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A Finite Element Modelling of Embrittlement in Composite Liquid Phase Sintered Heavy Alloys

Sintered tungsten base heavy alloys made of tungsten grains embedded in a nickel rich matrix can possess low room temperature ductility that may be improved by subsequent heat treatment. The sintering thermal cycle was simulated by a finite element procedure, and it was found that the vast differences in thermal and elastic properties of the microstructural components result in significant residual interfacial strains upon cooling to ambient temperature. These strains may contribute significantly to the low room temperature ductility of this class of liquid phase sintered alloys and should be relieved in order to improve ductility.

1 Introduction

It is well documented that tungsten base heavy alloys produced by liquid phase sintering exhibit low ductility that can be improved by post manufacturing heat treatment. Many theories have been proposed to explain these facts, which are based on thermally reversible processes such as hydrogen embrittlement, intermetallic phases, impurity segregation and ageing phenomena (Minakova et al., 1968, Edmonds and Jones, 1979, Ekbom, 1976, Yoon et al., 1983, Lea et al., 1983, Churn and German, 1984, German et al., 1983, Muddle and Edmonds 1983). The microstructure of these alloys is a composite consisting of tungsten spheres, embedded in a tungsten-iron-nickel matrix and the two microconstituents have different thermal and elastic properties. These differences have not yet been considered as a potential source for the room temperature lack of ductility of some heavy alloys. This is done in the present paper by considering the tungsten-matrix interface whose strength has been reported by Churn and German (1984) to govern the ductility to failure.

2 Experimental and Modelling Conditions

The model system consists of tungsten grains embedded in a nickel matrix. Such a system can be used to describe quite accurately a typical liquid phase sintered heavy alloy and the assumption is close to reality since the matrix contains about 80 weight percent nickel. The computational model views the material as made of an assembly of units of symmetry as shown in Fig. 1. The thermal cycle of liquid phase sintering can be summarized as follows: A mixture of tungsten and nickel powders is heated up to 1500°C followed by slow cooling to room temperature according to the following scheme: 1450°C–1500°C–1450°C–1000°C–420°C–Room-T.

- - - -heating- - - - - - - - - cooling - - - - - - -

It is assumed that matrix (nickel) liquefaction occurs at 1450°C. At this temperature the unit is considered to be stress free as the solid-liquid interface has just been created.

The thermal and mechanical properties of the components of the alloy are listed in Table 1 as a function of temperature (Samsonov, 1968), and it is assumed that they vary linearily with temperature in this range. A satisfactory approximation of an incompressible liquid (liquid matrix) was obtained by using a Poisson ratio of 0.45 along with a low Young modulus (i.e. 0.1 GN/MP^2) in the absence of a special "incompressible" element (Bercovier and Livne, 1979).

Meshing of the unit was accomplished by menas of Ingen software (Cook, 1982). A total of 16 (6-nodes) and 60 (8-nodes) isoparametric plane strain elements were used for calculation, utilizing LSD software (Bercovier et al., 1982).

3 Results

A computer finite element based simulation of the cooling

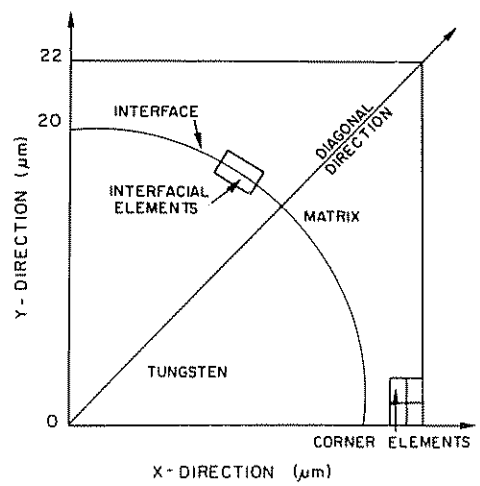

Fig. 1 The tungsten matrix unit utilized for simulation of liquid phase sintering process

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Table 1 Thermal and mechanical properties of the components of the unit as a function of temperature.
E = Young modulus; ν = Poisson ratio; λ = Linear thermal expansion coefficient, * = estimated value.

Tungsten

T [°C]	E [GN/M²]	ν	λ [*10⁻⁶/°C]
25	407	.27	5.5
800	371	.27	5.5
1600	324	.27	5.5

Matrix

T [°C]	E [GN/M²]	ν	λ [*10⁻⁶/°C]
25	196	.31	13.2
420	187	.31	13.2
590	188	.31	*14.3
1000	*188	.31	17.1
1450	*188	.31	23.8
1500	*188	.45	1

Table 2 Modified thermal and mechanical properties of the matrix utilized for the elasto-plastic assumptions.

T [°C]	E [MN/M²]	ν	λ [*10⁻⁶/°C]
25	.1	.45	13.2
420	.1	.45	13.2
1200	.1	.45	17.1
1450	188	.31	23.8
1500	.1	.45	.1

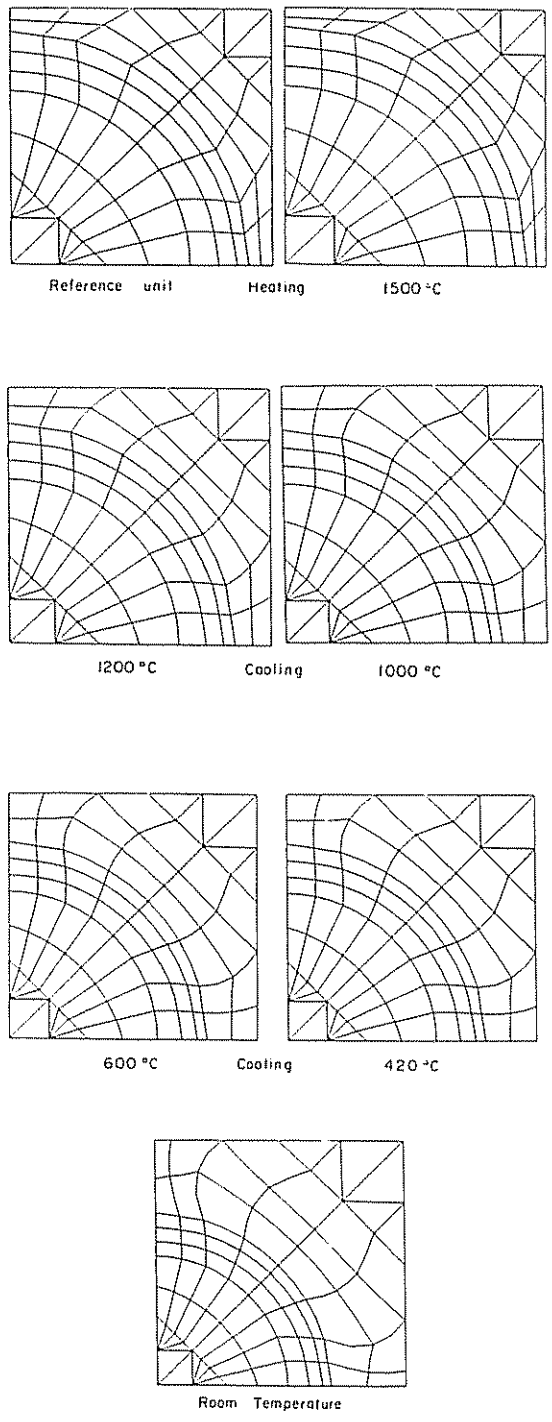

Fig. 2 Deformations states of the unit versus temperature (scaling factor for displacements = 50)

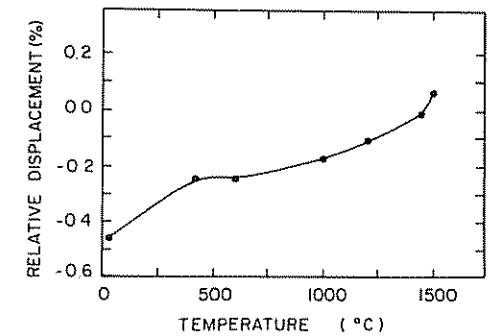

Fig. 3 Calculated interfacial relative displacement versus temperature

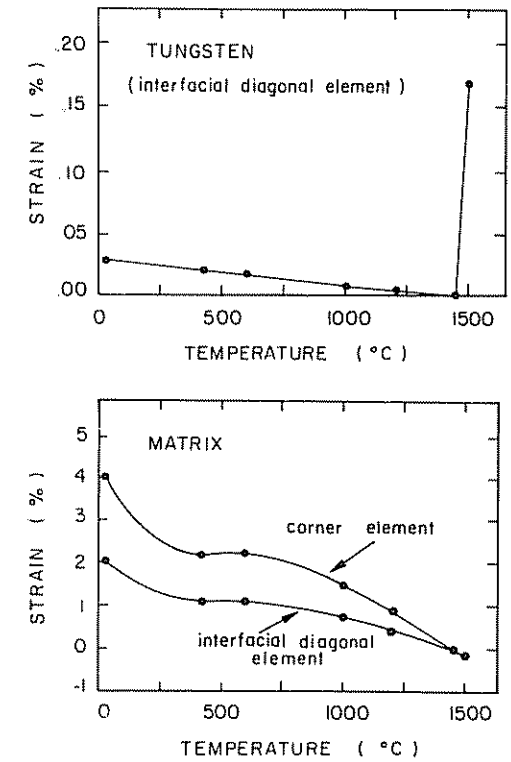

Fig. 4 Calculated strain versus temperature: (*a*) tungsten diagonal interfacial element; (*b*) matrix interfacial diagonal and corner element

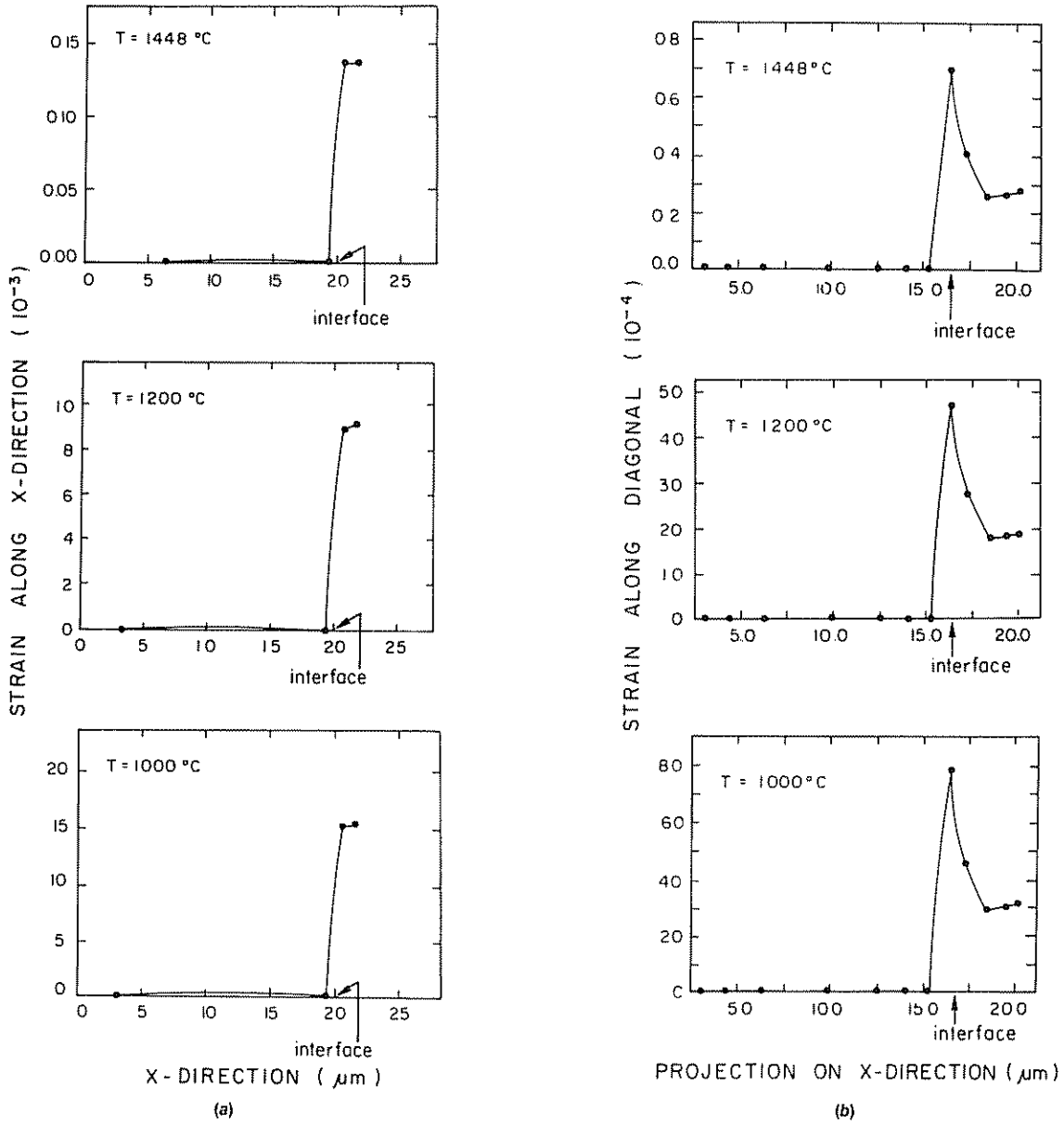

Fig. 5 Strain gradient at 1448, 1200, and 1000°C: (*a*) in x-direction; (*b*) in diagonal direction

process was performed for the 1500°C-room temperature range. Strains were calculated at discrete cooling steps and it was found that at room temperature the tungsten grains remain virtually unstrained while the matrix is plastically deformed, thus creating a state of residual strain in the alloy, which contributes significantly to the low ductility of the as sintered material.

3.1 Linear Elastic Assumptions. When assuming linear elastic behavior of the unit described above it is found that during cooling from 1500°C, large interfacial and corner strains (see Fig. 1) develop progressively in the matrix between 1300°C and 1100°C. Such strains, in excess of the elastic limit invalidate the use of linear elastic assumptions for the simulation of the actual process.

3.2 Elasto-Plastic Simulation. It is possible to overcome the difficulty described above as follows:
Instead of progressive matrix yielding (1300°C-1100°C) it is assumed, as a first approximation, that the entire matrix becomes plastic at 1200°C. It is also assumed that, during the entire sintering process, the tungsten-matrix interface remains intact, i.e. no decohesion or cracking occurs. In order to simulate plastic behavior, the incompressibility property of the matrix is introduced through the Poisson ratio and Young modulus as stated above. This was done for the liquid ($T > 1450$°C) and the plastic solid ($T < 1200$°C). In addition, negligible linear thermal expansion was assumed for the liquid phase. Appropriate thermal and mechanical properties of the matrix, utilized in this case are listed in table 2.

Figure 2 shows deformation states of the elasto-plastic unit at various stages of the thermal process. As a result of the near incompressibility of the liquid matrix, little deformation is noted in the heating stage (1450°C-1500°C). Cooling down from 1500°C to 1200°C results in little deformation, as expected from the elastic matrix. Subsequent cooling results in increasing deformation, which becomes drastically significant in the range 420°C to room temperature.

Tungsten-matrix interfacial displacement was calculated for a point situated on the interface in the diagonal direction. Relative displacement was defined with respect to 1450°C as reference temperature, according to:

$$\text{Rel. Dispt.} = (R(T)-R(1450^\circ C)*100)/R(1450^\circ C)$$

where R(T) is the distance of the interfacial point from unit's origin for a given temperature. Relative interfacial displacement as a function of temperature is shown in Fig. 3, whereas thermal strains calculated for interfacial elements on the tungsten and matrix side respectively are shown in Fig. 4. For the matrix side, two different element locations are displayed, namely diagonal and corner elements. The increase in strain observed for the tungsten side between 1450°C and 1500°C is due to the assumption that perfect bonding exists between the matrix and the grain. However, when matrix liquefaction occurs this is obviously not true. In Fig. 5, the strain distribution in the unit is shown for two directions, namely, diagonal and x-axis directions (see Fig. 1). From these figures it can be seen that the tungsten grains are nearly unstrained during the entire thermal cycle, as long as the matrix remains solid, while significant strains develop in the adjacent matrix which can reach values of 2 to 4 percent, depending on the elements location in the unit. Furthermore, it should be noted that a high strain gradient exists at the tungsten-matrix interface independently of the temperature or direction in the unit.

4 Discussion

In the present study, two kinds of solids bonded together are exposed to the same thermal conditions: high modulus, low thermal expansion tungsten grains and lower modulus, temperature dependent thermal expansion nickel matrix. The results of the computer modelled liquid phase sintering process indicate that while the tungsten grains remain nearly unstrained, the adjacent matrix is plastically strained up to 4 percent during the cooling process to room temperature. Mechanical studies of an alloy of the matrix composition have shown that it behaves like a non strain hardening solid, capable of sustaining significant plastic strains prior to failure (Krock and Shepard, 1963).

The results of the calculations suggest that the matrix yielding is a progressive process occuring during cooling between 1300°C to 1100°C. It begins at the corners of the unit and progresses simultaneously along the interface and inside the matrix. When assuming that yielding is completed at 1200°C, as in the present case, subsequent cooling results in further straining of the matrix, along with a high interfacial strain gradient. The calculated interfacial displacements are of the order of magnitude of 0.1 micron and such displacements are virtually undetectable by means of scanning electron microscopy, and thus have not been noticed experimentally. Consequently, it is reasonable to assume that these high interfacial residual strains contribute significantly to the observed lack of ductility of as-sintered heavy alloys, and to the reported failure mechanism by decohesion which occurs at the tungsten-matrix interface during tensile loading (Rittel and Roman, 1983).

It should be noted that the present suggestion does not contradict any of the previously proposed theories for these alloys lack of ductility, but rather adds a yet unconsidered aspect to this problem in particular, and to liquid phase sintering in general. In addition, the differences in thermal and mechanical properties cannot explain, solely, the effect of reheating the residually-strained unit which results in a much more ductile material, and post sintering ductility dependence on cooling rate.

Here, these thermal effects must be supplemented by improved interfacial adhesion resulting from processes, such as those proposed in the introduction, in order to explain the reported improvements in ductility.

5 Conclusions

Lack of room temperature ductility of some heavy liquid phase sintered alloys may stem from residual strains existing in the matrix and a high strain gradient present at the interfaces. These develop during the cooling of the alloy from the sintering temperature and are due to marked dissimilarity in the thermal and mechanical properties of the components of the alloy. This work provides a complementary insight to existing theories about the lack of ductility of some heavy alloys in the as-sintered condition.

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