THE EFFECT OF PHASE TRANSFORMATIONS ON THE MECHANICAL AND MAGNETIC PROPERTIES OF THE COLD WORKED Fe-49Co-2V(at.%) ALLOY

A. A. Couto and P. I. Ferreira
Instituto de Pesquisas Energeticas e Nucleares, Comissão Nacional de Energia Nuclear/SP, Travessa R 400, 05508-900, Brazil

Cold worked specimens of FeCo2V alloy (90% area reduction) were submitted to isochronal heat treatments in the 300- 1123 K range. Microhardness measurements as well as stress-strain and magnetic hysteresis curves, were were obtained from the heat treated samples. Transmission electron microscopy and X-ray diffraction were used to follow the microstructural changes occurring during the heat treatments. The mechanical test results showed that after isochronal heat treatments up to 823 K, the cold worked alloy hardens due to an intense precipitation of γ_2 phase, whereas softening is associated to the recovery, recrystallization and B2 (FeCo) ordering transformation. It was observed that the mechanical hardening was directly followed by magnetic hardening. The kinetics of B2 ordering and γ_2 precipitation transformation on the cold worked samples were investigated by using isothermal heat treatments at the temperatures 723, 773, 823 and 873 K. The precipitation of γ_2 phase, $(Fe,Co)_3V$ ordered $L1_2$, occurs mainly on free dislocations and subboundaries. The precipitation of γ_2 is accelerated by cold working. The ordering reaction is slowed down by the presence of a higher amount of cold work. Recrystallization is also partially developed by the ordering reaction (ordering induced recrystallization).

PACS NUMBERS: 81.40.-z ; 81.40.Cd ; 81.40.Ef

I. INTRODUCTION

The development of advanced motors and generators requires the use of magnetic materials that present both good soft magnetic properties and high mechanical strength. The Fe-49Co-2V (at%) alloy is a candidate material for these applications. Control of phase transformation that occur in this alloy can lead to improved properties. This has been the subject of a number of investigations[1-8].

Previous studies on Fe-49Co-2V alloy[9,10] showed that for temperatures above 1223 K the stable phase γ_1, has a fcc structure. For temperatures below 1143 K the γ_1 phase transforms to the bcc phase α_1. The phase α_1 can suffer an ordering transformation at temperatures below approximately 983 K. The resulting phase has a B2 structure and is termed α_2. Ordering leads to a strong alloy embrittlement. The ordering reaction can be by passed by quenching the alloy from temperatures above 983 K.

When the alloy is quickly cooled from temperatures where γ_1 is the stable phase, a martensitic transformation occurs and leads to a phase termed α_1'. When the FeCo2V alloy is aged at temperatures below 983 K, the precipitation of the phase γ_2 happens. The precipitates present a $L1_2$ structure and its compositions is approximately Co_3V with some Fe substituting Co atoms. This work is a contribution to the investigation of the effects of phase transformation, on the mechanical and magnetic properties of highly cold worked Fe49Co2V alloy, using isochronal and isothermal heat treatments.

2. EXPERIMENTAL

The material used is a commercial FeCo2V alloy with nominal composition 49Fe, 49Co, 2V (at.%), received as 0.1 mm thick strips, highly cold worked (above 90% area reduction). The heat treatments were performed in a tubular furnace under argon atmosphere, specimen cooling was done in iced brine solution. Vickers microhardness measurements were realized using 100 g load applied for 15 s. Tensile tests of 25 mm gage length specimens were performed at room temperature in an universal mechanical testing machine under a nominal strain rate of 10^{-4} s^{-1}.

Transmission electron microscopy of thin foils and extraction replicas were used for analysis. The long range order degree, S, was determined using CoKα X-ray diffraction data. The fundamental (200) and substructure (100) intensities were used. The first magnetization curve and hysteresis loop were obtained by using the a.c. technique and ring specimens.

3. RESULTS AND DISCUSSION

Figure 1 shows room temperature mechanical properties results obtained for initially cold worked specimens heat treated for 2 hours at temperatures in the range 673-1123 K. It can be also seen that the hardness initially increases up to temperatures around 823 K and then decreases for higher temperatures. A similar behavior is observed for the 0.2% offset yield strength and for the ultimate tensile strength. The ductility, measured by the uniform elongation, is small (≅ 1%) up to temperatures of 823 K and then increases continuously. The mechanical data obtained in this work are in agreement with previously published results by Josso[2] and Pinnel[11]. The values obtained for the long range order parameter S are encircled in figure 1 and indicate that quenching in an iced brine solution from temperatures of heat treatment above T_c (critical order-disorder transformation temperature) is sufficient for the alloy disordering.

In figure 2, the values obtained for the coercive force on isochronal heat heated specimens are correlated with the corresponding yield strength measured. Results reported by other authors are also included in the figure. Good linear correlation is obtained indicating that mechanical hardening/softening is directly followed by magnetic hardening/softening.

The cold worked FeCo2V alloy after heat treatment at 823 K still shows a highly cold worked microstructure, being partially recrystallized at 923 K, and completely recrystallized at 1023 K. Grain growth is observed after the 1123 K heat treatment. Simultaneously to the observed recovery and recrystallization , occurs the precipitation of the γ_2 phase. For heat treatment temperatures below 823 K the observation of γ_2 is difficult due to a dislocations high density. The strong mechanical hardening observed for heat treatments below 823 K can be associated with precipitation. The precipitation also occurs for heat treatments above 823 K, but its hardening effect is overran by the softening character of the recovery and recrystallization processes.

Vickers microhardness measuments and determination of the long range order parameter, as well as, microstructural observation were made on specimens submitted to isothermal heat treatments at the temperatures 723, 773, 823 and 873 K. Figures 3 and 4 illustrate the evolution with time of the microhardness and of the radio S/Smax (Smax = maximum equilibrium S value attained at a particular temperature), respectively. Comparison of the results shown in these figures indicate that the initial hardening observed at short times at these temperatures, cannot be associated with the ordering reaction since the degree of order reached at the microhardness maxima is relatively small (< 0.30) and this reaction is known to be softening in nature[12,13]. Furthermore, experiments in which specimens were cooled from

1123 K at various cooling rates, that is, with different final degree of order, showed that when the degree of order present in the alloy is increased, the yield strength is reduced[8,14].

Also, the observations made on thin foils and extractions replicas evidenced that the hardness increase at the short heat treatments times (figure 3) is well correlated with γ_2 precipitation on dislocations. Comparison of these results with those reported by Rawlings et al.[9,15] on ordered recrystallized, 25%, and 50% cold worked specimens, clearly shows that when the amount of cold work is increased to above 90%, the γ_2 precipitation on dislocations is accelerated.

The results presented in figure 4 include curves reported by Clegg and Buckley[16] for an initially disordered and recrystallized FeCo2.5V alloy heat treated at 823 K and 873 K. An important retardation of the ordering kinetics is verified when the alloy is highly cold worked. A similar slowing down of the ordering kinetics was also reported by Smith and Rawlings[15] for previously cold worked (25, 50 and 75% area reduction) FeCo-1.8V alloys.

Microstructural analysis performed on thin foils after 823 K for various times, showed the occasional presence of small B2 ordered grains at areas containing slip bands, as illustrated in figure 5. The presence of these ordered and recrystallized grains at temperatures lower than those for conventional recrystallization indicates that the ordering reaction may induce the recrystallization of the highly cold worked alloy as proposed by other authors[17].

4. CONCLUSIONS

Isothermal and isochronal heat treatments performed on highly cold worked FeCo2V for temperatures in the range 673 K-1123 K showed that recovery, recrystallization, B2 ordering and the precipitation of γ_2 occur in the alloy. The precipitation is predominant at lower isothermal heat treatment and induces an additional hardening of the alloy. B2 ordering occurs simultaneously to recovery leading to mechanical softening of the alloy and seems to assist alloy recrystallization. Mechanical tests and coercive force results are well correlated indicating that mechanical hardening/softening is directly followed by magnetic hardening/softening.

REFERENCES

[1]C. W. Chen, J. Appl. Phys., **32**, 348S (1961).

[2]E. Josso, IEEE Trans. Magn., **10**, 161 (1974).

[3]D. R. Thornburg, J. Appl. Phys., **40**, 1579 (1969).

[4]D. M. Pavlovic and F. G. Slone, IEEE Trans. Magn., **9**, 390 (1969).

[5]H. C. Fiedler, In American Institute of Physics, Proceedings of the Conference on Magnetism and Magnetic Materials (New York 1975), 739-740.

[6]M. R. Pinnel and J. E. Bennett, Metall. Trans., **5**, 1273 (1974).

[7]K. Kawahara and M. A. Uehara, J. Mater. Sci., **19**, 2575 (1984).

[8]A. A. Couto and P. I. Ferreira, J. Mater. Eng., **11**, 31 (1989).

[9]J. A. Ashby, H. M. Flower, and R. D. Rawlings, Met. Sci., **11**, 91 (1977).

[10]J. A. Rogers, H. M. Flower, and R. D. Rawlings, Met. Sci., **9**, 32 (1975).

[11]M. R. Pinnel, S. Mahajan, and J. E. Bennett, Acta Metall., **24**, 1095 (1976).

[12]N. S. Stoloff and R. G. Davies, Acta Metall., **12**, 473 (1964).

[13]T. L. Johnston, R. G. Davies, and N. S. Stoloff, Philos. Mag., **12**, 305 (1965).

[14]A. A. Couto, "Phase transformations and properties of FeCo-2%V alloy", MSc. Dissertation, University of São Paulo, Brazil 1989 (in Portuguese).

[15]A. W. Smith and R. D. Rawlings, Phys. Status Solidi (a), **34**, 117 (1976).

[16]D. W. Clegg and R. A. Buckley, Met. Sci. J., **7**, 48 (1973).

[17]R. A. Buckley, Met. Sci., **2**, 21 (1979).

REFERENCES

[1]C. W. Chen, J. Appl. Phys., **32**, 348S (1961).

[2]E. Josso, IEEE Trans. Magn., **10**, 161 (1974).

[3]D. R. Thornburg, J. Appl. Phys., **40**, 1579 (1969).

[4]D. M. Pavlovic and F. G. Slone, IEEE Trans. Magn., **9**, 390 (1969).

[5]H. C. Fiedler, In American Institute of Physics, Proceedings of the Conference on Magnetism and Magnetic Materials (New York 1975), 739-740.

[6]M. R. Pinnel and J. E. Bennett, Metall. Trans., **5**, 1273 (1974).

[7]K. Kawahara and M. A. Uehara, J. Mater. Sci., **19**, 2575 (1984).

[8]A. A. Couto and P. I. Ferreira, J. Mater. Eng., **11**, 31 (1989).

[9]J. A. Ashby, H. M. Flower, and R. D. Rawlings, Met. Sci., **11**, 91 (1977).

[10]J. A. Rogers, H. M. Flower, and R. D. Rawlings, Met. Sci., **9**, 32 (1975).

[11]M. R. Pinnel, S. Mahajan, and J. E. Bennett, Acta Metall., **24**, 1095 (1976).

[12]N. S. Stoloff and R. G. Davies, Acta Metall., **12**, 473 (1964).

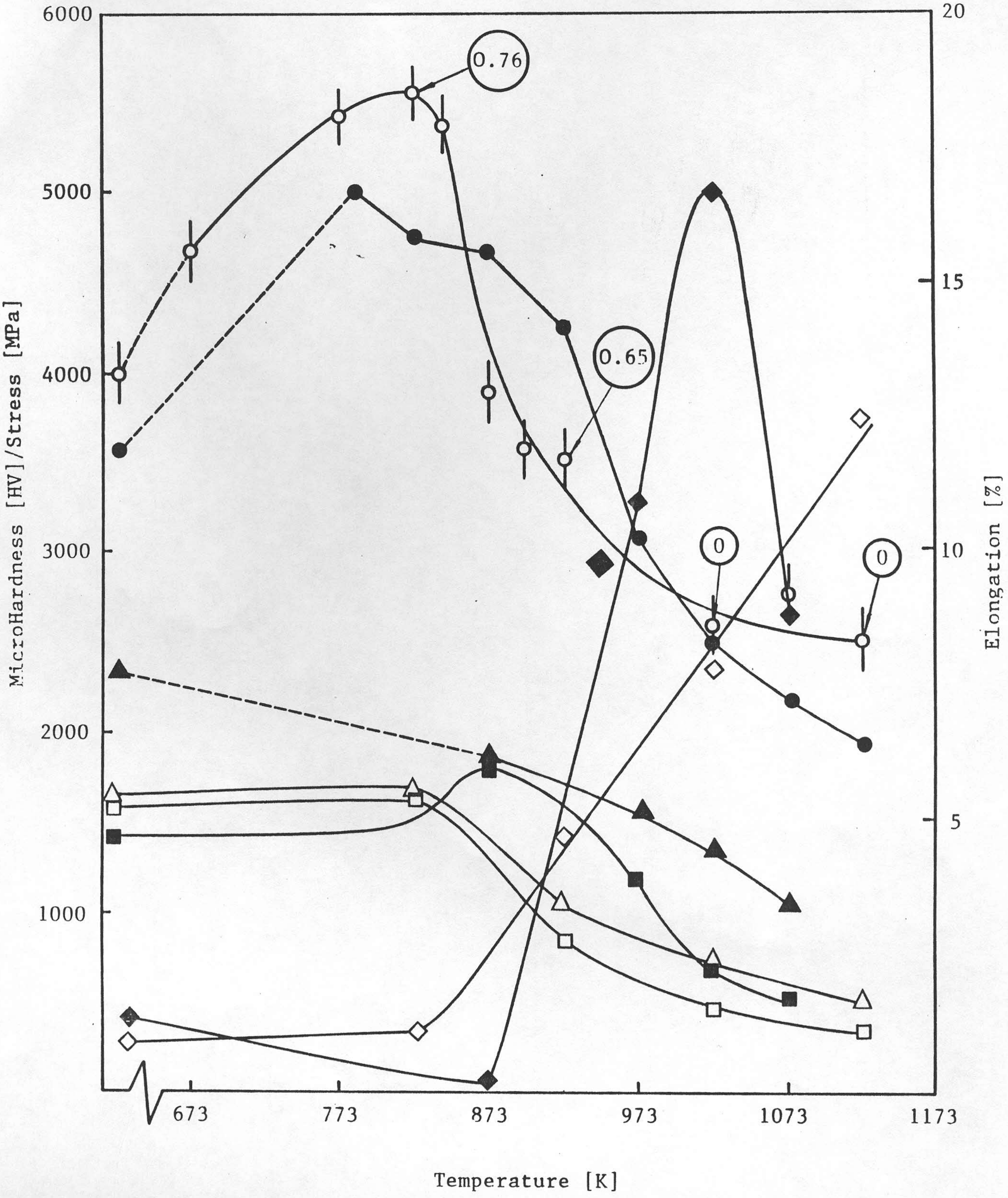
[13]T. L. Johnston, R. G. Davies, and N. S. Stoloff, Philos. Mag., **12**, 305 (1965).

[14]A. A. Couto, "Phase transformations and properties of FeCo-2%V alloy", MSc. Dissertation, University of São Paulo, Brazil 1989 (in Portuguese).

[15]A. W. Smith and R. D. Rawlings, Phys. Status Solidi (a), **34**, 117 (1976).

[16]D. W. Clegg and R. A. Buckley, Met. Sci. J., **7**, 48 (1973).

[17]R. A. Buckley, Met. Sci., **2**, 21 (1979).



	Present Authors	Josso[2]	Pinnel[11]
MicroHardness	○	●	
Yield Strength	□		■
Ultimate Strength	△		▲
Elongation	◇		◆

FIGURE 1

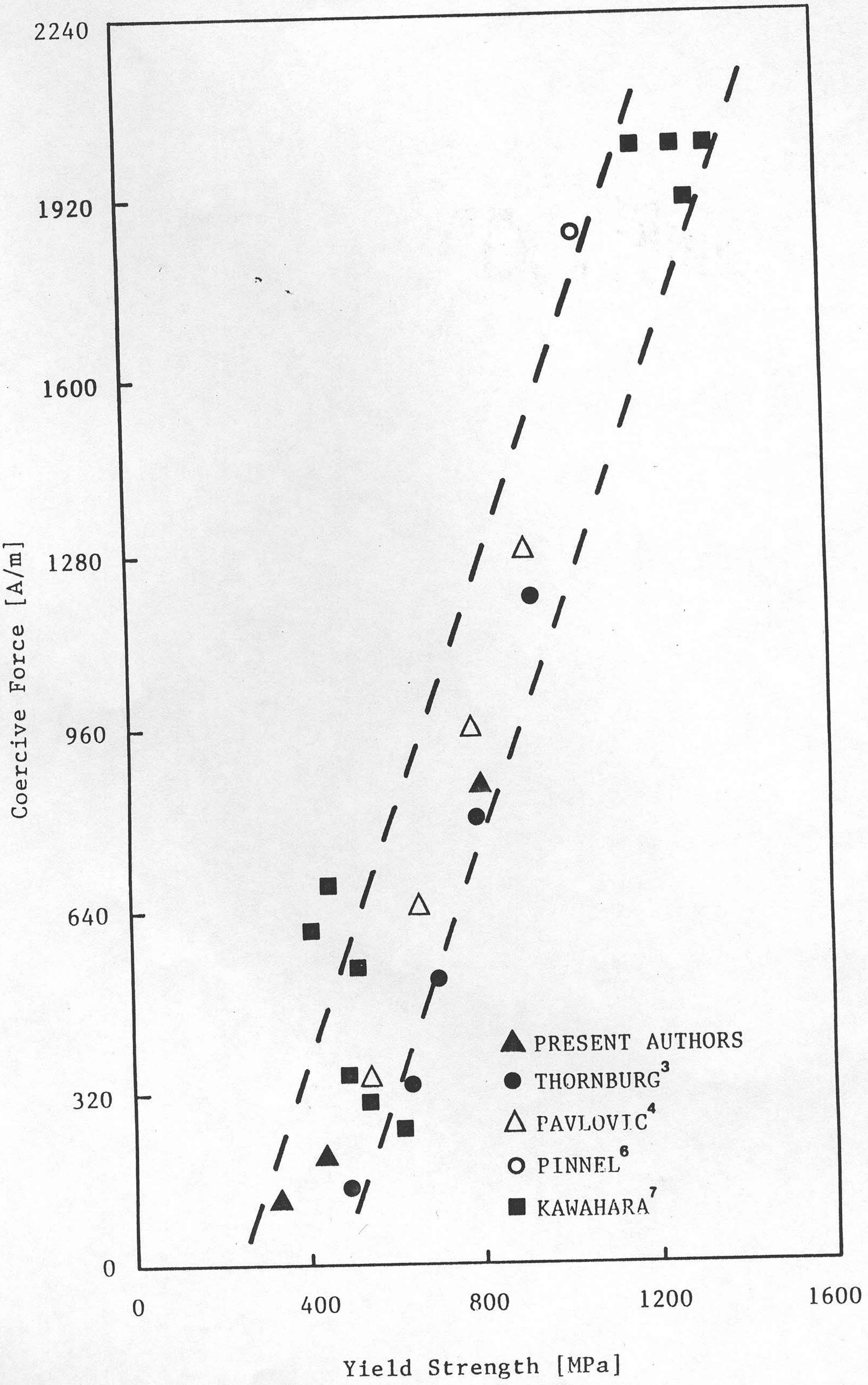

2240
1920
1600
1280
960
640
320
0
Coercive Force [A/m]
0
400
800
1200
1600
Yield Strength [MPa]
PRESENT AUTHORS
THORNBURG3
PAVLOVIC4
PINNEL6
KAWAHARA7

FIGURE 2

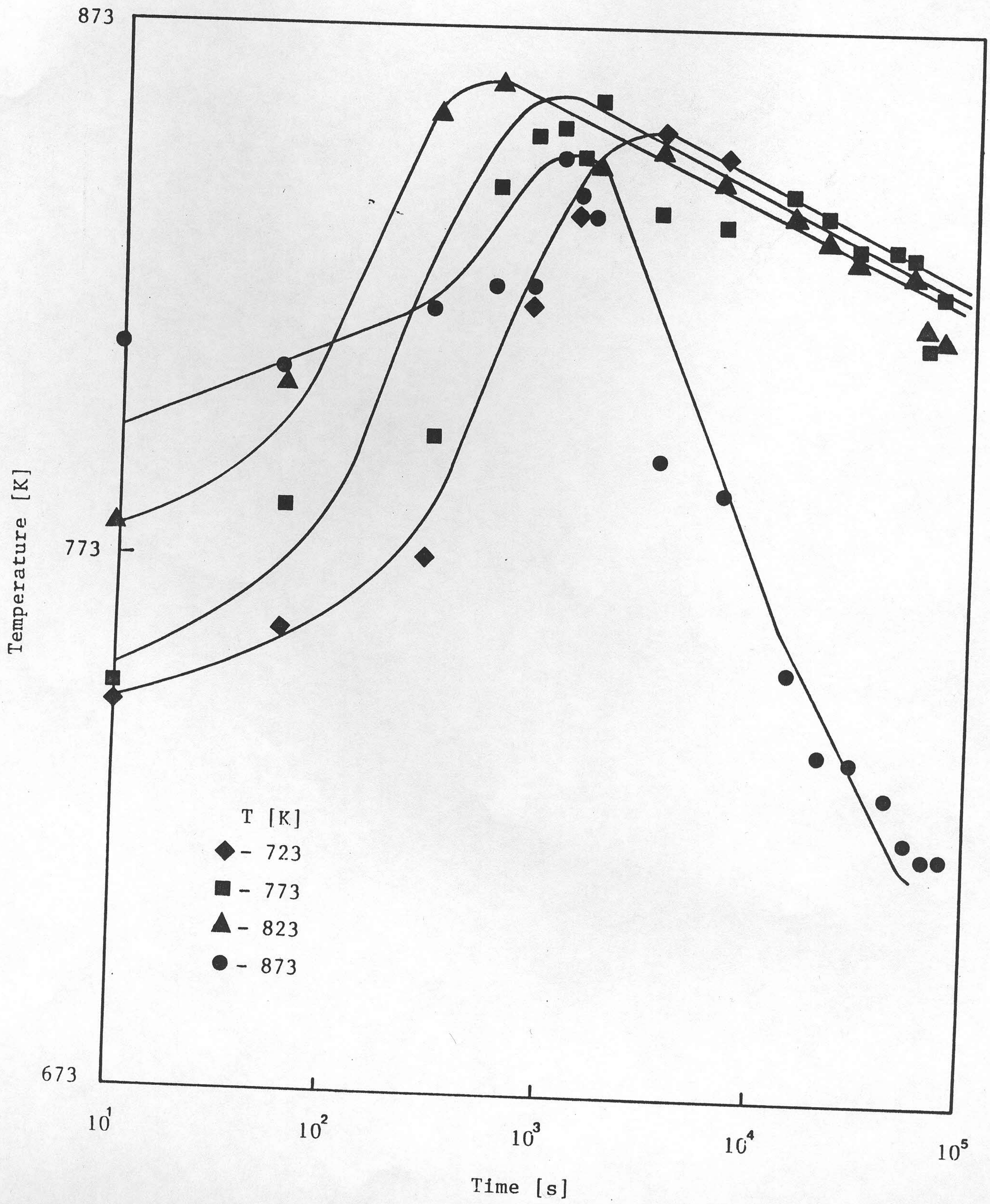
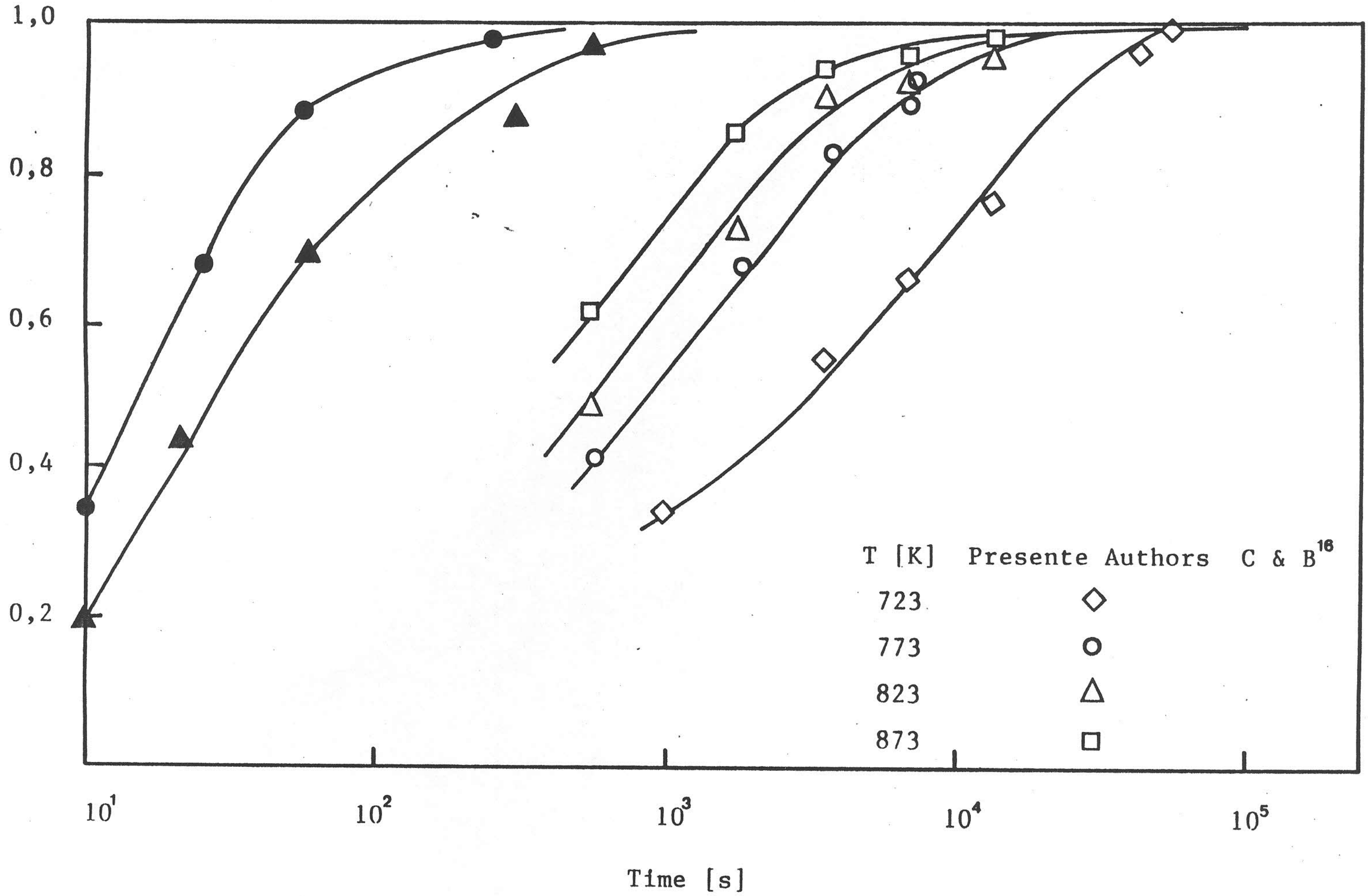

873
773
673
Temperature [K]
10^1
10^2
10^3
10^4
10^5
Time [s]
T [K]
- 723
- 773
- 823
- 873

FIGURE 3



1,0
0,8
0,6
0,4
0,2
T [K] Presente Authors C & B16
723
773
823
873
10¹
10²
10³
10⁴
10⁵
Time [s]

Figure 4

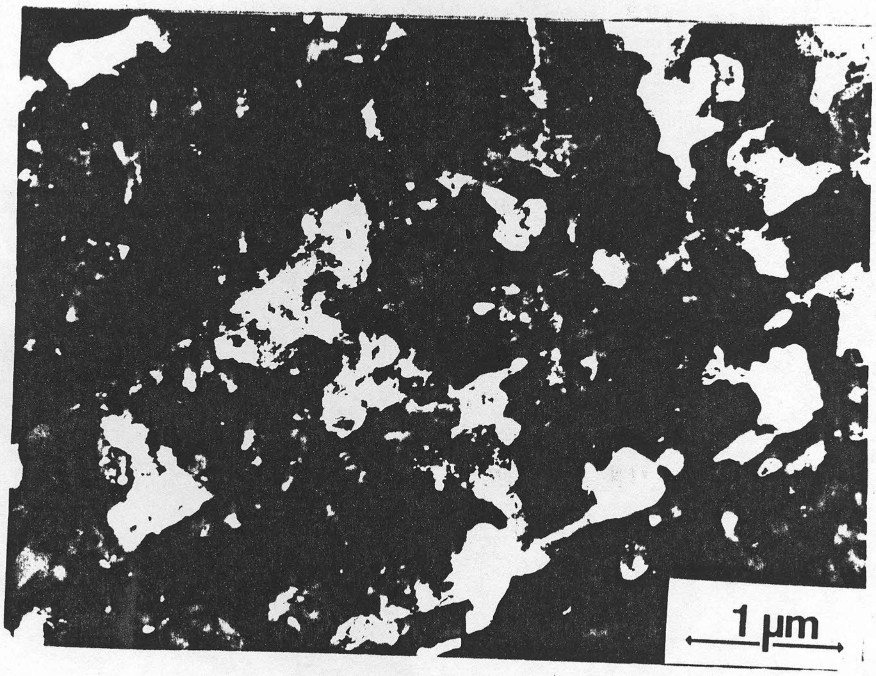


FIGURE 5

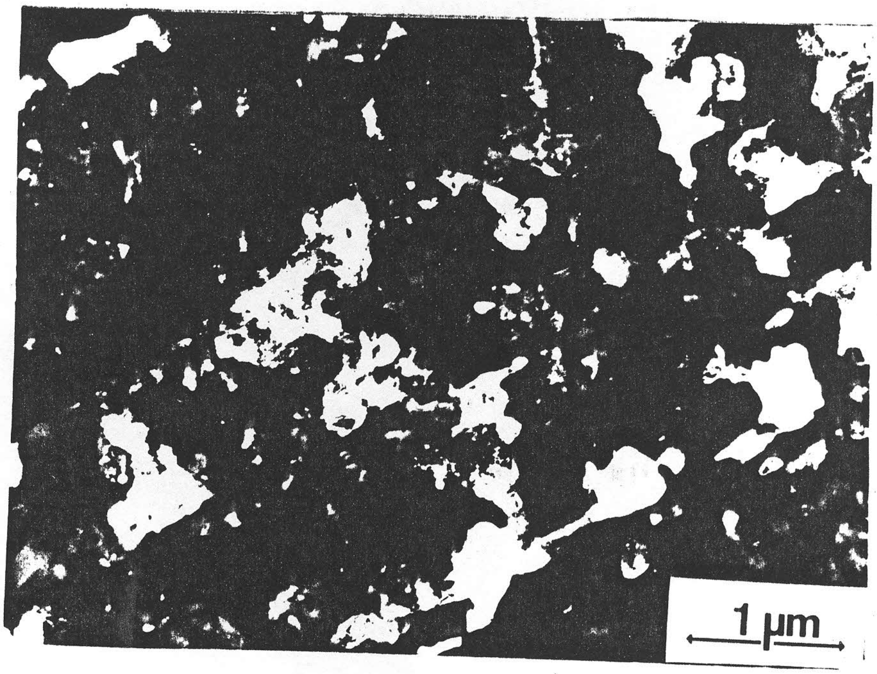


Figure 5