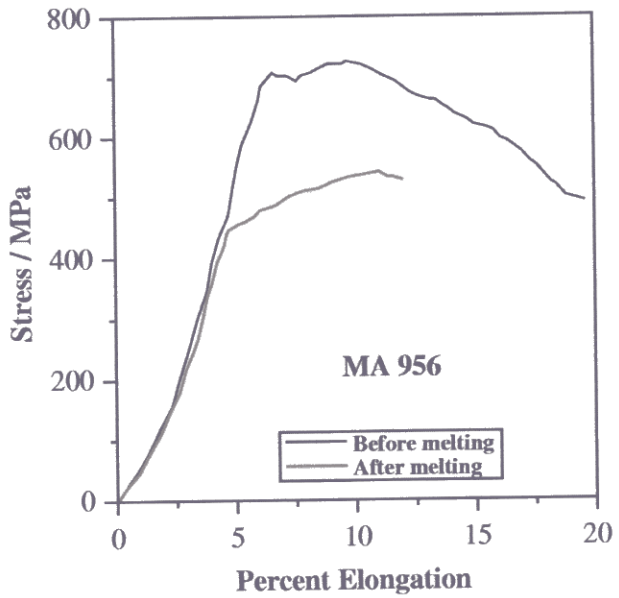

Figure 6.4 : Tensile properties of MA956 before melting and after melting.

6.4 Unrecrystallized MA956

There is a remarkable difference in the grain size of recrystallised MA956 (about 10 mm) and the unrecrystallized alloy which has grains less than one micron diameter. Grain size must therefore represent the major component of the reduction in strength following a recrystallisation heat treatment. If this is the case then the strength of the unrecrystallized MA956 is simply that of the recrystallized sample and the grain boundary strengthening.

This assumption can be verified by comparing calculated grain size strengthening values with the measured difference between the strength of the recrystallized and unrecrystallised MA956 as manifested in

† The incidental observation that a larger elongation is observed in the unmelted sample is because the melted sample fractured eventually by a cleavage mechanism. The reason for this has not been investigated in detail.

the neural network analysis [Chapter 4]. The Hall-Petch [Hall, 1951; Petch, 1953] relation is expressed as:

$$\sigma_g = k_o d^{-\frac{1}{2}} \tag{6.5}$$

where k_o is a constant which is a measure of the grain boundary resistance and d, is the grain size. According to equation 3, the value of k_o for ferritic stainless steels is $15.9\text{MPa}\,\text{mm}^{-\frac{1}{2}}$ [Lewis and Pickering, 1983].

Although the grain size strengthening can be calculated using the Hall–Petch relation, there is no adequate theory for its temperature dependence. We have therefore estimated the temperature dependence using the neural network model and the assumption that the difference between the recrystallised and unrecrystallised samples is essentially due to the respective grain structures. The ratio of the difference relative to that at room temperature was used to scale the results according to equation 6.5.

Figure 6.5 shows the calculated yield strength of the unrecrystallized MA956 as a function of the grain size in the range 0.5–1.0 μm. As before, the results are compared against the neural network interpretation of the experimental data. The yield strength can be explained rather well with the grain size set at about 0.9 μm.

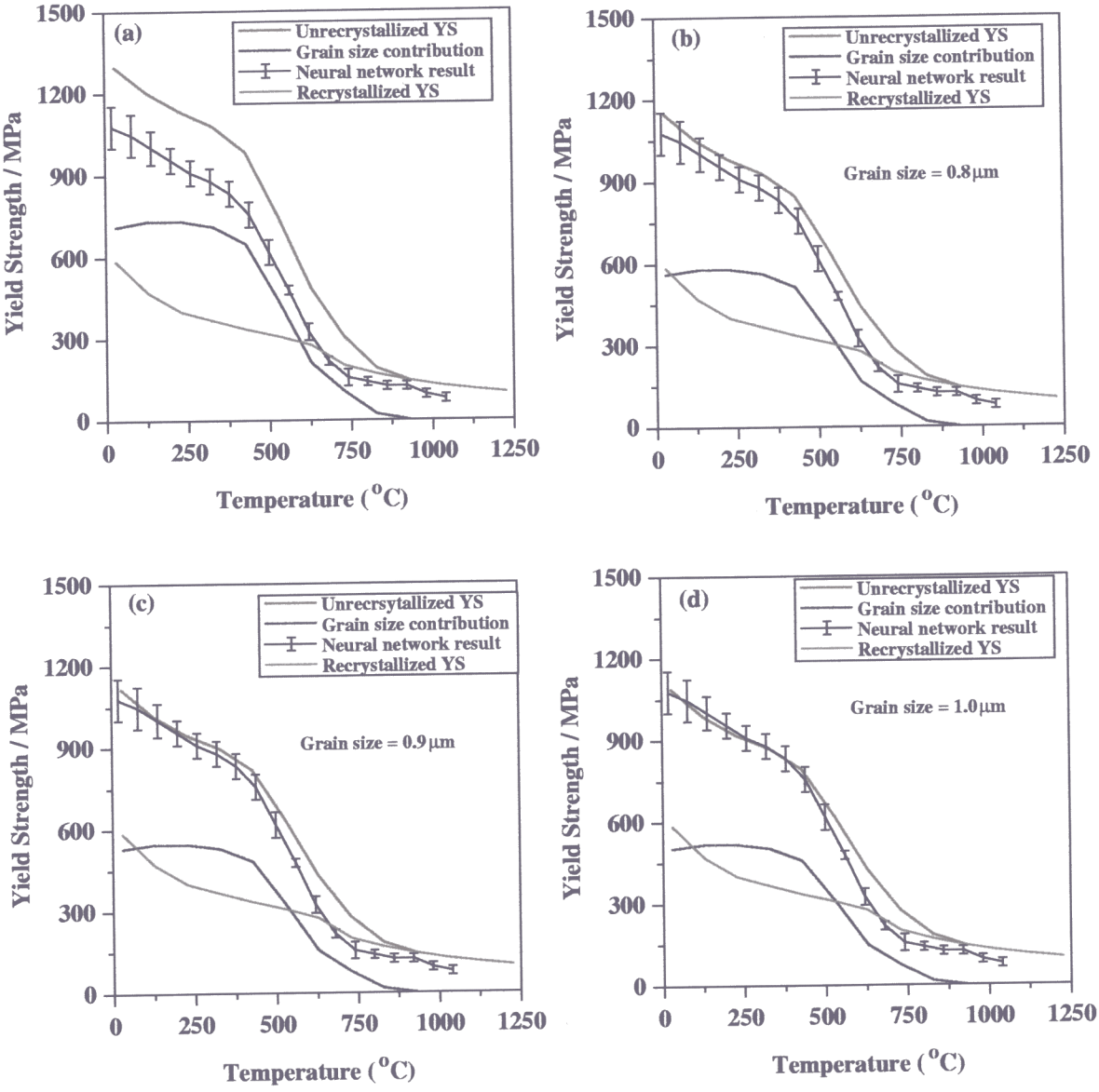

Figure 6.5 : Calculated yield strength of unrecrystallized MA956 using different grain sizes and compared with the neural network results. The plots are for grain sizes (a) 0.5 μm, (b) 0.8 μm, (c) 0.9 μm and (d) 1.0 μm.

There is a slight increase in grain size strengthening with temperature over the range 30–300 °C. This increase may not be significant given the uncertainty in the experimental data as apparent in the error bars, but it could be a consequence of strain ageing associated with the small concentration of interstitial carbon in MA956. A similar effect is found in the temperature dependence of the strength in ordinary ferritic steels [Tapsell, 1931].

The more significant decrease in the contribution from grain size strenghening occurs at higher temperatures. For austenitic steels, the reduction in grain size strengthening with increasing temperature has been associated with a weakening of dislocation locking effects at grain boundaries [Rao *etal.*, 1975]. This might apply to MA956, but a more likely explanation is that there is dynamic recrystallisation accompanying deformation at high temperatures. This has been observed experimentally by Chou and Bhadeshia [Chou and Bhadeshia, 1995] during the hot deformation of MA956 and MA957 (another ODS mechanically alloyed ferritic stainless steel). The dynamic recrystallisation could be observed even when the deformation temperatures was far less than the ordinary recrystallization temperature of the alloys. This would also explain why the grain size contribution remains constant until about 500 °C, because grain boundaries are not expected to be able to migrate until the iron and substitutional atoms acquire sufficient mobility.

To assess this, the grain sizes necessary to explain the reduction in the strengthening contribution σ_g were calculated from the difference between the recrystallised and unrecrystallised alloy strengths as a function of temperature (Figure 6.6). The grain sizes estimated for all cases are seen to be quite reasonable in the sense that a fully recrystallised microstructure will have grains some 10–50 μm in size [Alamo *etal.*, 1992].

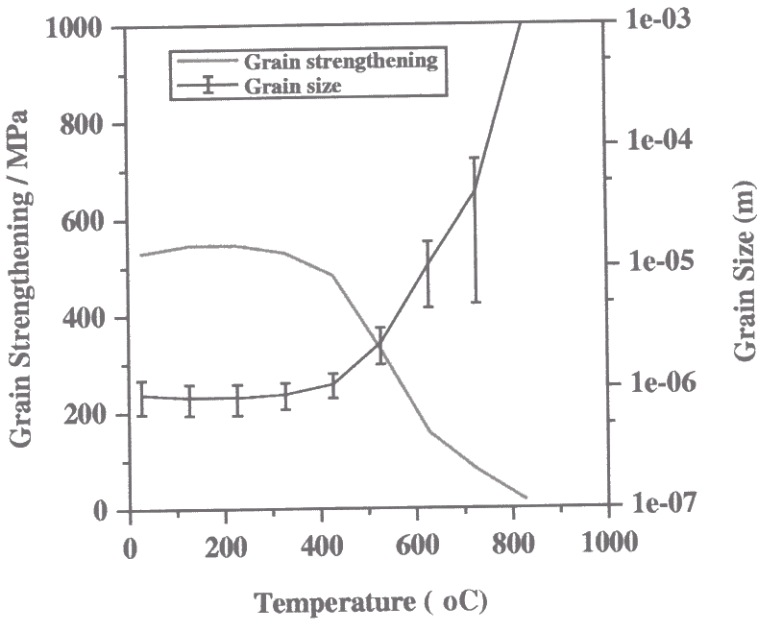

Figure 6.6 : Grain strengthening and estimated grain size of samples of MA956 which are unrecrystallized prior to testing as a function of temperature.

6.5 Summary

The ambient temperature yield strength of mechanically alloyed MA956 in the as–processed condition originates from its ultra–fine grain size, the intrinsic strength of ferritic iron, dispersoid strenthening via the yttria compounds and finally, the dislocation density. The contributions of these components decrease in the order stated. The dispersoids contribute only about 250 MPa, but it is emphasized that their prime purpose is to provide creep resistance, a property not discussed here.

Recrystallisation has the effect of virtually eliminating grain size strengthening but leaving the other contributions essentially unchanged.

The temperature dependence of the strength has also been estimated. The relatively sharp decline in the strength in the recrystallised condition beyond about 500 °C replicates the decrease in the strength of iron. It is believed that a further large temperature dependence in the case of the unrecrystallised sample comes from dynamic recrystallisation during testing which reduces the grain size contribution to strength.

Finally, it is interesting that we have used our earlier neural network analysis of a vast quantity of published data to validate the physical models. Mechanically alloyed materials are notorious in their variability so this is a good method of providing an assessed experimental datum. Furthermore, the network provides estimates of uncertainty in the experimental data which are useful in the validation excercise.

CHAPTER SEVEN

Conclusions and Further Work

7.1 Conclusions

A variety of studies have been conducted into the mechanical alloying process and the tensile properties of the mechanically alloyed oxide dispersion strengthened superalloys, with some fascinating results.

A model has been developed to deal with a situation in which a solution is created by continuously refining a mixture of powder particles of the pure components as in mechanical alloying. It is predicted that solution formation by the mechanical alloying of solid components cannot occur unless there is a gain in coherency as the particles become small. The inclusion of interfacial energy also predicts the existence of a barrier to the evolution of the solution. For cases where like atoms tend to cluster, it is possible in principle to obtain a metastable state before solution formation is completed.

A neural network technique trained within a Bayesian framework has been applied to the analysis of the yield strength, ultimate tensile strength and percent elongation of mechanically alloyed oxide dispersion strengthened ferritic steels as functions of variables which are known to influence mechanical properties. The analysis has produced patterns which are metallurgically reasonable, and which permit the quantitative estimation of mechanical properties together with an indication of confidence limits.

The components of the yield strength of a mechanically alloyed oxide–dispersion strengthened iron–base superalloy, MA956, have been investigated quantitatively. It is found that much of the difference in strength between the recrystallised and unrecrystallised forms can be explained in terms of the grain structure. The contribution from dispersion strengthening has been estimated using dislocation theory and has been demonstrated to be consistent with that measured experimentally. The temperature

dependence of the yield strength has also been studied; some of the effects observed in the range 500–600 °C can be attributed to the change in the intrinsic strength of pure, annealed iron.

7.2 Further Work

The thermodynamic treatment of the evolution of solutions in mechanical alloying is at present qualitative. The model could be applied to specific alloy systems where the interatomic interactions are used.

The neural network models produced are based on the data available in the literature which at moment are not very exhaustive, as more data become available the analysis will be repeated periodically to ensure that the models are firmly based and reliable. In the present state, the models have been shown to reproduce experimental results reasonably well, attempts will be made to use the models in the design of new alloys.

Only the tensile properties of the iron–base MA–ODS alloys have been analysed. Neural network analysis of the creep properties of the iron–base alloys will be conducted and similar analysis will be made for the tensile and creep properties of the nickel–base alloys.

The physical interpretation of the yield strength of MA956 shows that the temperature dependence of the yield strength of MA–ODS alloys in the as-extruded condition is to a large extent, dominated by dynamic recrystallization and grain growth. It is necessary to investigate the kinetics of the recrystallization and grain growth in order to understand the stress versus temperature relationship as it affects the phenomena.

Finally, we are no further in understanding the anisotropic mechanical behaviour in MA–ODS alloys which must be related to the deformation processing and consequent dispersoid alignment combined with crystallographic texture issues.

APPENDIX ONE

Effect of Grain Structure on the Creep Properties of MA956

A1.1 Introduction

Chou and Bhadeshia, (1993), determined that most of the stored energy of an alloy like unrecrystallized MA956 is in the form of grain boundaries and that the stored energy is so large that moving grain boundaries can easily overcome any drag from the particle dispersion. Furthermore, the alignment of oxide particles along the extrusion direction would lead to the development of a columnar recrystallized grain structure. They proposed and verified that a reduction in the stored energy via some process before recrystallization would lead to a more isotropic grain structure. This is because the grain velocity along the extrusion direction would be reduced. The objective of the work reported here was to see whether a more isotropic recrystallized structure improves the stress-rupture properties of MA956, especially the relatively poor transverse properties.

Various heat treatments procedures were employed in order to systematically vary the grain size and shape. In addition to the conventional recrystallization heat-treatment for the alloy, two other experimental heat-treatments were investigated. The latter involved the control of stored energy before recrystallization by "preannealing" the alloy at a temperature high enough to permit recovery but not recrystallization. The heat-treatments are described in Table A1.1. The heat-treatments were performed in air prior to the machining of test specimens for the stress-rupture tests.

Table A1.1 : Heat-reatments investigated for grain structure control.

Class	Type	Detail
A	Conventional	Recrystallization at 1315 $°C$ for 50 min
B	Experimental	Preannealing at 1050 $°C$ for 455 h + Recrystallization at 1315 $°C$ for 20 min
C	Experimental	Preannealing at 1100 $°C$for 150 h + Recrystallization at 1300 $°C$ for 15 min

A1.2 **Results and Discussions**

A1.2.1 *Structure*

The microstructures of the samples due to the different heat-treatments are shown in Figure A1.1 for sections taken parallel and transverse to the extrusion direction. The conventional heat-treatment A has led to a complete recrystallization with a coarse and uniform columnar grain structure. The experimental heat-treatment B produced refined elongated grains which are distributed non-uniformly within the structure, whilst the experimental heat-treatment C has produced a structure which is composed of elongated grains which are finer than the A–structure but coarser than B and are uniformly distributed within the structures. The longer preannealing time in B relative to C produced a higher reduction in stored energy and consequently, the driving force for recrystallization is lower in B than C. However, the persistent anisotropic grain shape suggests that stored energy is probably not the only controlling factor. The reduction in the stored energy can reach a level where the microstructure becomes sensitive to any inhomogeneous distribution of particles and the grain size begins to be limited by Zener pinning, as the pinning force becomes comparable to the driving force for grain boundaries migration [Chou and Bhadeshia, 1993]. This may explain the non–uniform structure in B.

A1.2.2 *Hardness Values*

The results of the hardness measurements are shown in Table A1.2. The samples are identified by heat–treatment (A, B or C), orientation with respect to the extrusion direction (L for longitudinal, T for transverse) and the sample serial number. As expected, there is no significant variation between the samples as a function of heat–treatment or plane of section. After all, the observed variation in grain structure is not very large and hardness tests, because of their 3–dimensional nature, are unlikely to be sensitive to the plane of section.

Table A1.2 : Vickers Hardness values of MA956 for different heat-treatment conditions.

Heat-Treatment	Specimen	Hardness (VHN)
A	AL1	261
	AL2	258
15 min / 1315 °C	AT1	265
B	BL1	258
455 h / 1050 °C	BL2	257
+ 20 min / 1315 °C	BT1	246
C	CL1	269
160 h / 1100 °C	CL2	241
+ 15 min / 1300 °C	CT1	264

A1.2.3 *Stress-Rupture Properties*

The stress–rupture properties of MA956 are summarized in Table A1.3. The number of hours at stress before failure are indicated below the respective stresses of 38, 48, 59, 69 and 79 MPa. Samples with a minimum of 24 hours life at 48 MPa are reckoned commercially as having passed. Where a sample was not tested at a particular load, it is indicated by NT. There are four results for each of the heat–treatments samples stressed in the longitudinal direction, and two in the transverse dirction.

The stress–rupture properties measured along the transverse direction are poor compared with the

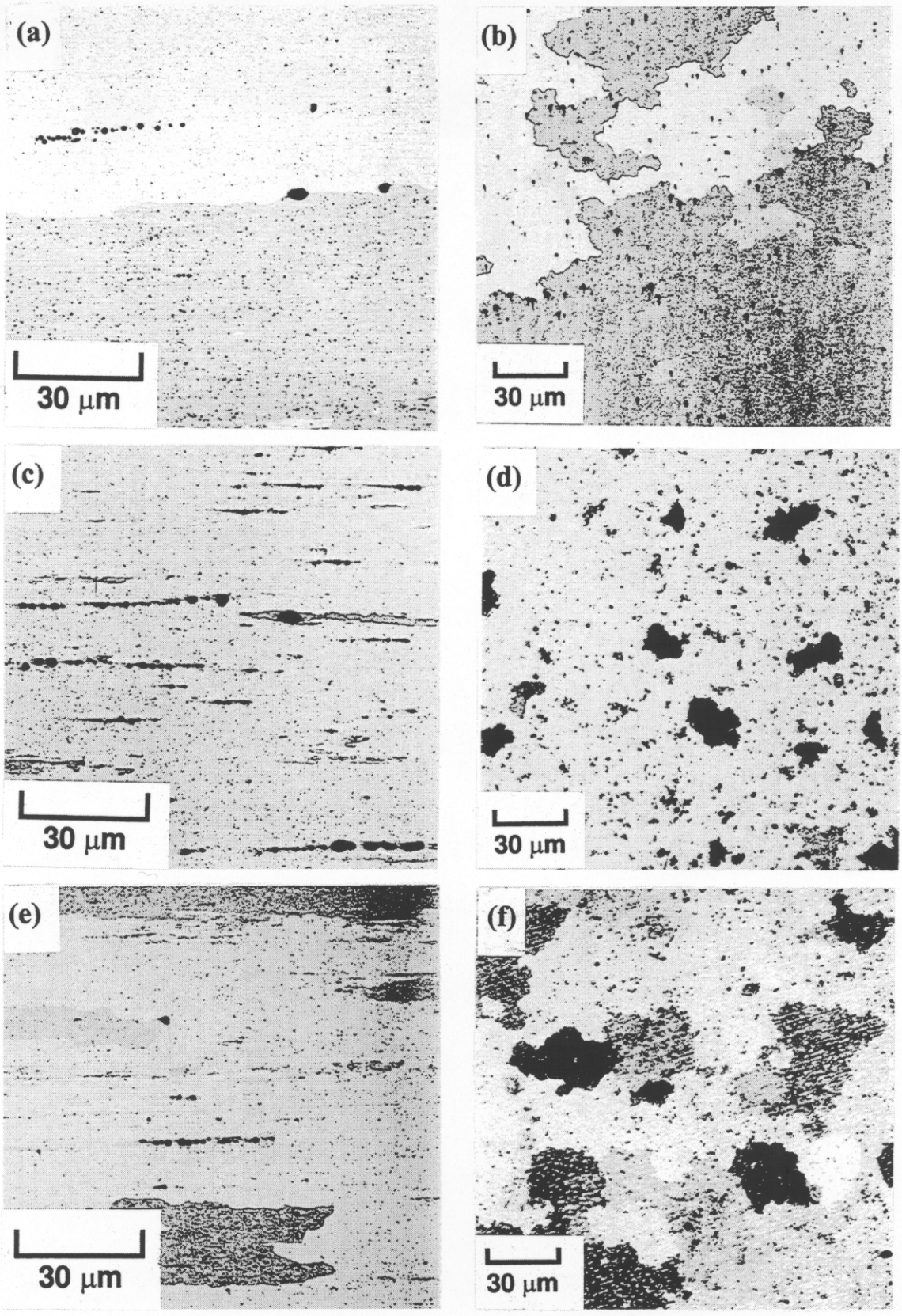

Fig. A1.1: Microstructures of sections parallel and transverse to the extrusion direction after heat-treatment. (a), (c) and (e) longitudinal sections after heat-treatments A, B, and C respectively (b), (d) and (f) transverse sections after heat-treatment A, B, and C respectively.

longitudinal samples for all the test conditions. The properties are generally better for the conventionally heat-treated samples. Heat-treatment C produced the worst effect on the stress-rupture strength of the alloy but with improved the transverse creep ductility. The refinement of the grains in the structure by the experimental heat-treatments B and C reduces the grain aspect ratio of the grains and have produces poorer stress-rupture properties. However, the refinement has not led to an equiaxed grained structure hence there is no significant improvement in the transverse stress–rupture strength.

Table A1.3 : Stress-rupture properties of MA956 alloy and the different heat-treatment conditions.

Heat-Treatment	Specimen	Hours at various Stresses					Elongation	Remark
		38 MPa	48 MPa	59 MPa	69 MPa	79 MPa	(%)	Pass or Fail
A	AL1	24	24	24	8	0	10.4	Pass
	AL2	24	24	24	24	3	11.7	Pass
15 min / 1315 °C	AL3	24	24	24	100	-	9.0	Pass
	AL4	24	24	24	24	83	7.4	Pass
	AT1	0	0	0	0	0	2.1	Fail
	AT2	0	0	0	0	0	1.9	Fail
B	BL1	24	24	24	6	0	14.9	Pass
	BL2	24	24	24	5	0	7.6	Pass
455 h / 1050 °C	BL3	24	24	24	4	0	11.5	Pass
+	BL4	24	24	24	0	0	16.1	Pass
20 min / 1315 °C	BT1	0	0	0	0	0	3.3	Fail
	BT2	0	0	0	0	0	3.0	Fail
C	CL1	24	3	0	0	0	5.8	Fail
	CL2	17	0	0	0	0	4.3	Fail
160 h / 1100 °C	CL3	24	24	24	1	0	9.1	Pass
+	CL4	24	24	24	24	0	10.2	Pass
15 min / 1300 °C	CT1	0	0	0	0	0	3.7	Fail
	CT2	0	0	0	0	0	14.9	Fail

Pronounced delamination was observed in one of the experimental transverse samples, CT2 (Figure A1.2). The delamination occurred over about 10 mm along the length of the specimen and the cracks

Fig. A1.2 : Optical micrograph of the section through delaminated region on sample CT2.

contained particles which were analysed using energy dispersive X–ray (EDX) microanalysis method (Figure A1.3). Some of the contents of the cracks are simply large regions of the alloy which have become detached during the delamination process. However, a large number of the particles which imaged brightly in the scanning electron microscope were aluminium rich, perhaps alumina. Alumina is an insulating phase and would therefore tend to charge up during scanning electron microscopy and hence appear bright (Figure A1.3).

A1.3 *Summary*

The original notion that the transverse rupture properties might improve with the refinement of grain structure, or with a decrease in the anisotropy of grain structure (Chou and Bhadeshia, 1993) appears incorrect. After all, heat-treatments *B* and *C* gave generally the worst stress-rupture properties in all the test orientations.

The results can in fact be understood if the grain boundaries which are normal to the stress axis become particularly susceptible to oxidation. There is an established phenomenon known as "stress-assisted grain boundary embrittlement by oxygen" (Smith *et al.*, 1980 and 1984; Bricknell and Woodford,

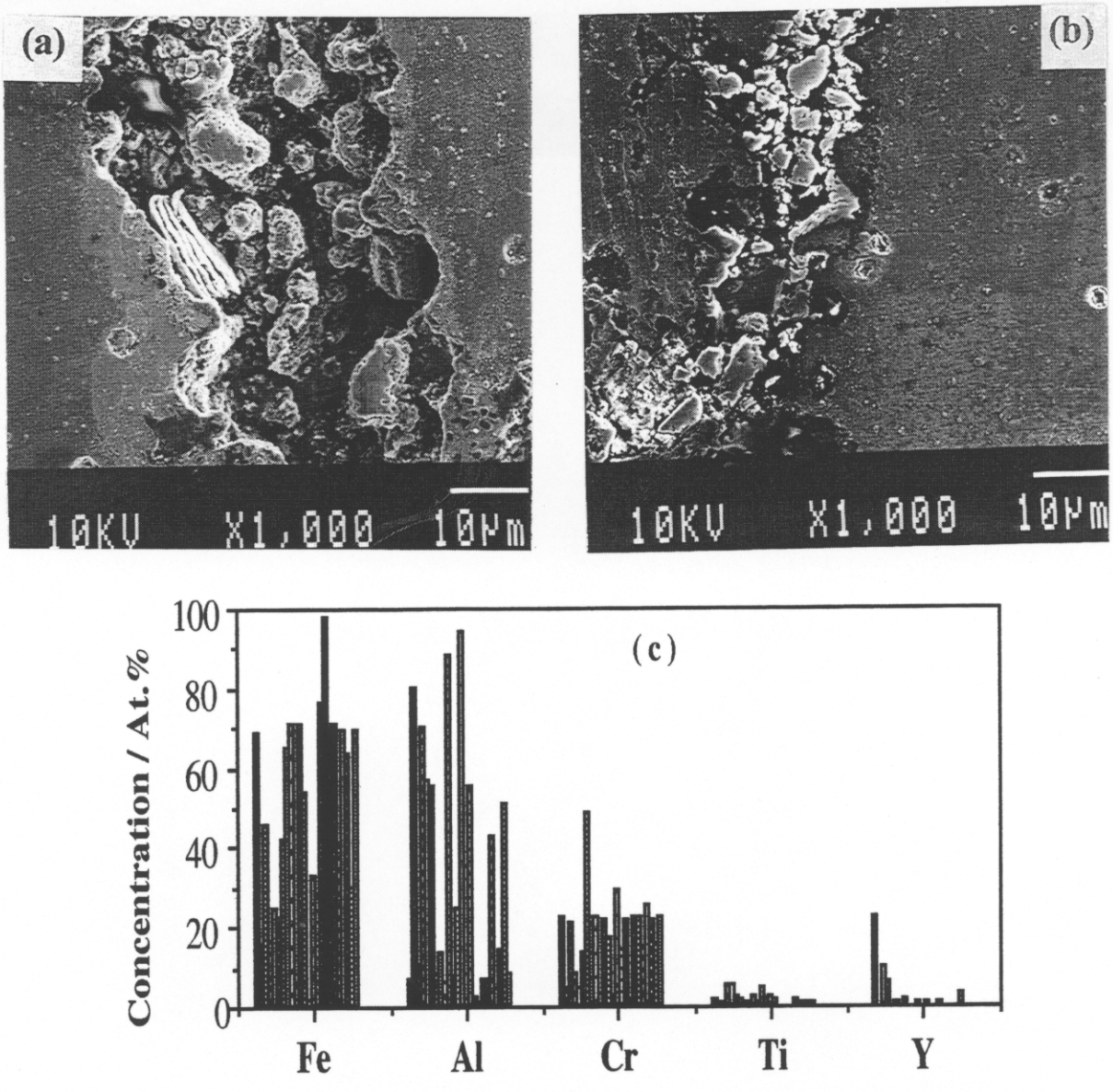

Fig. A1.3 : Scanning electron micrograph of the delaminated sample CT2 and the energy dispersive X-ray analysis of the particles. (a) particles which are chunks of matrix metal, (b) typical particles with high aluminium concentration and (c), EDX analysis of a number of particles chosen at random.

1981). The ODS alloy studied here should be particularly susceptible to oxygen effects because of the high concentration of aluminium which has a strong affinity for oxygen. When a sample is tested parallel to the columnar grains, the amount of grain surface normal to the stress axis should be minimal. Consequently, failure during a stress-rupture test should involve considerable ductile deformation. There should exist a high probability for the formation of alumina films at the grain boundaries for tests in which the stress is applied perpendicular to the columnar grains. This would lead to premature failure

with little plastic deformation. This theory is illustrated schematically in Figure A1.3. The hypothesis is consistent with the observation of substantial alumina particles at the cracks in the failed transverse samples, although this may have occurred after failure.

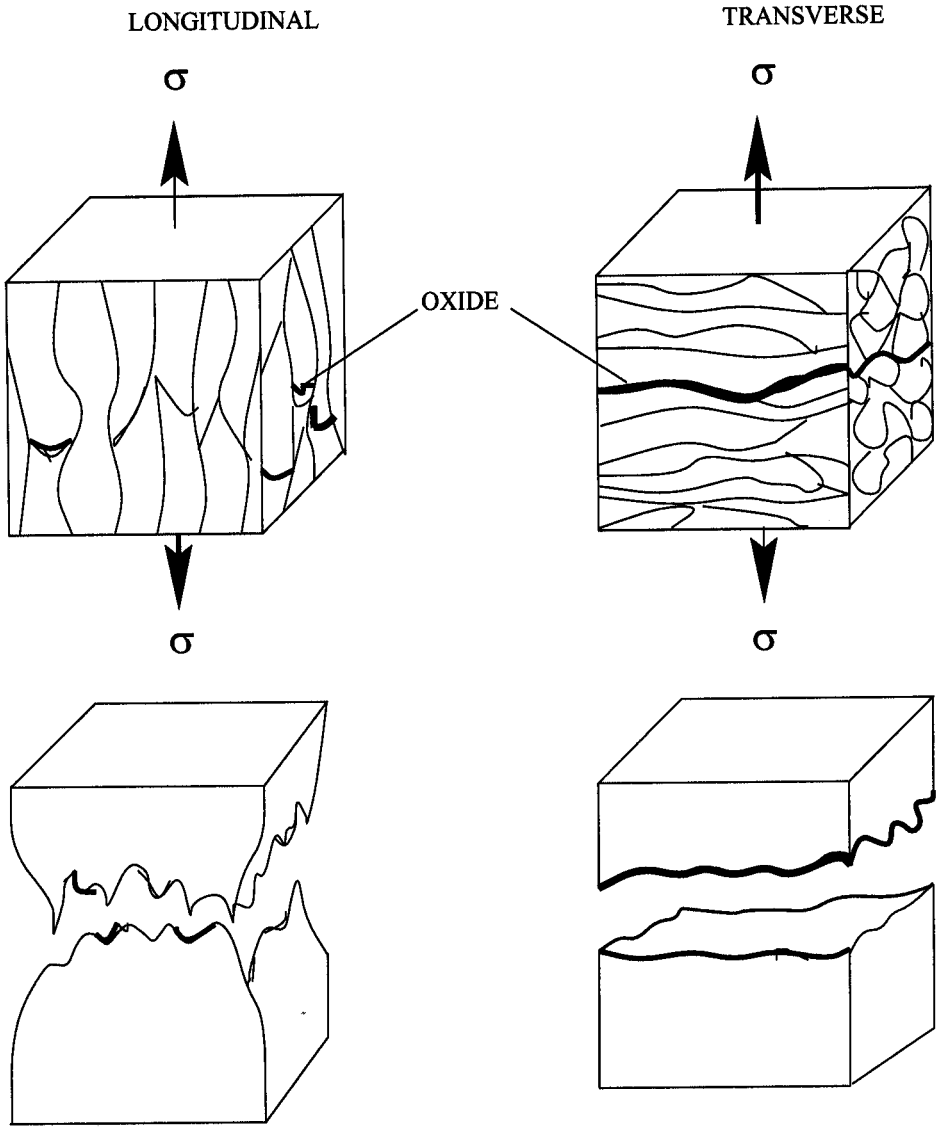

Fig. A1.3 : Schematic illustration of the effect of stress versus grain-boundaries relation on the "stress-assisted grain boundary embrittlement by oxygen".

APPENDIX TWO

Grain Boundary Oxidation in MA-ODS Alloys

A2.1 Introduction

The observation of aluminium–rich particles in the cracks in a delaminated stress–rupture specimen (Appendix 1) prompted a further investigation on possible grain boundary oxidation in mechanically alloyed ODS metals. A nickel–base ODS alloy (MA758, Table 1.1) was used to investigate this phenomenom. MA758 is a nickel–base mechanical alloy without γ' strengthening. It is the higher-chrominum version of MA754 (Table 1.1), the first mechanically alloyed ODS superalloy to be produced on a large scale. MA758 was developed for applications in which the higher chromium content is needed for greater oxidation resistance. Its mechanical properties are comparable to those of MA754. The alloy is used in metal processing industry and in the glass-processing industry. Variants of the alloy exist with difference only in their aluminium concentrations. MA758 with 0.36 wt.% Al has been found to fail in service by cracking. The work reported here deals with two variants of MA758 having different aluminium contents.

A2.2 Experimental Procedures

Two forms of MA758 alloy; one containing 0.36 wt.% Al and the other 0.22 wt.% Al were provided by INCO Alloy. The sample with 0.36 wt.% Al was a failed nozzle while the 0.22 wt.% Al sample was in the form of a round bar in a recrystallised condition. The nozzel is produced by forging the recrystallized alloy. The recrystallization heat–treatment is by zone annealing whereby a hot zone is passed along the bar and recrystallization takes place under the influence of a temperature gradient.

intrinsic strength of iron. Although this intrinsic resistance to dislocation motion becomes smaller at high temperatures, it never vanishes but reaches a limiting value known as the athermal resistance [Seeger, 1954]. The athermal resistance arises from the long–range stress fields of obstacles. Fluctuations caused by thermal vibrations are important over distances of the order of a few atoms and hence cannot assist the dislocations to overcome any fields which extend over large distances. This is why the strength of the iron does not tend to zero with increasing temperature (Figure 6.2a).

The next largest contributions to the overall strength come from the dispersoids and solid solution strengthening. These contributions naturally depend on the particle characterisitics and solute concentrations respectively so it is not possible to make general comments about their magnitudes.

Table 6.2 : Calculated yield strength of recrystallized MA956

Temperature / °C	Y.S. of pure iron / MPa	Solutes contribution / MPa	Dispersoids contribution / MPa	Total Y.S. / MPa
27	216	116	248	580
127	158	113	193	465
227	144	92	160	396
327	144	80	139	362
427	144	63	123	330
527	144	48	112	304
627	129	39	103	271
727	72	32	95	199
827	52	26	89	168
927	38	21	85	144
1027	28	17	80	125
1127	20	14	77	111
1227	15	11	74	100

Figure 6.2b shows the comparison of the calculated yield strength with the experimental data as represented by the neural network estimates (Chapter four). The agreement is impressive indicating

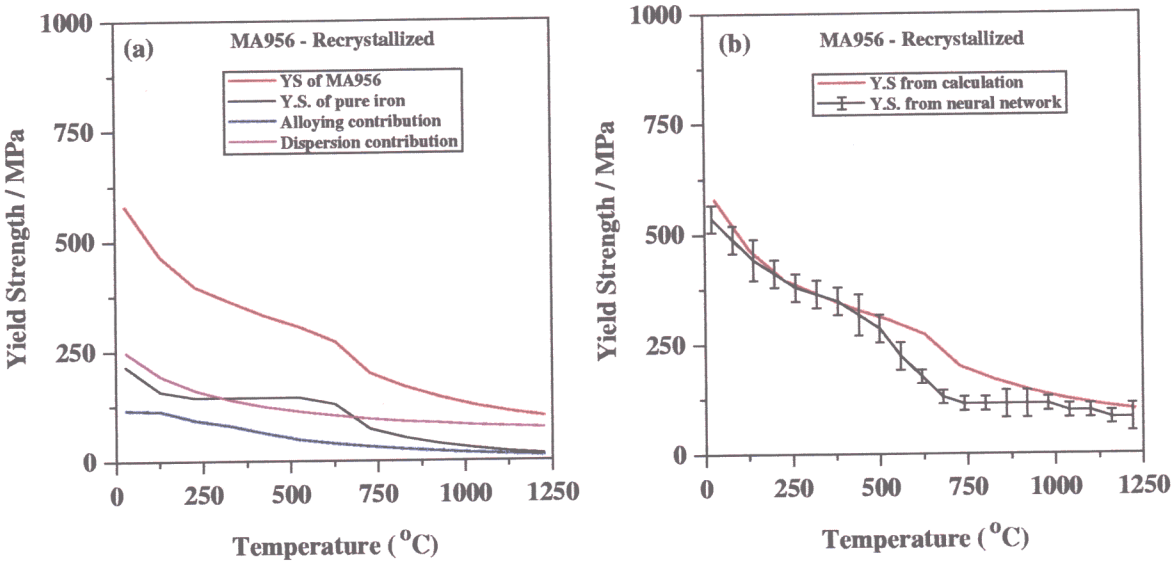

Figure 6.2 : (a) Calculated yield strength of MA956 and contributions from the various components as functions of temperature. (b) Calculated yield strength compared with the result of a neural network analysis.

that the factorisation of strength is reasonable. Furthermore, the accelerating decrease in strength observed in the temperature range 550–650 °C is, by comparison with Figure 6.2a, seen to be a consequence of the similar variation in the strength of the pure iron. Such behaviour is expected because iron atoms become significantly mobile in this temperature range when considered for the slow strain rates typical of tensile tests. There are many other phenomena which reflect the mobility in this temperature range; for example, secondary hardening in alloyed steels.

6.3 Measured Dispersoid Strengthening

There might be considerable uncertainties in the estimation of dispersion strengthening. For example, the particles may not be uniformly distributed and are unlikely to have a uniform size [Krautwasser *et al.*, 1994; Dubiel *et al.*, 1994]. To gain more confidence in the analysis, the dispersoids were effectively removed from a recrystallised sample and the strength measured. This was done by arc melting the alloy in an argon atmosphere, which causes many of the oxides (which have a relatively low density)

The temperature range between the start of recrystallization T_{sR} and melting T_M is 100 °C–150 °C (Jongenburger *et al.*, 1987).

For the purpose of this investigation the samples were again heat-treated in air at 1150 °C for 1 hour and their microstructures were studied metallographically using optical and scanning electron microscopies.

A2.3 Results and Summary

Figure A2.1 shows the microstuctures of the two variants of MA758 after heat–treatment. The grain boundaries of the 0.36 wt.% Al sample are decorated with a phase which appears bright in the scanning electron microscope (Figure A2.1c). The phase is likely to be oxide which tends to charge up under the influence of electron beam and hence as a result appear bright.

The higher aluminium variant is therefore found to be more susceptible to grain boundary oxidation, although direct evidence for oxide formation has not yet been obtained.

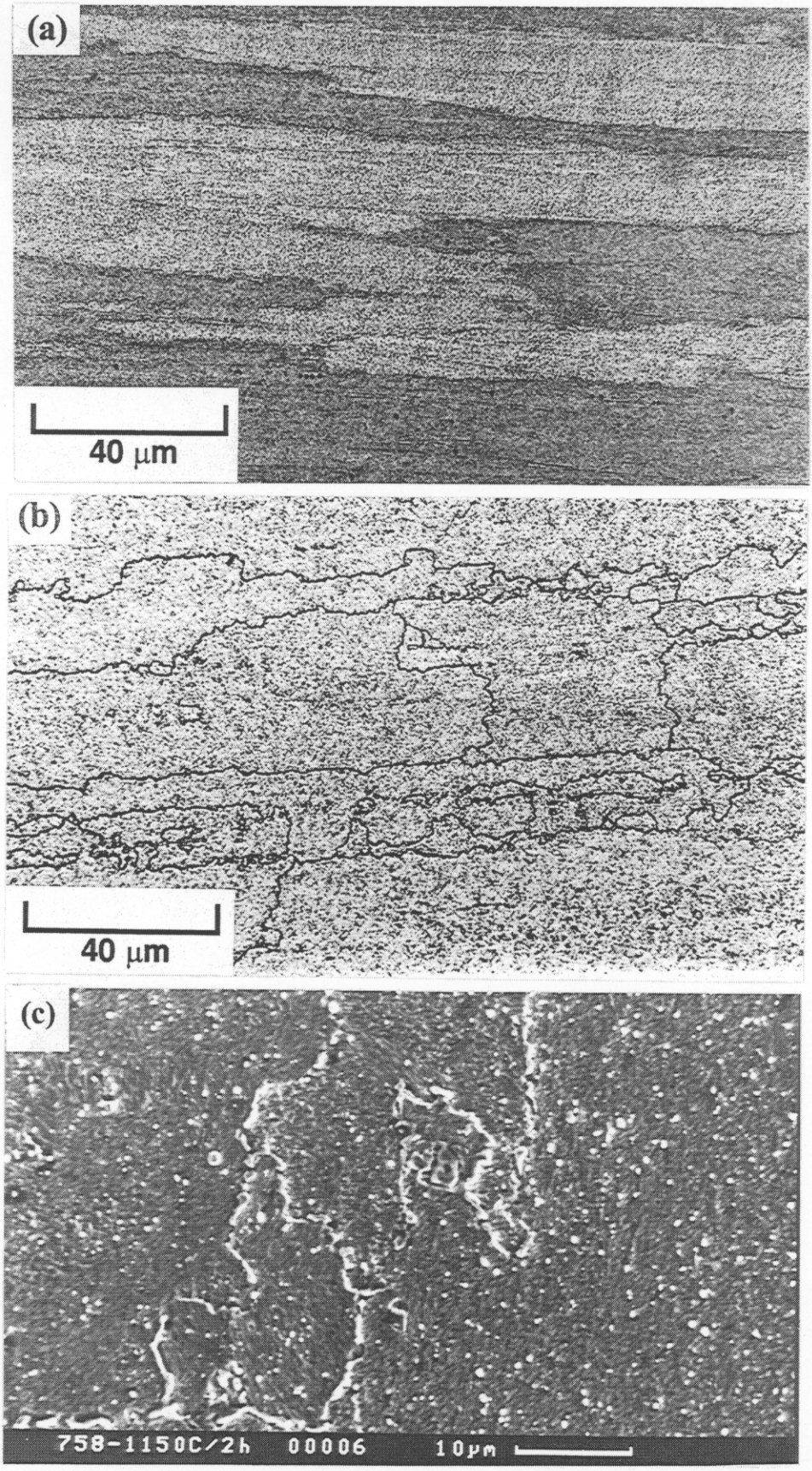

Fig. A2.1 : Optical micrographs of the samples of MA758 after heat–treatment. (a) 0.22 wt.% Al, (b) 0.36 wt.% Al, and (c) Scanning electron micrograph of the sample with 0.36 wt.% Al.

APPENDIX THREE

Some Tensile Tests on MA956

A3.1 **Introduction**

Anisotropic mechanical behaviour MA–ODS steels has been sutied mostly using high temperature tests (Whittenberger, 1981, 1984, Alamo *et al.*, 1992) but the corresponding behaviour at room temperature is not well established. The work reported here was an attempt to investigate the room temperature tensile properties of MA956. The neural network analysis (Chapter five) showed that the unrecrystallized alloy is not only stronger but also more ductile than when it is in the recrystallized condition, when the stress is applied parallel to the working direction. This is unusual given the high hardness in the unrecrystallized condition.

Standard tensile specimens were machined from a rectangular bar of MA956 in the as-extruded condition both along the direction parallel and normal to the extrusion direction. After the machining, a number of longitudinal and transverse samples were recrystallized by annealing at 1300 °C for 30 min before the test.

A3.2 **Results and Discussion**

The plots of stress versus percent elongation for the room temperature tests along the longitudinal and transverse directions are shown in Figure A3.1 for both the recrystallized and the unrecrystallized conditions. The strength in the recrystallized sample is higher along the longitudinal direction than along the transverse direction but the ductility is identical in both directions. For the unrecrystallized sample the strength is isotropic but the longitudinal ductility far exceeds that along the transverse

direction. Naturally, the unrecrystallized sample is always stronger than the recrystallized sample (Figure A3.1c,d), although its ductility is more anisotropic.

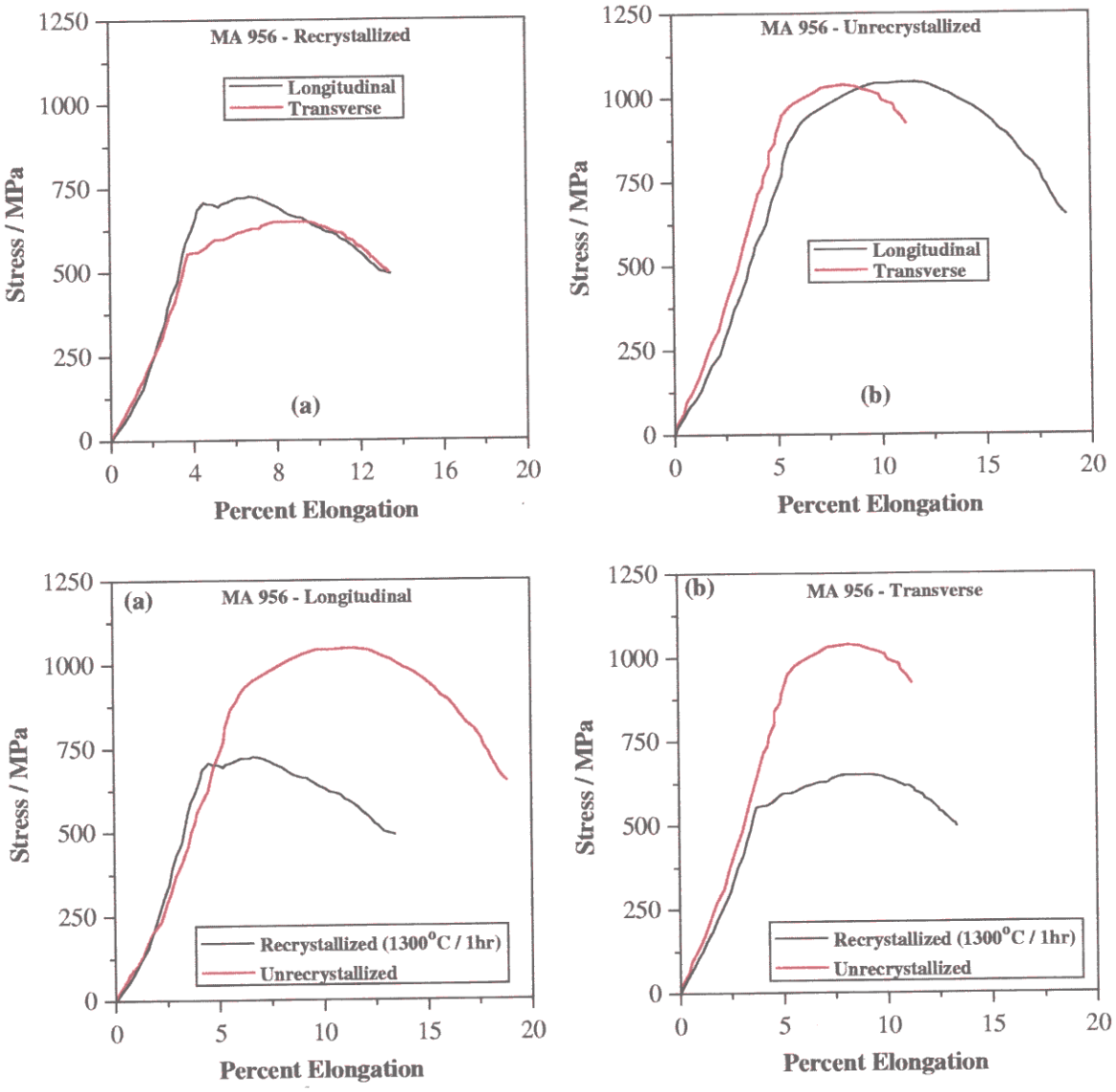

Fig. A3.1 : Stress versus percent elongation for the room temperature tensile testings along the longitudinal and transverse directions. (a) recrystallized, (b) unrecrystallized, (c) longitudinal recrystallized and unrecrystallized compared and (d) transverse recrystallized and unrecrystallized compared.

The elongation results are difficult to interpret given the complex nature of the failures illustrated in Figure A3.2. Deformation is clearly anisotropic and there are signs of delamination along the rolling

plane for both the recrystallized and unrecrystallized samples. There are longitudinal features even on the transverse samples. The ductility of the transverse recrystallized sample is low because the fracture facets are able to propagate over large distances due to the coarse grain structure.

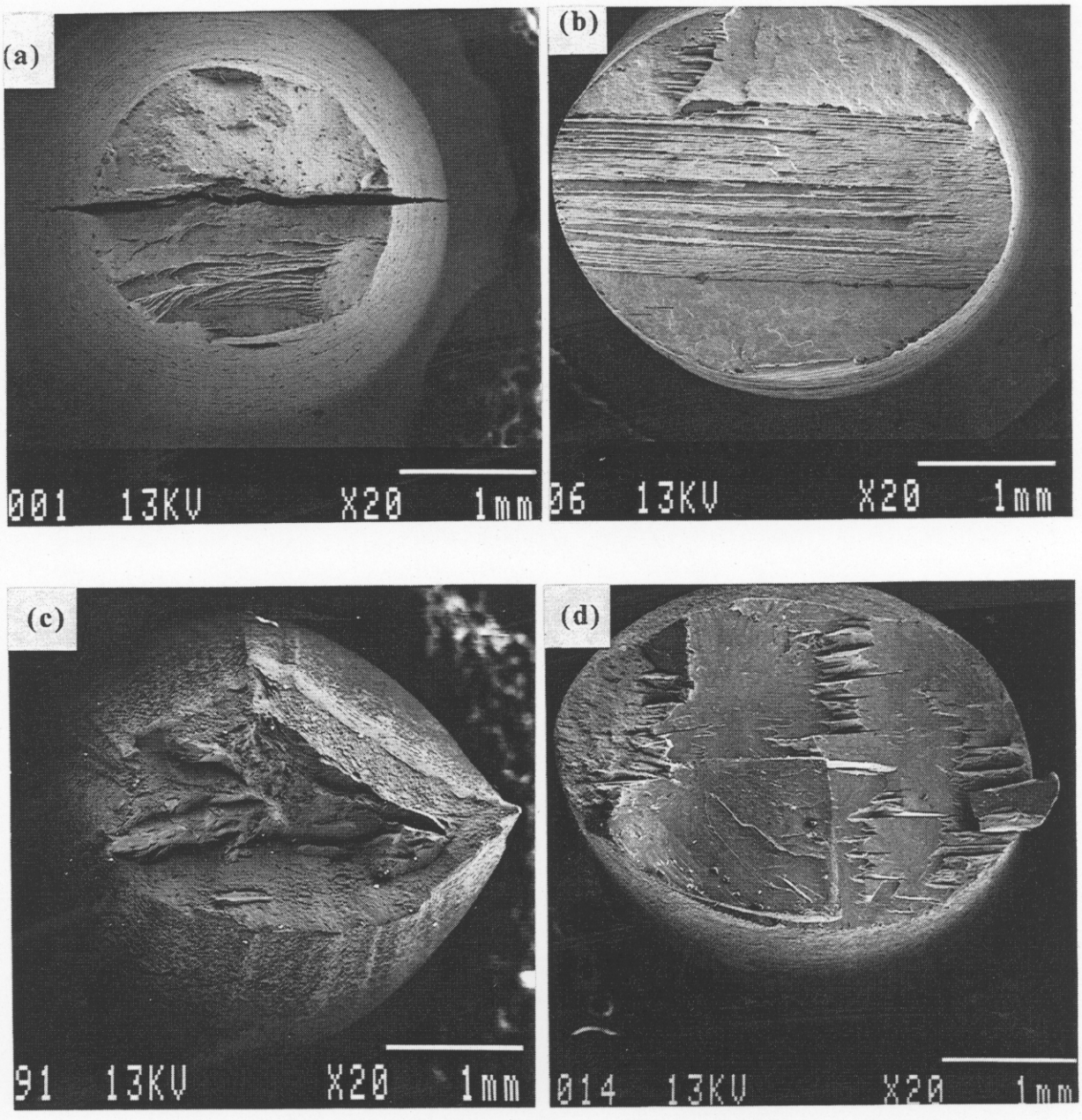

Fig. A3.2 : Scanning electron micrographs showing the fracture surfaces after the room temperature tensile tests. (a) and (b), unrecrystallized longitudinal and transverse samples respectively; (c) and (d), recrystallized longitudinal and transverse samples respectively.

Figure A3.3 shows the measured stress versus percent elongation data for different temperatures for the unrecrystallized MA956. The strength falls sharply between 450 °C and 600 °C, and the ductility increases with the test temperature. The sudden decrease is, as indicated by the physical model (Chapter six), due to dynamic recrystallization (Figure A3.4). These results are consistent with Regle (1994) and and with the neural network analysis (Chapter five). The slight drop in strength between room temperature and 200 °C is interesting. Though, this is not apparent in the earlier work by Regle (1994), it is consistent with the neural network analysis and the results of the physical model as compared in Figure A3.5

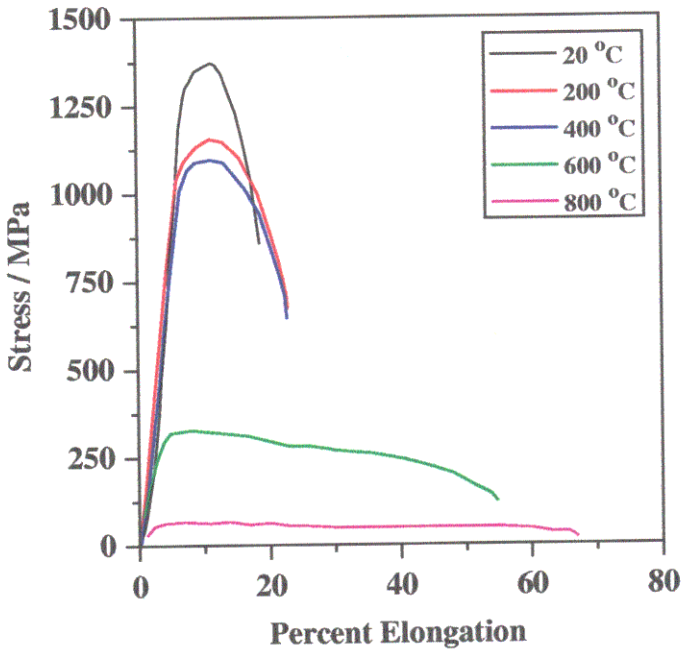

Fig. A3.3 : Temperature dependence of the tensile properties of unrecrystallized MA956.

A3.3 Summary

The room temperature tensile properties of recrystallized MA956 reveal a greater strength along the longitudinal direction than the transverse direction but isotropic ductility. By contrast, the strength is isotropic but the ductility is poor along the transverse direction for the unrecrystallized samples.

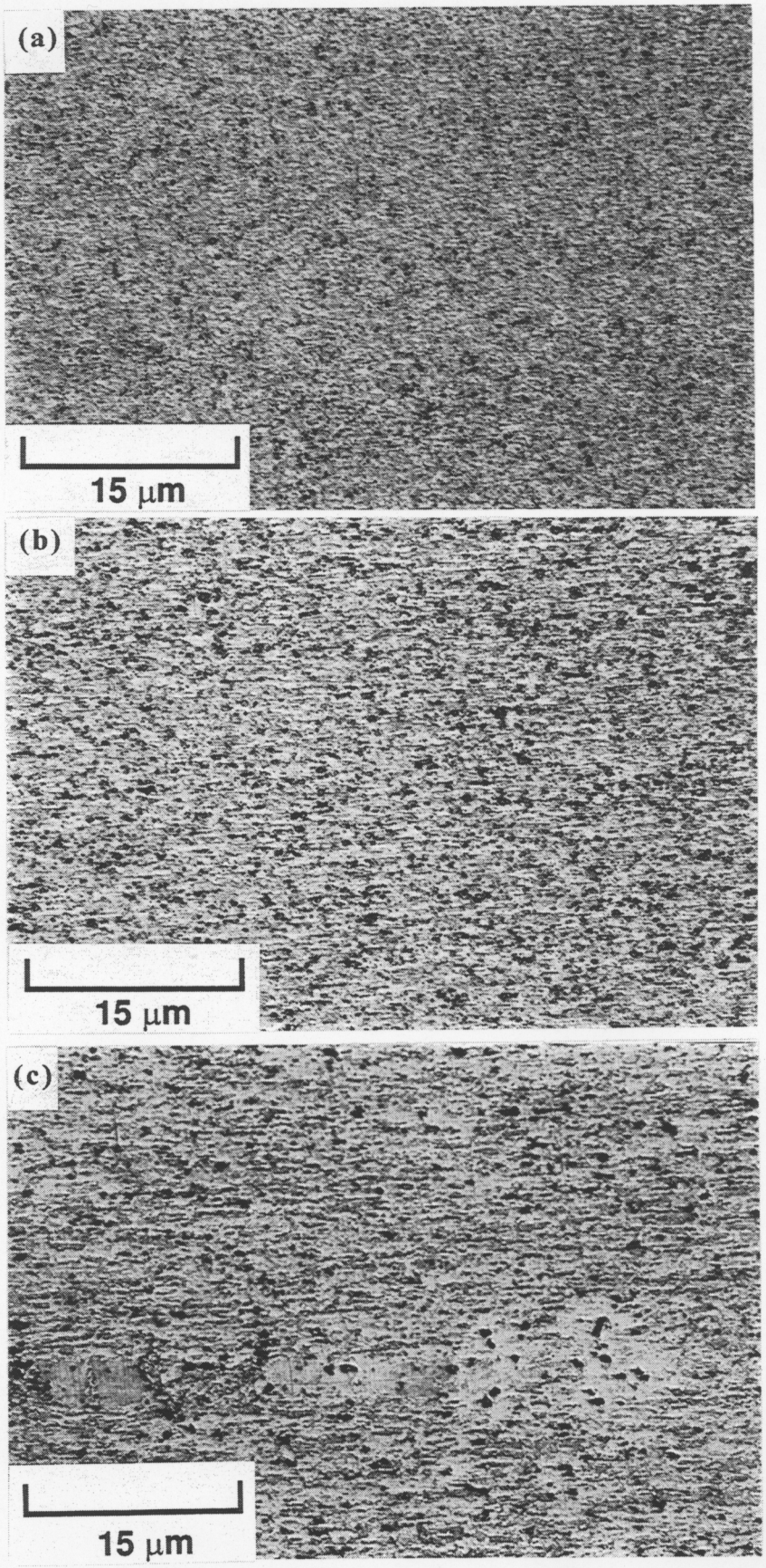

Fig. A3.4 : Microstructures at the fracture regions of the samples of unrecrystallized MA956 tested at different temperatures. (a) 20 $°C$ (b) 600 $°C$ and, (c) 800 $°C$.

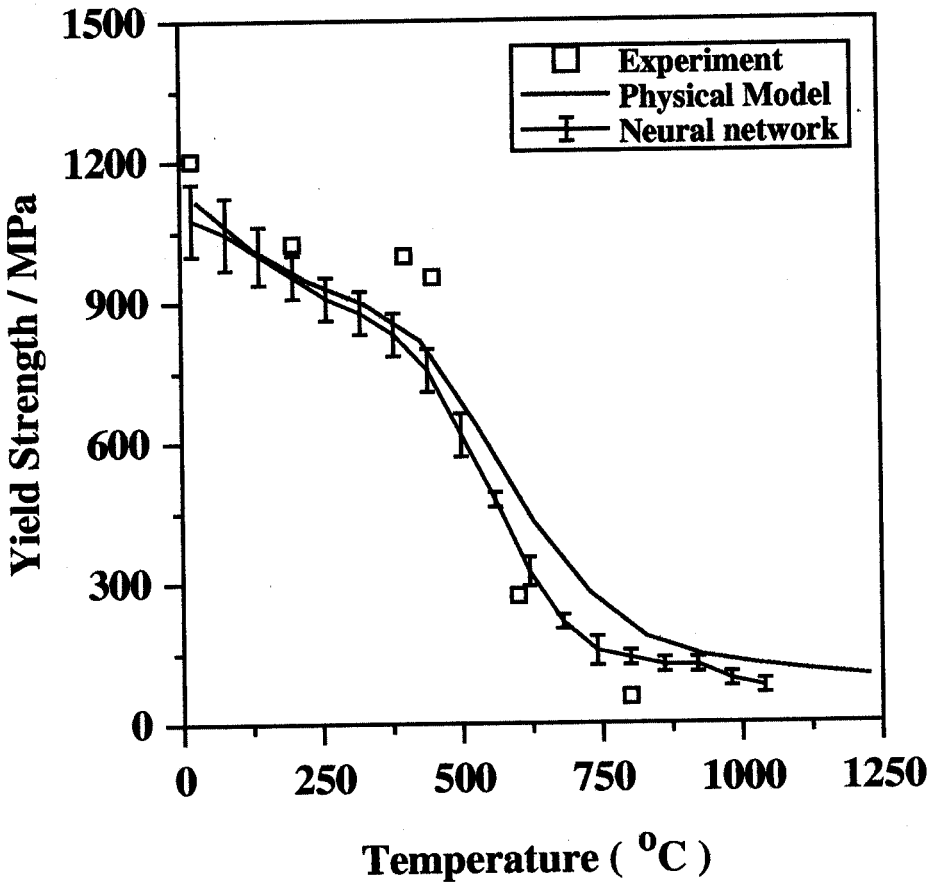

Fig. A3.5 : Yield strength of MA956 at different temperatures compared with the neural network and physical model results.

APPENDIX FOUR

Data for the Neural Network Analysis

PM2000 → 5.5 Al

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	20	8.33E-5	645.00	553	10.00	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	400	8.33E-5	543.00	423	11.00	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	600	8.33E-5	275.00	201	21.00	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	800	8.33E-5	139.00	122	12.00	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	900	8.33E-5	115.00	108	8.00	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1000	8.33E-5	100.00	97	4.50	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1100	8.33E-5	91.00	85	3.50	INCO Alloy
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1200	8.33E-5	79.00	76	2.00	INCO Alloy
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	20	8.10E-4	752.48	386	12.92	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	100	8.10E-4	722.77	366	12.08	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	200	8.10E-4	696.34	336	10.83	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	300	8.10E-4	663.37	321	10.01	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	400	8.10E-4	633.66	310	9.17	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	450	8.10E-4	598.32	287	9.17	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	500	8.10E-4	554.46	277	10.83	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	550	8.10E-4	485.05	257	12.92	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	600	8.10E-4	386.14	227	19.17	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	650	8.10E-4	305.93	198	27.08	Zakine *et al.*, 1993
13	0.00	2.90	1.50	0.00	1050	15.0	800	1444	0	700	8.10E-4	257.43	168	35.02	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	20	8.10E-4	831.68	702	7.08	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	100	8.10E-4	811.88	693	5.42	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	200	8.10E-4	797.80	712	5.01	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	300	8.10E-4	792.08	702	3.33	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	400	8.10E-4	752.48	653	2.51	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	450	8.10E-4	693.07	613	3.33	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	500	8.10E-4	663.37	565	4.17	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	550	8.10E-4	613.86	445	5.01	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	600	8.10E-4	544.55	386	8.35	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	650	8.10E-4	396.04	316	10.02	Zakine *et al.*, 1993
13	0.00	2.90	1.5	0.5	1050	15.0	800	1444	0	700	8.10E-4	297.03	247	11.25	Zakine *et al.*, 1993

CW–cold work; T–test temperature; SR–strain rate; UTS–ultimate tensile strength; YS–yield strength; EL–elongation. Compositions are in wt.%; temperature in °C; time in second.

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	350	8.33E-08	319.74	230	10.62	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	400	8.33E-08	302.25	198	8.5	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	500	8.33E-08	280.4	186	6.75	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	600	8.33E-08	258.54	183	5	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	700	8.33E-08	236.69	169	4.25	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	800	8.33E-08	219.21	153	3.25	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	900	8.33E-08	206.09	149	2.38	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	1000	8.33E-08	188.62	147	1.75	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	1050	8.33E-08	179.87	138	1.75	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	1100	8.33E-08	166.75	140	1.75	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.00	0.00	0.00	1152	8.33E-08	158.01	139	1.5	Whittenberger, 1981
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	3.33E-2	84.10	81	24.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	8.33E-3	80.10	78	19.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	8.33E-4	80.40	79	6.10	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	3.33E-4	81.00	79	4.50	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	8.33E-5	77.20	75	1.90	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	8.33E-6	77.10	75	1.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	3.33E-6	76.90	76	1.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	8.33E-7	77.80	76	1.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	8.33E-8	73.30	73	1.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1093	3.33E-8	70.70	69	1.00	Whittenberger, 1979
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1092	5.8E-3	94.30	91	4.8	Whittenberger, 1978
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1092	1.5E-3	92.50	85	4.1	Whittenberger, 1978
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1092	1.5E-4	87.30	80	2.1	Whittenberger, 1978
20	4.50	0.50	0.00	0.50	1300	60	20.0	0.0	0	1092	1.5E-5	76.10	71	1.4	Whittenberger, 1978
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	0	20	7.10E-04	1011.21	994	18.54	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	0	150	7.10E-04	924.11	934	17.71	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	0	300	7.10E-04	867.14	826	16.88	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	0	500	7.10E-04	668.13	657	20.02	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	0	600	7.10E-04	498.16	487	26.88	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	0	750	7.10E-04	213.3	191	32.45	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	1000.00	120.00	20.00	0.00	0	20	7.10E-04	1145.23	1124	15.21	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	1000.00	120.00	20.00	0.00	0	150	7.10E-04	1041.12	1029	13.96	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	1000.00	120.00	20.00	0.00	0	300	7.10E-04	972.21	946	13.54	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	1000.00	120.00	20.00	0.00	0	500	7.10E-04	813.2	795	16.88	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	1000.00	120.00	20.00	0.00	0	600	7.10E-04	564.35	546	20.34	Alamo *et al.*, 1992
14	0.00	1.00	0.30	0.27	1000.00	120.00	20.00	0.00	0	700	7.10E-04	356.24	324	18.45	Alamo *et al.*, 1992

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	0	8.10E-4	645.12	563	12.92	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	150	8.10E-4	610.21	522	11.96	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	300	8.10E-4	568.23	482	10.01	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.10E-4	498.67	434	10	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	500	8.10E-4	387.54	337	19.17	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.10E-4	296.45	209	23.19	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	800	8.10E-4	189.89	128	21.9	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	900	8.10E-4	173.43	120	12.23	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1000	8.10E-4	115.56	104	8.45	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1100	8.10E-4	113.53	104	4.5	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1200	8.10E-4	99.34	88	3.5	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1250	8.10E-4	89.78	76	2.9	Singer and Gessinger, 1984
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	647	550	10	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	556	549	10.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	624	551	8	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	624	552	8	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	20	8.33E-5	1218	1208	1.6	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	200	8.33E-5	1007	1001	0.8	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	545	422	11	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	542	425	10.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	555	424	10.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	552	422	10.5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	400	8.33E-5	987	915	9.6	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	500	8.33E-5	418	334	12	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.33E-5	272	200	19	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.33E-5	279	203	23	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.33E-5	279	204	23	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	600	8.33E-5	494	305	19.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	650	8.33E-5	218	154	22	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	700	8.33E-5	173	138	23	INCO Alloy
13	0.00	2.2	1.50	0.5	1050	15.0	800	1444	0.00	22	5.0E-3	874	724	10.3	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	1444	0.00	22	5.0E-3	930	768	10.3	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	1444	0.00	500	5.0E-3	622	546	15.2	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	1444	0.00	500	5.0E-3	624	542	15.3	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	1444	0.00	700	5.0E-3	236	216	20.0	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	1444	0.00	700	5.0E-3	240	217	20.6	Hendrix and Vandermeulen, 1982

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	500	5.0E-3	660	560	12.6	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	500	5.0E-3	661	550	12.7	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	600	5.0E-3	413	366	24.6	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	600	5.0E-3	410	365	21.0	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	700	5.0E-3	247	219	21.6	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	700	5.0E-3	248	213	23.2	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	22	5.0E-3	1000	795	7.7	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	22	5.0E-3	991	768	7.7	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	200	5.0E-3	909	692	7.0	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	200	5.0E-3	909	697	7.0	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	400	5.0E-3	804	653	5.7	Hendrix and Vandermeulen, 1982
13	0.00	2.2	1.50	0.5	1050	15.0	800	2888	0.00	400	5.0E-3	808	658	6.0	Hendrix and Vandermeulen, 1982
20	4.50	0.50	0.00	0.50	1330	60	20.00	0.00	0.00	400	1.00E-03	632.04	521	10.23	Dubiel *et al.*, 1994
20	4.50	0.50	0.00	0.50	1330	60	20.00	0.00	0.00	600	1.00E-03	344.75	322	20.4	Dubiel *et al.*, 1994
20	4.50	0.50	0.00	0.50	1330	60	20.00	0.00	0.00	800	1.00E-03	159.12	145	12.42	Dubiel *et al.*, 1994
13	0.00	3.50	1.50	0.00	1050	15.0	800	1444	0.00	0	8.10E-4	1148.21	1054	15.21	Dubiel *et al.*, 1984
13	0.00	3.50	1.50	0.00	1050	15.0	800	1444	0.00	150	8.10E-4	1098.78	956	13.96	Dubiel *et al.*, 1984
13	0.00	3.50	1.50	0.00	1050	15.0	800	1444	0.00	200	8.10E-4	1056.45	945	13.96	Dubiel *et al.*, 1984
13	0.00	3.50	1.50	0.00	1050	15.0	800	1444	0.00	300	8.10E-4	1023.43	917	13.54	Dubiel *et al.*, 1984
13	0.00	3.50	1.50	0.00	1050	15.0	800	1444	0.00	530	8.10E-4	776.48	683	18.56	Dubiel *et al.*, 1984
13	0.00	3.50	1.50	0.00	1050	15.0	800	1444	0.00	610	8.10E-4	626.58	522	21.4	Dubiel *et al.*, 1984
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	450	4.10E-03	623.02	543	21	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	500	4.10E-03	505.28	432	26.14	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	550	4.10E-03	382.64	234	33	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	600	4.10E-03	230.57	197	49.29	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	650	4.10E-03	142.26	121	42	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	700	4.10E-03	112.83	87	34.29	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	20	4.10E-03	932.29	834	1.82	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	200	4.10E-03	786.32	657	1.36	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	400	4.10E-03	630.94	523	3.18	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	500	4.10E-03	484.98	324	5	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	600	4.10E-03	343.72	231	20.45	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	650	4.10E-03	258.97	200	19.55	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	1125	5	20.00	0.00	10.00	700	4.10E-03	202.47	156	16.36	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	20	4.10E-03	1108.68	1064	3.43	Alamo *et al.*, 1990

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	100	4.10E-03	1059.62	946	7.24	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	150	4.10E-03	1000.62	903	7.74	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	200	4.10E-03	978.68	956	8.4	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	250	4.10E-03	966.63	948	8.56	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	300	4.10E-03	946.79	850	9.5	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	350	4.10E-03	892.83	745	12.86	Alamo *et al.*, 1990
20	4.50	0.50	0.00	0.50	20.00	0.00	20.00	0.00	70.00	400	4.10E-03	750.57	670	18.43	Alamo *et al.*, 1990
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	647	550	10	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	556	549	10.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	624	551	8	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	20	8.33E-5	624	552	8	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	20	8.33E-5	1218	1208	1.6	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	200	8.33E-5	1007	1001	0.8	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	545	422	11	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	542	425	10.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	555	424	10.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	400	8.33E-5	552	422	10.5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	400	8.33E-5	987	915	9.6	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	500	8.33E-5	418	334	12	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.33E-5	272	200	19	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.33E-5	279	203	23	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	600	8.33E-5	279	204	23	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	600	8.33E-5	494	305	19.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	650	8.33E-5	218	154	22	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	700	8.33E-5	173	138	23	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1200	8.33E-5	80	76	3	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1200	8.33E-5	78	75	1	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1200	8.33E-5	76	78	1	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	700	8.33E-5	298	211	22.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	750	8.33E-5	155	122	16	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	800	8.33E-5	140	124	10	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	800	8.33E-5	138	120	13	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	800	8.33E-5	135	121	12	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	800	8.33E-5	137	122	11	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	800	8.33E-5	233	162	10	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	800	8.33E-5	257	166	11	INCO Alloy

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	800	8.33E-5	244	180	11	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	900	8.33E-5	115	107	9	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	900	8.33E-5	116	109	7.5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	900	8.33E-5	170	118	6.5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	900	8.33E-5	157	109	6	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	900	8.33E-5	170	118	5.5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	950	8.33E-5	147	95	4	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	950	8.33E-5	145	98	3.5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	982	8.33E-5	124	96	3.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1000	8.33E-5	100	97	4.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1000	8.33E-5	101	97	5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1000	8.33E-5	101	94	6.5	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1000	8.33E-5	101	93	5	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	1000	8.33E-5	130	93	5.4	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	1000	8.33E-5	113	94	1.2	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	1000	8.33E-5	110	97	1.8	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	1030	8.33E-5	92	72	3	INCO Alloy
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	1093	8.33E-5	81	63	1	INCO Alloy
20	4.5	0.5	0	0.5	1330	60	20.00	0.00	0.00	1100	8.33E-5	91	85	3.5	INCO Alloy
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	0	7.10E-04	1270.64	1163	10.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	100	7.10E-04	1196.27	1127	10.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	150	7.10E-04	1173.73	1092	10.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	200	7.10E-04	1154.18	1063	10.50	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	250	7.10E-04	1102.27	1023	11.80	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	300	7.10E-04	1101.73	1018	13.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	350	7.10E-04	1079.18	987	13.80	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	400	7.10E-04	1012.45	945	14.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	450	7.10E-04	948.73	872	15.20	Regle, 1994
14	0.0	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	500	7.10E-04	834.45	745	18.45	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	550	7.10E-04	721.36	636	20.0	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	650	7.10E-04	501.00	400	24	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	25	750	7.10E-04	463.27	327	20.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	0	7.10E-04	1680.3	1600	6.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	100	7.10E-04	1579.09	1509	6	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	200	7.10E-04	1481.82	1381	6.4	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	300	7.10E-04	1372.73	1272	6.80	Regle, 1994

Cr	Al	Ti	Mo	Y_2O_3	Annealing		Ageing		CW	T	SR	UTS	YS	EL	Ref.
					Temp.	Time	Temp.	Time	/%		/s	/MPa	/MPa	/%	
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	400	7.10E-04	1281.82	1181	6.4	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	450	7.10E-04	1156.73	1072	6.8	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	500	7.10E-04	1009.09	909	10.4	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	550	7.10E-04	908.18	818	13.60	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	600	7.10E-04	717.18	618	16.80	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	650	7.10E-04	556.27	527	14.40	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	700	7.10E-04	496.55	454	12.00	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	720	7.10E-04	450.00	400	11.78	Regle, 1994
14	0.00	1.00	0.30	0.27	20.00	0.00	20.00	0.00	60	750	7.10E-04	401.82	381	10.40	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.0	0	7.10E-04	1055.32	931	9.26	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	100	7.10E-04	996.70	896	9.96	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	200	7.10E-04	943.96	843	11.96	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	300	7.10E-04	908.79	808	12.96	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	450	7.10E-04	794.88	720	16.26	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	550	7.10E-04	609.89	509	19.30	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	650	7.10E-04	306.74	263	23.43	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	750	7.10E-04	192.08	123	23.43	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	800	7.10E-04	188.08	121	11.43	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	0.00	850	7.10E-04	178.08	115	10.43	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	10	7.10E-04	1242.86	1142	8.43	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	131	7.10E-04	1154.95	1054	7.74	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	273	7.10E-04	1031.87	931	8.74	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	465	7.10E-04	891.21	791	13.65	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	557	7.10E-04	652.64	562	20	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	658	7.10E-04	396.48	316	24.39	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	25	749	7.10E-04	198.24	158	22.65	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	20	7.10E-04	1486.92	1476	5.22	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	120	7.10E-04	1453.85	1353	7.83	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	212	7.10E-04	1348.35	1248	9.13	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	293	7.10E-04	1260.44	1160	9.13	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	394	7.10E-04	1154.95	1054	10.43	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	465	7.10E-04	1067.03	967	13.04	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	557	7.10E-04	856.04	756	19.57	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	587	7.10E-04	680.22	580	20.39	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	668	7.10E-04	396.48	316	21.61	Regle, 1994
20	4.5	0.5	0	0.5	20	0	20.00	0.00	60	749	7.10E-04	297.24	158	20.34	Regle, 1994

APPENDIX FIVE

Weights from the Neural Network Models

The data are arranged in a continuous horizontal sequence in the following order:

$$\theta_1^{(1)}, w_{1,1}^{(1)} \ldots w_{1,22}^{(1)},$$
$$\theta_2^{(1)}, w_{2,1}^{(1)} \ldots w_{2,22}^{(1)},$$
$$\theta_3^{(1)}, w_{3,1}^{(1)} \ldots w_{3,22}^{(1)},$$
$$\theta_4^{(1)}, w_{4,1}^{(1)} \ldots w_{1,22}^{(1)},$$
$$\theta^{(2)}, w_1^{(2)} \ldots w_4^{(2)}$$

Table A5.1a: First member of committee for the yield strength

-0.00963549	0.0965139	0.0925577	0.116975	-0.0618065	0.401545	-0.073527	0.0223006	-0.0422882	-0.00578501	0.00911521	-1.97707
0.526691	-0.0496755	-0.0307015	-0.0244288	0.0102626	0.0328008	-0.14324	0.179606	-0.0141432	0.0350717	0.00245982	-0.129273
4.21674	-0.740116	-0.123192	-0.0433204	-0.0383476	0.00922208	0.0503388	-0.150428	0.70438	-0.00466108	0.0458901	-0.000548582
0.0930819	-2.64046	0.803751	0.001186760	0.001055560	0.00100383	-0.001269660	0.000921421	-0.0011365	-0.002285790	0.0006872240	0.000960586
3.15534e-05	0.000562953	-0.0842606	0.0126547	0.0014289	0.0121175	0.01406	-0.030977	-0.011318	0.107937	0.320192	-0.000796604
-0.00765068	0.0006504	-0.00266111	1.19158	-0.0216612	0.008047	-0.0612125	-0.0739391	-0.000184482	-0.0075718	-0.246463	-0.830796
-0.0287112	-0.021068	0.00341582	0.166202	-2.23336	0.62458	-0.102769	-0.101849	-0.105986	0.124744	0.0254157	-0.171295
0.554864	0.0280342	0.0116805	0.0112502	0.0552873	-0.329057	1.3266	-0.138577	0.0427931	0.0594477	0.029996	0.0351689
-0.0954499	-0.69618	-0.0240259	0.0393423	-0.00391515	0.0172212	1.77225	-1.02043	0.0110008	-0.00360183	-0.00393565	-0.126096
-0.000794104	0.247329	0.493305	-0.0165823	-0.00670078	0.00115444	0.0150564	1.34508	0.505875	-0.0578569	0.0629772	0.0707605
0.0409896	0.00721293	0.0801678	0.566736	-0.010257	0.0180833	0.00381571	0.0897526	-3.91079	0.663554	-0.0846936	0.0894762
0.0983313	-0.0898865	0.000762335	0.0381056	-0.823754	-0.0580365	0.0133889	0.00187751	0.14364	-3.832	0.499408	-0.0166071
-0.00149307	-0.00920792	-0.0182418	-0.0293844	0.058198	-0.617381	-0.00223201	-0.0284824	0.00316078	0.126999	0.181151	-0.251154
0.0067604	0.0743512	0.0625915	0.0755425	-0.0796998	0.00979387	0.1445	-0.0232309	-0.0657325	0.00459906	-0.0402862	1.33049
-1.04415	-0.0204567	-0.100487	-0.112823	-0.109906	0.0151989	-0.163481	0.291148	-0.0223562	-0.00407049	-0.00568125	-0.213171
-1.1985	-0.202536	2.03748	7.76675	-3.90774	6.29014	-0.100933	2.77667	5.48912	7.51574	6.8865	4.89917
-3.7766	-4.79932	5.26614	9.462	5.76393							

Table A5.1b: Second member of committee for the yield strength

-0.000479841	-0.080894	-0.0566454	-0.481207	1.19845e-06	-0.026999	0.00291564	0.0958271	-1.25876e-05	0.000363673	0.571339	1.18035
-0.0164984	0.00783428	-0.120645	-0.0969914	1.32047	-0.000268118	-0.0701938	-0.00915339	-0.28708	-0.000239954	0.00258108	-0.112142
0.522203	-0.00837235	-0.020773	0.0669092	0.0307038	-0.159074	-0.000125815	-0.0429729	0.00501487	-0.187528	-7.03826e-05	0.00215657
-0.0388266	4.02114	0.0722661	-0.00389438	0.0900116	0.0372058	-0.369534	-0.000436431	-0.0724181	0.0160896	-0.0114118	-0.000270958
-0.00182226	-0.625313	1.31446	-0.00919318	0.00369866	0.00118469	-0.00486987	-0.081186	-0.000106909	0.0107155	0.0125951	-0.0115773
-6.17585e-05	0.00275412	0.164982	-4.68842	0.0581995	0.0120208	0.0329765	0.0237619	-0.0286545	-6.30028e-06	0.0661794	-0.0136737
0.0443705	1.41052e-05	0.00131798	0.23689	1.85265	-0.0277388	0.0147457	-0.0730213	-0.050437	0.288591	-8.32148e-05	0.02025
0.0202056	0.234573	-8.52194e-05	0.00143649	-0.331085	4.39506	0.0147006	0.00557663	-0.0784979	-0.0585164	-0.814308	-0.000184722
0.0924946	0.0103568	0.0938725	-0.000160631	-0.00203449	0.0407442	-0.724849	0.0117738	-0.00596456	0.0424843	-0.00371166	0.551819
0.000520677	-0.136086	0.0100122	0.0787932	-0.000366828	-0.00192239	0.500614	-1.60109	-0.0249172	0.00413362	-0.0665368	-0.0253032
0.365263	0.000432091	0.0150216	-0.0171807	-0.04984	0.000284983	0.00194207	-0.288606	-0.136877	-0.0244974	0.000665767	2.95024
-4.27317	3.71539	-4.86999	4.73214								

Table A5.1c: Third member of committee for the yield strength

0.0111686	0.000513835	0.000915135	-0.614221	0.0027999	-0.705282	0.0156934	-0.0438029	0.00992358	0.000523633	-0.0107421	2.80273
-0.0013653	0.000344816	0.000446912	0.000840785	-0.45659	-0.00217312	0.705721	0.00142425	0.0228917	-0.00773212	0.00038918	0.0117391
0.00861147	-0.000584812	0.000699813	0.00110132	0.00182711	-0.0718401	0.0041612	1.20762	-0.0135958	-0.080141	0.0144494	-0.00025302
-0.0328696	-0.180552	0.000494674	9.47707e-05	0.000280604	0.000513438	-0.0628378	0.00162964	-0.21303	0.00266005	0.0115696	0.00379684
-0.000298489	-0.00239189	-0.177089	0.000278522	-0.00869256	0.000312494	0.000487341	-0.89976	9.78971e-06	0.054823	0.0218672	-0.0230295
0.000430279	0.000237624	-0.0145111	-4.2505	0.000580097	-0.00598911	-2.19728e-05	7.14292e-05	1.26367	0.00324245	0.0538918	0.0301093
-0.0226274	0.00832274	0.000857329	-0.0225582	4.88311	0.000494719	-0.00136541	-0.00073581	-0.00130109	0.28367	-0.0062407	0.725167
0.00307591	0.00789855	-0.0177861	4.55922e-05	0.0129765	-0.627652	-0.000583237	-0.00137532	0.000780332	0.00113514	-0.0378393	-0.00133812
1.33401	0.0125562	0.0294919	0.000824316	0.000858741	0.0123309	1.17111	0.000867602	0.000513162	0.00056529	-0.0010657	0.234629
-0.00321355	0.407127	-0.00661531	-0.0173622	-0.00983219	0.000396889	0.00662486	-0.255557	-0.000542891	-0.0115531	-0.00105509	-0.00188393
-0.117758	-0.00519656	-0.503067	-0.0220496	0.0228599	-0.0163451	-0.00122879	-0.00600514	3.02262	0.00102054	-0.00116953	0.00119135
0.00196547	0.187605	0.0019297	-0.347273	0.0121794	0.0789616	0.00879436	-0.000722831	0.0016718	-1.03949	0.00128759	0.13138
-6.792	4.22032	-7.96332	-2.44187	10.7267	5.79018	8.23147	-4.24521	5.03287	11.6311	-8.74722	

Table A5.1d: Fourth member of committee for the yield strength

0.159532	0.00290407	0.026766	-0.0421247	0.0300843	-0.00715896	-0.118799	-0.00974685	0.0503236	-0.000934039	0.101898	-2.39015
-0.253355	-0.0085277	-0.000588758	0.00110915	0.0130785	0.00793374	0.000796952	-0.000879590	0.00117743	0.00897762	-0.000168296	0.0419299
0.0487008	-0.0457585	-0.00436873	0.00124661	-0.0079201	0.0189455	0.0114009	0.000957158	-0.00635505	0.00138663	0.0128424	-0.000175083
0.0637722	0.126983	-0.0813309	0.259109	0.0112149	0.0731733	-0.14875	-0.041569	0.00325189	-0.465913	-0.00146259	-0.0267647
-0.00153577	-0.15108	0.632046	-1.47131	-0.00763351	-0.000883071	-0.00269156	0.0148357	0.00909743	0.000984364	-0.00225762	0.00129097
0.0102737	-0.000120321	0.047111	0.0658001	-0.0579833	-0.0490487	-0.000288779	0.00182585	-0.0130966	-0.00261055	-9.3699e-05	-0.151546
-0.0157964	-0.0056739	0.000845638	-0.136263	4.47863	-0.550282	0.0751759	-0.00332587	-0.011507	-0.0302009	0.0461843	-0.0107403
0.555795	0.00726828	0.0499782	-0.00156177	-0.162855	1.83786	-0.773382	-0.0240014	0.00482511	0.0417295	0.00981655	0.0115417
0.00475328	-0.086799	0.00212839	0.0294109	-0.000357487	-0.896385	-0.15953	0.120242	-0.000442462	-0.001402	-0.0147898	0.0223207
0.0126185	0.00118032	-0.00830763	0.00120729	0.0141335	-0.000230848	0.0924055	0.195859	-0.0967801	-0.0914877	0.00138303	0.00715003
0.0438356	-0.0512911	0.00952944	0.0371721	-0.00635303	-0.060733	0.00151042	-0.199299	1.54513	-1.49592	0.0236022	0.000153603
0.00012138	-0.0274921	0.0233275	-0.00543471	0.375913	-0.00390227	0.0344317	-3.62297e-05	-0.49207	-0.636365	-0.371759	-0.13481
0.00963923	0.0692669	-0.0625224	-0.0200018	-0.0100646	-0.599592	-0.00634331	0.00436452	0.000215584	0.188714	-2.31365	-0.138081
-0.0835945	-0.00145542	-0.00638343	0.0184797	0.0205098	-0.00106605	0.322343	-0.0248421	0.0265942	0.00162393	0.105615	-3.46061
0.386295	-0.315707	-0.00631695	-0.0447263	0.0839225	0.0079156	0.0135124	0.389969	0.013607	-0.00587022	-0.000457088	0.142843
-2.66646	0.590344	-0.0585182	0.00786098	0.0564949	-0.0625116	0.00167564	-0.00686104	-0.498317	-0.00735161	0.0200765	-0.000155038
-0.0224441	0.87859	0.0420037	0.00248752	-0.00172136	-0.0197388	0.0239668	0.0127726	0.00151953	-0.00800416	0.000981033	0.0142215
0.000213625	0.115764	0.237914	-0.101812	4.50604	5.63772	-1.47655	-2.12898	-10.477	-1.68101	-3.5525	-10.5474
-6.19706	-2.49771	12.8885	7.89824	-8.85184	-7.14897	7.52268	10.2248	-2.69307			

Table A5.1e: Fifth member of committee for the yield strength

-0.0259302	-0.00365445	-0.00536243	-0.0337601	0.000310952	-0.213329	-0.00941427	-0.0270979	0.0262863	-0.00108941	0.227612	0.589634
0.00677463	-0.0621279	0.00548046	0.00814872	0.102793	-0.000275551	-0.0170769	0.0321402	-0.00259142	0.729878	0.00176537	0.107266
-3.75006	-0.00562428	0.0132497	0.000324811	0.000453659	0.00539878	-5.0641e-05	0.0281538	0.00260119	-0.0265404	-0.0920023	0.00126405
-0.0911509	2.98587	-0.0334892	-0.0690042	0.00171631	0.00262012	-0.379718	-4.23394e-05	0.525282	-0.00551508	-0.0783784	0.423882
-0.000273353	-0.253961	-0.476097	0.00924853	-0.0168103	-0.002659	-0.00400945	-0.0688522	5.55807e-05	-0.0388019	-0.0319606	0.0362799
-0.649416	-0.000516097	0.13173	-3.6579	-0.0103472	-0.0449844	0.00373307	0.00553848	-0.297556	-0.000231097	0.233472	-0.025231
-0.127335	0.315857	0.00190638	0.0727127	0.658191	0.00435382	-0.85127	-16.2858	-7.83256	-18.0333	-11.7221	-7.38475
11.6568											

Table A5.2a: First member of committee for the UTS

1.00194e-05	-0.00449607	-0.0140179	0.083752	0.000132986	-0.00674224	0.000352941	0.0107345	-2.30727e-05	0.00115664	-0.121739	-0.0463532	
-8.15173e-06	7.22279e-06	9.33279e-06	2.93662e-05	-0.000183054	4.05038e-07	1.36027e-05	6.99629e-07	-2.43989e-05	2.86272e-08	-9.0036e-06	0.000256543	
0.000207307	1.32503e-06	1.72093e-05	-0.00549973	-0.0169191	0.0995514	7.9089e-05	-0.00824879	0.000427773	0.0130112	-6.39134e-05	0.00191553	
-0.14521	-0.0130601	-1.14795e-05	0.000171176	-0.0284269	-0.0540541	-0.690413	0.00273164	0.057608	0.000779254	-0.199665	0.00307389	
0.0100769	-0.309797	-1.21296	2.97205e-05	-3.48664e-05	0.00772921	0.023099	-0.127469	-9.6053e-06	0.0107881	0.000531587	-0.0204764	
4.93559e-05	-0.00207339	0.190089	-0.101627	3.78781e-05	0.000390663	-0.0124019	-0.0200093	-0.273655	0.00142268	-0.0153261	0.000354396	
0.0303364	0.00162364	0.0124604	-0.110351	5.05038	7.77396e-05	4.12245e-05	0.0264171	0.11068	0.0782625	0.00137503	0.0491792	
0.00169869	0.0900135	0.00203095	0.00543807	0.646922	0.70837	0.000154631	-9.28845e-05	0.00904841	0.0404087	0.261771	0.00061598	
0.0133764	0.000789421	-0.0108577	0.000893154	0.00228527	-1.34315	-0.463565	9.89333e-05	-1.70044e-05	-0.00201929	-0.00639125	0.0388801	
0.000123867	-0.00292181	-0.000150745	0.00520457	3.84837e-05	0.00065963	-0.0553398	-0.0424107	-1.63177e-05	9.83891e-06	-0.00898159	-0.026614	
0.139487	1.69755e-05	-0.011762	-0.000558349	0.0258918	8.11291e-06	0.00246947	-0.212947	0.162817	-2.66017e-05	0.000886088	-0.0170558	
-0.0366058	0.654992	0.00137122	0.0599953	-0.00202417	0.108544	0.00154575	0.016141	0.532581	-1.12733	9.06099e-05	0.00033529	
-0.0444541	-0.142651	-0.0510537	0.000323983	-0.00293111	0.00175323	0.417036	-0.000133211	-0.00925274	0.112657	-0.849673	-2.47267e-05	
0.00110398	0.00675206	0.0596415	0.136372	0.00234631	-0.013493	0.000355416	-0.0309081	0.00304565	0.0137703	0.0624086	-3.769	
4.08584e-06	0.000422792	0.0334234	0.0697999	-0.420428	-0.0027351	0.00341986	-0.000468818	0.115397	-0.00299455	-0.00516834	-0.207216	
-1.87483	-5.74682e-05	2.03522e-06	-0.011535	-0.0293557	-1.1606	0.000701687	0.0525189	-0.00134293	0.141903	0.000714396	0.0101316	
-0.506287	0.731841	-8.49946e-05	-1.8261e-05	0.00906052	0.0268378	-0.14018	-2.0123e-05	0.0118168	0.00055975	-0.0262453	-4.53733e-06	
-0.00250991	0.214338	-0.16636	1.96635e-05	0.0242118	0.928532	-0.00181482	1.12585	-5.24073	-1.41491	-2.12654	-6.2175	
-3.60747	0.3971	1.50596	6.19473	-4.99662	-3.46794	4.66004	4.73158	-1.51067				

Table A5.2b: Second member of committee for the UTS

0.00266309	-0.000877124	0.000764849	0.171752	0.0088005	-0.00337489	0.00530304	-0.00327245	0.00950929	-0.000350317	-0.149156	0.281726	
-0.0251104	-0.00272268	0.000929556	0.000725187	-0.174725	-0.00894128	0.00349421	-0.00536842	0.00333569	-0.00962627	8.73488e-05	0.151194	
-0.282626	0.025548	-0.00308296	0.039266	0.0444776	0.198868	-6.57098e-05	-0.0507454	-0.0742087	0.117095	0.0128166	-0.0188182	
-0.442262	1.90335	0.030889	0.0378914	-0.0390215	-0.0401346	0.0328211	0.0256818	-0.0466509	-0.218961	-0.143627	0.0168211	
-0.0206349	-0.705752	-0.277975	0.0442456	-0.00230519	0.00060702	-0.000965151	-0.156276	-0.00801179	0.00276749	-0.00487455	0.00290558	
-0.00883028	0.0015532	0.137735	-0.276452	0.02266	0.00894659	-0.00977548	-0.013902	-0.261472	-0.0195949	-0.0395902	-0.0540345	
-0.0655935	-0.0245617	0.0285268	-0.34327	5.51658	0.0546765	-0.102258	0.0836905	0.0883326	-1.20074	-0.0382294	0.110723	
0.075202	0.186583	-0.0155581	0.0269765	0.238716	-0.743301	0.0482235	-0.00269729	0.000906754	0.000742628	-0.173429	-0.00888035	
0.00344216	-0.00534061	0.00330851	-0.00957588	0.000204461	0.150311	-0.282241	0.0253587	0.00262513	-0.000845279	0.000788573	0.169938	
0.00871318	-0.00330235	0.00525941	-0.00323312	0.00943568	-0.000506125	-0.147903	0.281177	-0.0248388	0.0575877	0.000352439	0.00175879	
0.203102	-0.0115632	0.022069	0.0824549	0.00640308	-0.0122525	0.0234343	0.395988	-4.1399	0.00271999	0.0451754	-0.0250978	
-0.0339836	0.871235	-0.031636	-0.0677784	0.014965	0.105369	-0.0419008	0.0178232	-0.506004	1.19559	0.0189046	-0.00258444	
0.000812208	0.000813167	-0.168042	-0.00862083	0.0032268	-0.00521073	0.00319165	-0.00935709	0.000667281	0.146587	-0.280612	0.0245514	
-0.00236864	0.000650438	-0.000933321	-0.158794	-0.00814746	0.00286421	-0.00495194	0.0029708	-0.00894912	0.00138366	0.139714	-0.27743	
0.0230793	0.0273991	-0.0129686	-0.0122439	-0.0613964	0.0150807	-0.0135877	0.120912	-0.0935396	0.0106243	-0.0121976	1.28611	
0.128462	-0.0398728	-0.00271904	0.000926244	0.000727743	-0.174537	-0.00893248	0.00348667	-0.00536451	0.00333176	-0.00961904	0.000104437	
0.151065	-0.282569	0.0255207	-0.574919	1.62247	-1.6474	-5.67043	5.02031	-1.48351	-2.1747	4.89095	-1.63661	
1.60701	-3.85411	4.75653	-1.59067	-1.50726	4.01159	-1.64584						

Table A5.2c: Third member of committee for the UTS

0.00536019	-0.00365323	-0.00374455	0.00287123	0.044019	-0.000956509	0.0315297	0.000270369	0.0114277	-0.00174762	0.0287925	-0.364824
0.00616023	-0.00689612	0.00399365	0.00396585	-0.00281105	-0.0475672	0.00105505	-0.0341416	-0.000361033	-0.0123153	0.00217028	-0.0309939
0.359831	0.00141128	0.00435865	-0.00297204	-0.00305424	0.000503715	0.0293828	-0.000741511	-0.00565099	3.86842e-05	0.009139	-0.00155864
-0.0414419	-0.33127	0.0161293	-0.0157832	-0.00338723	-0.00385564	0.0304572	-0.00762934	-0.00169581	-0.182684	-0.00210317	-0.0354686
0.000231114	1.31061	0.302556	-0.316709	-0.0305457	-0.000474872	0.000383390	0.00237898	0.052719	0.000646706	0.0887717	0.00893044
0.0439046	-0.00832935	0.284666	-4.87683	0.0353703	-0.00728009	0.00430688	0.00450225	-0.00261986	-0.0513464	0.00106399	-0.0364067
0.000381917	-0.0132118	0.00247124	-0.0342298	0.353756	0.000945518	0.00624366	0.00380324	0.00385428	-0.00287542	-0.0454177	0.00100145
-0.0327839	-0.000303866	-0.011807	0.0019759	-0.0295528	0.36298	-0.00101475	-0.0366284	-0.00366461	-0.00428235	0.0606492	-0.0454994
0.000855838	-0.449222	-0.000437004	-0.0711036	0.00532488	-0.608079	-0.776577	0.61579	-0.00406105	-0.000237422	0.000288223	0.0145438
-0.0260157	0.0054139	-0.0693192	0.00138114	-0.0277979	0.00522286	0.645794	-2.42018	0.138786	0.0307242	-0.00110865	-0.00125792
0.0623756	0.0156587	-0.00193345	0.124071	-0.00948324	0.00301435	0.0119207	0.320078	-3.95267	0.137039	0.00535327	-0.00777016
-0.00842157	0.0300379	0.011493	-0.000680287	-0.217257	0.00568004	-0.0479269	0.0040118	-0.159139	1.43472	0.35685	-0.0173283
-0.00091579	-0.000599229	0.0508499	0.0725614	0.000342303	0.566938	-0.00143415	0.0631393	0.0036299	-0.774685	-0.0914317	-0.771357
0.00941636	-0.00612487	-0.00630338	0.0764781	0.0569868	0.00314024	0.219469	-2.25887e-05	-0.00168398	0.00664988	-0.684572	2.08671
0.0563295	0.021485	0.00160655	0.00124126	-0.0521167	-0.0663511	0.00135643	-0.0685732	0.00418759	-0.0509395	-0.0006527	-0.680815
-0.451037	-0.539262	0.00592261	-0.00374095	-0.00381115	0.00289202	0.0447871	-0.000972901	0.0322971	0.000285363	0.0116515	-0.0018977
0.0291341	-0.363726	0.00263818	1.16751	-3.13306	3.41094	-2.53338	6.74894	3.82915	3.68794	3.25021	8.28787
5.11917	-6.04969	-5.93088	8.46761	4.64965	-6.47855	-3.20007					

Table A5.3a: First member of committee for the elongation.

-0.0745008	-0.0105203	-0.0171355	0.0455913	0.0119687	-0.0614878	-0.15747	0.0084879	0.031441	0.00100191	0.254446	-0.113693
0.273654	0.218311	0.0616403	0.0159437	-0.015612	-0.0332434	0.0208012	0.000934114	-0.0407106	-0.405327	-0.0169563	-0.00639367
0.00100904	0.194131	-2.59598	0.232	0.0819451	0.115095	0.0589815	-0.00248828	-0.00502106	0.0316421	0.00188288	-0.0767515
0.932134	-0.0135202	0.00410166	0.00131234	-0.099234	2.29787	-0.0443353	-0.0350258	-0.29659	0.00818787	0.00880872	0.019562
-0.00175117	0.000774314	0.0295598	-0.196915	0.0070217	0.00928947	0.000143244	-0.0030145	0.484183	-0.12256	-0.0248379	-0.0572268
0.00619757	-0.0105519	-0.0244764	-0.00424514	-0.00282516	-0.0280598	-0.313275	-0.00908655	-0.0144753	-0.000342879	0.0557421	-0.0669999
0.0552251	0.0499244	0.125362	0.099921	-0.00320856	-0.00982379	0.0432607	-0.00703065	0.0348196	0.0677272	0.0124424	-0.0245925
0.000485282	0.218079	6.32628	0.210079	-0.134835	-0.0874474	-0.0320355	0.0023913	0.0112909	-0.0164674	0.0114981	-0.0221565
0.135396	-0.00255034	0.0388836	-0.00109095	0.245014	7.64961	0.0544577	-0.013856	0.0748451	-0.000514741	0.00256434	0.00586549
-0.00136261	-0.000379572	0.00921963	0.0167964	-0.0033729	-0.00446497	-6.5904e-05	0.00682211	-0.238703	0.0321075	0.0139704	0.016394
0.00078661	-0.00338814	-0.00720033	0.000441655	0.000839007	-0.0103522	0.0380523	-0.00407999	-0.00462857	-7.85571e-05	0.0128431	-0.482126
0.0316318	0.0150496	0.0109848	-0.0872472	0.0155377	0.0333181	0.0246819	-0.00096056	-0.0110563	-0.63249	-0.00645007	0.00553504
0.000830717	0.125201	1.26857	0.0696577	0.154407	0.234607	-0.00510571	-0.00425982	-0.0110086	-0.0200238	-0.00281466	0.0118825
0.0148731	-0.0188307	-0.0107491	0.000665439	0.154786	5.3068	-0.177093	-0.103093	-0.477886	-0.0332541	-0.0276029	-0.0561952
0.0350201	0.00726893	-0.0694918	0.531102	-0.0120883	0.00585297	-3.92799e-05	-0.193458	1.34835	0.350898	0.00381134	-0.0627182
0.0503533	0.00400502	0.00861631	0.0394241	-0.000744562	-0.0677136	0.272162	-0.0104532	0.00112558	0.000775704	0.238539	-1.88039
-0.166201	0.0363123	-0.432826	0.00139544	-0.00222183	-0.00441138	0.000761954	0.000789925	0.00578542	0.0115439	-0.00314862	-0.0027303
-4.26697e-05	0.0164396	-0.647315	-0.00621638	0.0111866	0.00784842	-0.0854402	-9.41934	-11.3696	-10.7221	-5.48995	6.35634
15.1834	-7.61171	2.19262	2.80573	10.7522	-8.63799	13.1299	14.1913	2.17388			

Table A5.3b : Second member of committee for the elongation.

0.0301019	0.121517	0.182024	-0.00194643	5.44705e-05	0.0101013	0.12897	-0.0238512	-7.75571e-05	0.000930936	-0.0618289	-6.28198	
0.16281	-0.180587	-0.342744	0.0057816	-0.137904	-0.214054	-0.00119854	2.55516e-05	-0.00949255	-0.213071	0.0357813	-1.1789e-05	
0.00152644	-0.0257962	4.0593	0.153294	0.0904911	-0.222793	-0.0137223	0.0242711	0.102009	-0.00176617	0.0001988280.00343221		
0.100601	-0.00300490.000604057		0.00167151	-0.00609095	1.06126	0.173169	-0.170512	0.703459	0.00111864	0.00661667	0.0217882	
-0.00133588	4.77281e-05	0.00185418	-0.0665885	-0.0120201	0.000129683	0.000619017	-0.00344353	0.32921	0.00266224	-0.0400165	-0.0999159	
0.00302706	-0.0587574	-0.121508	0.00314818	-8.77498e-05	0.00711449	0.120833	-0.0420066	-0.000280181	-0.00274657	0.0251753	0.129828	
-0.104185	-0.253143	-0.846239	0.0135343	0.00153136	0.0474895	-0.00176051	0.000147364	0.00273694	0.0907888	-0.0345919	0.0004289	
0.00125022	0.0251917	-2.03888	-0.0626182	-0.101803	-0.143614	0.0662642	-0.111961	-0.156275	-0.00253351	8.5009e-05	0.0141891	
0.188481	0.009989860.000175702		0.00509662	-0.00390154	-7.22039	-0.191466	0.123858	0.877387	-0.00220335	-0.00736722	-0.0312849	
0.00169266	-5.50113e-05	-0.0020906	0.0944239	0.0154432	-0.000180995	0.000808001	0.00425469	-0.42253	0.0116485	0.0518902	0.129161	
0.0246891	-0.0699259	-0.13436	-0.00643982	6.07239e-05	-0.00441801	0.917459	0.0871391	-0.000198693	0.00287858	0.0675696	-0.0964831	
0.0255148	0.169637	-0.946907	-0.00166437	0.08478	0.00834102	-0.00225784	-0.000449829	0.00256942	0.241542	0.14702	-0.00123464	
0.00296256	-0.0746134	-5.69595	-0.755812	0.324634	0.6448	-0.039503	-0.229694	-0.304292	0.002814150.000228594		-0.00427342	
0.141397	-0.092532100005247880		0.00348055	0.0619425	-8.59047	0.0248629	0.116366	0.380848	0.0121133	-0.0605815	-0.0945357	
0.00183616	8.83037e-05	0.0318346	-0.155317	-0.101005	7.10316e-05	-0.00303264	0.0718359	6.68788	0.314799	-0.146146	0.519519	
0.00702782	0.101862	0.108634	0.00662434	-0.000186002	-0.00663234	0.505473	0.0952548	-0.000467822	-0.00303721	0.0560313	0.0718143	
-0.133875	0.315246	0.135854	0.010682	-0.0971105	-0.182383	0.00532115	-8.37067e-05	-0.00220235	0.383548	0.00706179	-0.000290045	
0.00274859	-0.040939	0.0193539	0.415258	-0.109892	-0.387889	0.233782	-9.74511	-7.75219	-7.13984	-3.06335	8.79098	
-7.13021	16.8943	3.92484	-14.535	-15.9101	-9.30996	-13.0783	14.5079	11.8499				

Table A5.3c : Third member of committee for the elongation

0.0370769	0.0514359	0.0353873	-0.000585384	-0.0156681	0.00338796	-0.566864	0.00050415	-0.00568823	0.00283634	0.00321732	0.354993	
-0.366533	0.355984	0.0861148	0.00117097	0.0230824	0.0189446	0.000615662	0.00218215	-0.000449988	-0.443305	-0.003519170.00177516		
0.00186752	-0.0127677	-1.05622	0.0448273	-0.59614	-0.0752848	0.167228	-0.0611791	-0.0447181	0.00181787	0.00398464	0.00664942	
-0.0102759	-0.07740680.000461769		-0.00328124	0.0442472	6.88135	-0.161461	-0.359099	0.0108286	0.022324	-0.0466723	-0.039551	
-0.00042515	-0.00127799	-0.00313254	-0.985074	-0.00636547	-0.00038825	-0.00263803	0.101341	-0.00376178	-0.0216829	-0.0140537	-0.0262414	
0.0259891	0.00286923	-0.0225642	0.00185406	-0.030297	0.00582893	0.113538	-0.0113726	-0.014199	-0.000377488	0.00658813	-5.82291	
0.323171	0.195156	0.165512	-0.0154769	0.00357713	0.00461503	0.00154635	0.0034791	-0.0127783	-0.684007	-0.0228538	0.00238445	
0.003895	0.0384662	2.28703	0.260629	0.286426	-0.0478254	-0.00995393	0.225249	0.174495	0.00158575	-0.0296509	-0.00396501	
0.471634	0.0851422	-0.00798795	0.00220846	-0.0648104	4.45166	-0.269553	-0.26634	0.131066	-0.0967287	-0.128844	-0.0869517	
0.00308005	0.0302232	-0.00248292	-0.138239	-0.0115796	0.0117111	0.00151138	0.150832	0.773512	0.342719	0.126994	-0.123916	
0.0701628	-0.0604757	-0.0462929	0.00278186	0.0068604	-0.0243401	0.418371	-0.0594458	0.001568	0.00552655	0.0477772	-2.82015	
-0.117517	-0.0873828	-0.237285	-0.0326492	-0.111086	-0.0888155	0.002758690.00982146		0.00210218	0.292468	-0.007737750.00279322		
0.000587384	0.0163538	3.92695	0.208295	-0.125505	-0.158683	-0.0441899	-0.0781376	-0.0347271	0.0052771	0.0474481	0.00694641	
-1.0843	0.0370285	0.0198197	-0.00187163	0.0386568	-4.52269	-0.0735063	0.212422	0.0424436	-2.06988	-12.6059	-10.2958	
8.33286	11.5706	17.1457	12.2333	14.5225	-15.7288	15.8026	14.4659	13.2644				

Table A5.3d : Fourth member of committee for the elongation

-0.020193	0.0448449	0.0339259	-0.009559360	0.00607867	-0.0171082	0.235784	-0.00706618	0.00830511	-0.00158306	-0.0258376	-10.2375
0.0455348	0.015526	0.115596	-0.0111427	0.0336342	0.0286378	-0.010803	0.0276051	0.0149528	-0.0477241	0.00452018	0.0181715
-0.00244213	-0.0641433	-4.82541	-0.232181	0.0272955	0.0732292	0.0751036	0.154373	0.0934853	-0.0250491	-0.0808118	0.0422474
0.0452459	-0.00294873	-0.03657	-0.00462145	-0.103771	0.376437	-0.619407	-0.00139012	0.312204	0.00954491	-0.0242783	-0.00729928
-0.00375946	0.0514059	-0.0456138	-0.285684	-0.00959054	0.0281991	-0.000485044	-0.0798895	10.8936	-0.223225	0.010417	0.0575702
-0.0534281	-0.0958925	-0.068741	-0.00805738	0.0108425	-0.0252296	-0.159321	0.00380677	-0.00218474	-0.00170697	0.0643879	-7.17243
0.0672609	0.0188323	-0.19832	-0.0278828	0.0602626	0.0293837	-0.0290397	-0.0739594	0.0830003	0.202847	0.00561231	-0.0384574
-0.00721035	0.0825382	6.70756	0.0454583	0.0289002	-0.0640086	0.0694243	0.100431	0.0559076	-0.0137281	-0.0759375	0.0656731
-0.644073	0.000999541	-0.0378366	0.00105717	0.0710577	0.324748	-0.223564	-0.0101244	0.121984	0.0009023	-0.00186473	0.000492629
0.00070837	-0.000497952	0.000829272	0.0266968	-0.000165752	7.72062e-05	-0.000160364	0.00748324	0.324458	-0.009594290	0.000864071	-0.00435185
0.0212846	0.00100684	0.000148737	0.000459156	-0.00482937	0.00590924	-0.0638173	-0.00127163	-0.00422942	0.000580833	-0.051817	1.58417
-0.00421807	-0.00376076	-0.0896277	0.00147055	-0.00223882	0.0009090660	0.00100498	0.0001927390	0.00218195	0.0700261	-0.000373238	0.000576326
0.000537463	0.0194467	0.275985	-0.0178869	0.00269397	-0.0238967	-0.000170069	7.04213e-05	1.14896e-05	1.59254e-06	1.84454e-06	6.70868e-05
0.00191296	-1.19401e-05	2.00777e-06	2.22428e-05	0.000540013	0.0250845	-0.000218694	2.61435e-05	0.000438537	0.0353563	0.0501018	0.0188
0.000304365	-0.0758125	0.0427048	0.0569031	-0.00335015	-0.0425281	-0.000840355	0.0236807	-4.77096	0.0618546	-0.0224205	0.0123008
-0.0289149	-0.0477012	-0.0336078	-0.0101186	0.00531455	0.0109715	-0.735881	-0.002060590	0.000952574	-0.0034055	0.152574	-0.372863
0.386907	0.0110083	-0.164155	-0.184159	-9.95568	-9.18333	12.7581	-8.8568	-10.0412	-12.8849	-14.4681	0.768885
3.59765	2.196	0.051791	8.11692	13.4352							

Table A5.3f : Fifth member of committee for the elongation

-0.090234	0.0205732	0.077368	0.0218687	0.00176121	-0.0414751	0.25648	-0.0062435	0.00128332	0.00105938	-0.00432934	-10.1276
-0.000853758	0.0103565	0.0401002	-0.0967551	0.0650808	0.157336	-0.0792891	0.000243323	0.0761057	-0.218877	-0.003426540	0.000476554
-0.00518596	0.187104	6.50365	-0.0330413	0.0739246	-0.0739554	0.0601146	0.00260953	0.091717	0.0374004	0.00688336	-0.0145799
-0.115905	-0.001875190	0.004589190	0.00171113	0.116514	0.44266	0.104957	-0.0530803	-0.067722	0.00634209	0.0359525	0.0369352
0.00981496	-0.0040129	0.00205756	0.428697	0.000755988	-0.00248303	-0.00254312	-0.237902	-0.0109649	0.39958	-0.0173779	-0.360207
-0.0586657	-0.127212	-0.237429	-0.0134442	0.00467323	0.00563057	0.291094	-0.002528090	0.00245703	-0.00354923	-0.138825	-5.92699
-0.221178	0.0699772	-0.0980035	-0.0141631	0.0362728	0.0285346	0.00412974	-0.0041837	0.00224147	1.04844	3.67414e-05	-0.00266071
-0.00224203	0.163416	0.457109	-0.28733	0.0318935	0.227609	-0.213857	0.0383232	0.103883	-0.0361088	0.00130758	0.0257916
1.60594	0.000473076	0.001089510	0.00245146	-0.349241	0.195557	-0.0286046	0.0467965	-0.120458	0.04546	-0.0501972	-0.0774169
0.0294513	0.00396867	-0.0357505	-0.330947	-0.00463649	0.00235718	0.00159036	-0.136724	11.1711	-0.182287	-0.011839	0.0260563
-0.578728	-7.14487	-8.88831	-5.74086	9.35647	-6.68984	8.58008	-9.60545	-4.86136			

Table A5.3g : Sixth member of committee for the elongation

-0.0832945	0.044772	0.389189	-0.00346995	0.00590356	-0.0242468	-0.933486	-0.0132668	0.0132219	0.0112537	0.0965041	0.105633
-0.418713	0.150403	-0.194985	0.131605	0.00457758	0.0768434	-0.0200813	0.00552868	0.00986155	0.818728	0.0149287	0.00982856
0.0123857	-0.0423408	0.0186902	-0.0943879	-0.00744999	-0.148479	0.0364402	0.0306001	0.157186	0.0110313	-0.00454903	0.0232104
0.0744224	0.000497818	-0.00544221	0.0049015	0.0301545	7.53362	0.240678	-0.13868	-0.0551636	0.0552989	-0.0267163	-0.206242
-0.0259089	-0.00712814	-0.0392377	0.0421706	0.00769304	-0.0102166	0.00556094	-0.0100853	-1.25978	0.0280164	0.0379419	-0.0406369
0.0405625	0.00243521	-0.200488	0.0691052	-0.0240288	-0.0841019	-0.10617	-0.0545487	-0.0364122	0.00986978	-0.0799652	-8.47056
-0.122341	-0.039802	-0.356674	-0.0817946	0.0457894	0.132618	0.02273	-0.0203267	-0.0122117	0.0990098	-0.0716797	-0.027427
0.00240908	-0.00743098	7.49067	3.26751e-05	-0.0884498	-0.509448	0.184845	-0.0602837	-0.339193	-0.0118911	0.00895189	0.00633034
0.0988389	0.0379036	0.00935246	-0.00593667	-0.0233831	-0.511795	0.315044	-0.119116	0.258223	2.03658	-10.9238	-10.3566
14.0747	6.38983	6.5575	-7.07208	-14.7028							

APPENDIX SIX

FORTRAN Program for Thermodynamic Calculations

Introduction

This appendix describes the computer program that was used to calculate the thermodynamic functions in the analysis of the mechanical alloying (Chapter Four). It is presented using documentation defined in the MAP format [Bhadeshia, 1995, http:/www.msm.cam.ac.uk/map/mapmain.html].

MAP FORTRAN LIBRARY

Program MAP_MALLOY

0. Provenance of Source Code

A.Y. Badmos and H.K.D.H. Bhadeshia, Phase Transformation Group, Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK.

1. Purpose

To calculate free energy of mixing, configurational enthropy of mixing, enthalpy of mixing, and structural interfacial energy in mechanical alloying as functions of concentration, particle size and temperature.

2. Specification

The program is self-contained

3. Description

Molar entropy of mixing, ΔS_M expressed as a function of atoms per particle is

$$\frac{\Delta S_M}{kN_a} = \frac{(1-x)m_B + xm_A}{m_A m_B} \ln\left\{ N_a \frac{(1-x)m_B + xm_A}{m_A m_B} \right\} - \frac{1-x}{m_A} \ln\left\{ \frac{N_a(1-x)}{m_A} \right\} - \frac{x}{m_B} \ln\left\{ \frac{N_a x}{m_B} \right\}$$

where N_a is Avogadro's number, m_A is atoms per powder particle of A, m_B is atoms per particle of B, and x is the mole fraction of B.

Molar enthalpy of mixing, ΔH_M, is expressed as:

$$\Delta H_M = \Omega \ 2\delta S_V \ x(1-x)$$

where Ω is the regular solution parameter, 2δ is the boundary thickness (two monolayer) and S_V is grain boundary area per unit volume.

Molar interface energy, ΔH_I, is expressed as:

$$\Delta H_I = V_m S_V \sigma$$

where V_m is the molar volume and σ is the interface energy per unit area.

The molar free energy, ΔG_M, is then expressed as:

$$\Delta G_M = \Delta H_M - T\Delta S_M + \Delta H_I$$

4. References

1. A.Y. Badmos, Ph.D. Thesis, University of Cambridge, UK., 1997.

2. A.Y. Badmos and H.K.D.H. Bhadeshia, Metallurgical Transactions, **28A**, 1–5, 1997.

5. Parameters

Input parameters

KTEMP - integer

Temperature in Kelvin at which the thermodynamic functions are to be evaluated.

OMEGA - integer

Regular solution parameter, Ω.

Output parameters

DELTAS - real

Predicted molar configurational entropy of mixing.

DELTAH - real

Predicted molar entropy of mixing.

DELTAE - real

Predicted molar interface energy.

DELTAG - real

Predicted free energy of mixing.

6. Error Indicators

In the case of $\Omega > 0$, the effect is appreciable only when the value of Ω is above about 100.

7. Accuracy

Qualitative

8. Program text

```
      IMPLICIT REAL*8(A-H,K-Z), INTEGER(I,J)
      OPEN(2, FILR='PRN')
      WRITE(*,3)
      WRITE(2,11)
      READ(*,*) KTEMP,OMEGA
      LATP = 2.867D-10
      RGAS = 8.31432D+00
      AVOG = 6.023D+23
      MOLV = 8.634D-7
      ATOD = 2.0*(SQRT(3.0D*00)/2.0D+00)*LATP
      AVOA = LATP**3.0/2.0
      AVOB = AVOA

C  This section defines the particle sizes
       DO 10 J=1,10
       DUMMY = (10.0-1.0*J)
       MA = 10.0D+00**DUMMY
       MB = MA

C  Interface energy per unit area
       MDUMMY = 1.0D+7
       IF(MA .GT. MDUMMY) THEN
       SIGMA = 0.5D+00
       ELSE
       SIGMA = 0.5*(1.0-((MDUMMY-MA)/MDUMMY))
       ENDIF

C
      DO 1 I=1,51
```

```
      X = (I-1)*0.2D-01
      NA = AVOG*(1-X)/MA
      NB = AVOG*X/MB
      SA = 3.0*(NA*(MA*AVOA)**(2.0/3.0) + NB*(MB*AVOB)**(2.0/3.0))
      VT = NA*MA*AVOA + NB*MB*AVOB
      SV = SA/VT
      VB = SV*2.0*ATOD

C  Molar Interface Energy
      DELTAE = SV*SIGMA*MOLV

C
       IF(X .EQ. 0.0D+00 .OR. X .EQ. 1.0D+00) THEN
       DELTAS = 0.0D+00
       TDELTAS = 0.0D+00
       DELTAH = 0.0D+00
       ELSE

C  Molar Entropy
       DELTAS = RGAS*((((1-X)*MB+X*MA)/(MA*MB))*
     &      DLOG(AVOG*(((1-X)*MB+X*MA)/(MA*MB)))
     &      -((1-X)/MA)*DLOG(AVOG*((1-X)/MA))
     &      -(X/MB)*DLOG(AVOG*X/MB))
       TDELTAS = -KTEMP*DELTAS

C  Molar Enthalpy
       DELTAH = X*(1-X)*VB*OMEGA

C  Molar Free Energy
       DELTAG = DELTAH + TDELTAS + DELTAE
       ENDIF
```

```
C
C     WRITE(2,2)MA, MB,X,DELTAS,TDELTAS,DELTAG,KTEMP,SIGMA, DELTAE
2     FORMAT(2D10.2,F6.2,D10.2,2F14.7,F8.0,3F14.7)
3     FORMAT(10x, ' KTEMP, OMEGA')
11    FORMAT(// 7x,'MA, MB, X, DELTAS, TDELTAS, '
     & ' DELTAG, KTEMP, SIGMA, DELTAE'/)
C
1     CONTINUE
      WRITE(2,11)
10    CONTINUE
      STOP

C ***********************************************************************
C     LATP is lattice parameter:  value for iron is used
C     RGAS is Gas constant, R.
C     AVOG is Avogadro constant.
C     MOLV is molar volume calculated for iron.
C     ATOD is diameter of atom.
C     AVOA and AVOB are volume per atom for component A and B respectively.
C     MA and MB are atoms per particle of component A and B respectively.
C     X is mole fraction.
C     NA and NB are number of particles of A and B respectively.
C     SA is total surface area of the particles.
C     VT is total volume of the particles.
C     SV is surface area per unit volume.
C     VB is volume fraction of material within a grain boundary.
C     SIGMA is interface energy per unit area.

C     DELTAE is molar interface energy.
```

APPENDIX SEVEN

FORTRAN Program to Calculate Yield Strength of MA–ODS Steels

Introduction

The progam described in this appendix was used to calculate the components of the yield strength of MA956 in the model discussed in Chapter Six. It is presented using documentation defined in the MAP format [Bhadeshia, 1995, http:/www.msm.cam.ac.uk/map/mapmain.html].

MAP FORTRAN LIBRARY

Program MAP_YSMA956

0. Provenance of Source Code

A.Y. Badmos, Phase Transformation Group, Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK.

1. Purpose

To calculate the components of the yield strength of the recrystallized and unrecrystallized mechanically alloyed ODS ferritic steel, MA956.

2. Specification

The program is self-contained

3. Description

The yield strength of the MA956 is calculated as a linear combination of contributions from a number of mechanisms generally expressed as:

$$\sigma_y = \sigma_{Fe} + \sigma_s + \sigma_p + \sigma_g + \sigma_d \tag{7.1}$$

where

σ_{Fe} is the strength of the pure, annealed matrix,

σ_s is solid solution strengthening,

σ_p is the particle strengthening,

σ_g is the grain boundary strengthening,

σ_d is the dislocation strengthening.

The recrystallized alloy has coarse grain structure and there is no contribution from the grain boundary strengthening.

4. References

1. A.Y. Badmos: Ph.D. Thesis, University of Cambridge, UK., 1997.

2. A.Y. Badmos and H.K.D.H. Bhadeshia (1997) - Submitted for publication in *Materials Science and Technology.*

5. Parameters

Input parameters

MO - real

Concentration of molybdenum in wt.%.

CR - real

Concentration of chromium in wt.%.

TI - real

Concentration of titanium in wt.%

PWT - real

Concentration of particles in wt.%.

PRAD - real

Particle radius.

PWT - real

Concentration of particles in wt.%.

PARTD - real

Density of the particle.

MATRD - real

Density of the matrix.

GSIZE - real

Grain size of the unrecrystallised alloy.

DDENS - real

Dislocation density.

AVAC - real

Area associated with a vacancy.

DDIF - real

Constant of difussivity coefficent.

QES - real

Self–difussion activation energy for the alloy.

SRATE - real

Strain rate.

RGAS - real

Gas constant.

BUGV - real

Burgers vector.

SMOD - real

Shear modulus.

A(I,J) - Double precision.

A 13×4 array consisting of temperature in column 1 and corresponding scale factors relative to room temperature for matrix strength in column 2, solid solution strenghtening in column 3 and grain boundary strengthening in column 4.

Output parameters

PIRON - real

Strength of pure iron.

SSOL - real

Solid solution strengthening.

PARTS - real

Particle strengthening.

GRAS - real

Grain size strengthening in the unrecrystallized alloy.

RYST - real

Total yield strength of recrystallized alloy.

URST - real

Total yield strength of of unrecrystallized alloy.

6. Program data

MO = 0.0D0

CR = 20.0D0

TI = 0.5D0

PRAD = 5.695D-09

GSIZE = 0.9D-06

DDENS = 10D+14

RGAS = 8.314510

AVAC = 1.95D-20

DDIF = 5.0D-05

QES = 240000.0

K = RGAS/6.023D23

SMOD = 8.6D+10

BUGV = 2.485D-10

MATRD = 7200.0

PARTD = 5030.0

PWT = 0.5/100

SRATE = 3.3D-4

A(I,J):

20.0d0	1.0d0	1.0d0	1.0d0
100.0d0	0.7334d0	0.9713d0	1.03d0
200.0d0	0.6667d0	0.7856d0	1.03d0
300.0d0	0.6667d0	0.6858d0	1.0d0
400.0d0	0.6667d0	0.5427d0	0.9118d0
500.0d0	0.6667d0	0.4143d0	0.6177d0
600.0d0	0.5999d0	0.3364d0	0.2941d0
700.0d0	0.3333d0	0.2731d0	0.1471d0
800.0d0	0.2425d0	0.2217d0	0.0294d0
900.0d0	0.1765d0	0.1800d0	0.0d0
100.0d1	0.1284d0	0.1461d0	0.0d0
110.0d1	0.0935d0	0.1186d0	0.0d0
120.0d1	0.0680d0	0.0963d0	0.0d0

7. Program text

IMPLICIT DOUBLE PRECISION (A-H,K-Z), INTEGER (I,J)

```
      DOUBLE PRECISION A
      DIMENSION A(20,4)
      OPEN(3, FILE='YIELD')
      IROW1=13
      ICOL=4

C  This do loop reads the data in the array file, A(I,J).
      DO 100 I=1,IROW1
      READ(*,*)A(I,1),A(I,2),A(I,3),A(I,4)
  100 CONTINUE

C  Volume fraction of particle from weight percent
      VFRAC = PWT*MATRD/PARTD

C  Particle spacing
      PSPA = SQRT(2.0*PIE/3.0)*SQRT(PRAD**2.0/VFRAC)

C  Strength of pure iron at room temperature
      PIRON20 = 215.76DO

C  Solid solution strengthening at room temperature.
      SSOL20 = 8.5*CR + 58.0*MO - 107.0*TI

C  Grain boundary strengthening at room temperature
      K = 15.9*(1.0/1000.0)**0.5
      GRAS20 = K*(GSIZE**(-0.5))
      I=1
      DO 1 IJI = 3,15
      KTEMP = 100.0*IJI
      CTEMP = KTEMP-273.15

C  Particle strengthening
```

```
      MODD = (SMOD*BUGV)/PSPA
      EXPT = QES/(RGAS*KTEMP)
      DIFF = DDIF*DEXP(-EXPT)
      LOGN = SRATE*K*KTEMP*PRAD**2.0D0
      LOGD = 4.0D0*PIE*DDENS*BUGV**2.0D0*AVAC*SMOD*PSPA*DIFF
      LOGT = 0.12D0*DLOG10(LOGN/LOGD)
      ENGT = 0.052D0*EXPT
      SPT = 0.51D0 + LOGT + ENGT
      PARTS = MODD*SPT/1E6
      PIRON = PIRON20*A(I,2)
      SSOL = SSOL20*A(I,3)
      GRAS = GRAS20*A(I,4)

C  Recrystallized yield strength
      RYST = PIRON + SSOL + PRAD

C  Unrecrystallized yield strength
      URST = RYST + GRAS

C  Results are in MPa
      WRITE(*,2)CTEMP,KTEMP,PIRON,SSOL,PARTS,GRAS,RYST,URST
      WRITE(3,2)CTEMP,KTEMP,PIRON,SSOL,PARTS,GRAS,RYST,URST

2       FORMAT(2F8.0,6F10.0)
      I = I + 1

1       CONTINUE
      END
```

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