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MARTENSITIC TRANSFORMATION INDUCED BY TENSILE STRESS PULSES

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Résumé - La cinétique de la transformation martensitique induite par un pulse de tension tractive, produit par la reflection d'une onde de choc compressive sur une surface libre, a été etudiée dans un interval de temps d'à peu près une microseconde. Deux alliages ont étés employés: Fe-32% Ni - 0,035%C et Fe-22,5% Ni - 4% Mn. Le component hydrostatique de tension interagit avec la dilatation (0,04) de la martensite et augmente la temperature de transformation spontanée. Les essais d'impact ont étés conduits en variant la température ou bien la durée du pulse à une pression constante. Il a été demontré que la transformation martensitique, normalement considerée athermique dans l'alliage Fe-Ni-C, mnontre une nature isothermique dans le regime de microsecondes. La fraction transformée augmente avec la diminuition de température et avec l'augmentation de la durée de pulse, à une pression constante. A partir des résultats obtenus, les paramètres cinétiques et energetiques de la transformation martensitique dans les deux alliages ont étés obtenus et comparés aux théories en existance.

Abstract - The kinetics of martensitic transformation induced by a tensile stress pulse (produced by reflection of compressive shock waves at free surfaces) in time durations in the microsecond range were studied in Fe-32wt%Ni-0.035wt%C and Fe-22.5wt%Ni-4wt%Mn alloys. The tensile hydrostatic component of stress interacts with the dilatational strain (0.04) of the martensitic transformation and increases the Ms temperature. Shock impact experiments were conducted by varying either the temperature or pulse duration at a constant pressure. The martensitic transformation, normally considered to be athermal (exhibiting burst characteristics) in the Fe-Ni-C alloys, exhibits an isothermal nature in the microsecond regime in both alloys. The fraction transformed at a constant impact pressure increases with decrease in temperature at a constant pulse duration, and increase in pulse duration at a constant temperature. From the results obtained, the isothermal kinetic parameters and the energetics of the martensitic transformation were obtained and interpreted in terms of the existing theories.

1 - INTRODUCTION

The formation of martensite--the product of a diffusionless, displacive transformation, with kinetics and morphology determined principally by strain energy /1/—is known to be affected by externally applied stresses. Patel and Cohen /2/, systematically investigating this effect, first studied by Scheil /3/, found that tensile and compressive uniaxial stresses raised M_s (the temperature at which martensitic transformation starts) while hydrostatic compressive stresses lowered the M_s. They proposed a rationale based on the interaction of externally applied forces and the stresses generated by the martensitic transformation; the latter can be considered as a dilatational strain of 0.04 and a shear strain of 0.10. Meyers and Guimaraes /4/ in 1976 found that tensile pulses produced by the reflection of shock waves at a free surface generated martensite in a Fe-Ni-C alloy, while compressive pulses only generated dislocations. Later, Meyers /5/ observed the same phenomenon in a paper published by Snell et alii /6/ and used this interpretation in the estimation of a nucleation time for martensite.

Martensitic transformation has been classified, according to its kinetic behavior, into athermal and isothermal /7/. While the fraction of the transformed phase increases with time, at a specific temperature, for the isothermal case, it is considered constant for the athermal martensite There have been proposals (e.g., /8/)) that athermal martensite is an ultra-fast isothermal transformation. This investigative program used shock waves with the objective of generating conditions for martensite formation in the microsecond range. Shock waves were used as a metallurgical tool in order to gain an improved understanding of martensitic transformations. The results presented herein have been analyzed in greater detail by Thadhani and Meyers /9/ and Chang and Meyers /10/.

2 - EXPERIMENTAL TECHNIQUES

The Fe-Ni-C (Fe-32wt% Ni-0.035 wt%C) and Fe-Ni-Mn (Fe-22.5wt% Ni-4wt%Mn) alloys were received as slabs and prepared by a homogenization treatment followed by rolling interspersed with annealing treatments. The procedures are described in /9/ and /10/. The alloys were machined into disks that were pressure fit into stainless steel rings (Figure 1). Each stainless steel ring was mounted in a micarta and an aluminum ring. This consisted of the target assembly. The target assembly was cooled by copper coils attached to its back (surface opposite to impact). Impact events were carried out using a 2.5 in (6.35 mm) gas gun at SRI-International. AISI 304 stainless steel and aluminum projectiles were used, attached to sabots. The projectiles always had a thickness equal to half the thickness of the target; this ensured that the maximum duration of the tension occurred in the center of the target. The heat treatments produced grain sizes of 0.06 mm for the Fe-Ni-C alloy and of 0.08 mm for the Fe-Ni-Mn alloy.

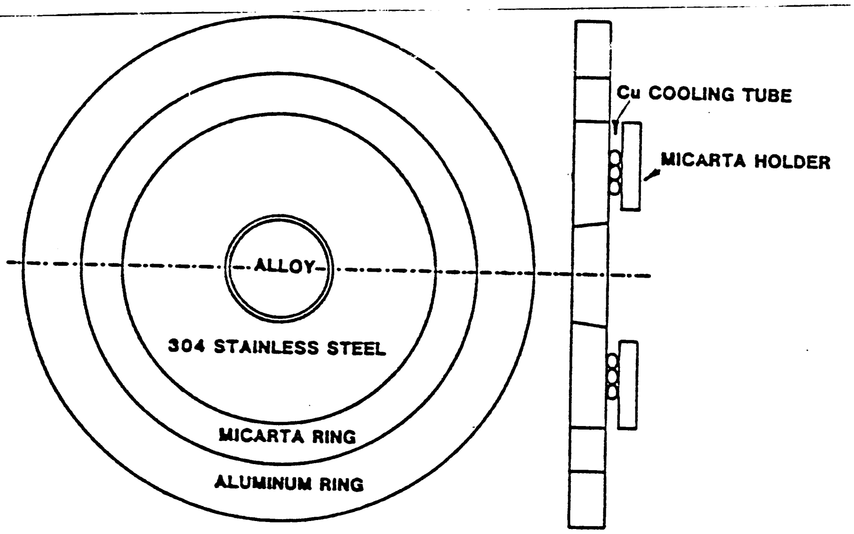

Figure 1. Experimental assembly used for target (marked as alloy); aluminum ring was fastened to end of barrel and copper cooling tube was circulated with nitrogen.

3 - RESULTS AND DISCUSSION

It was demonstrated that tensile hydrostatic stresses produced by the reflection of a shock wave at a free surface induce martensitic transformation in the burst-transforming Fe-32wt%Ni-0.035wt%C alloy at temperatures above the ambient-pressure M_s and in Fe-22.5wt%Ni-4.5wt%Mn alloy (which exhibits very sluggish transformation kinetics in the absence of stress). Figure 2 shows the morphology of the individual stress-pulse-induced martensite lenses. The classical "lenticular" shape is observed, and the martensite lenses exhibited a mid-rib and lateral expansions.

This effect having been confirmed, systematic experiments led to the conclusion that the martensitic transformation in the Fe-32wt%Ni-0.035wt%C alloy, considered to be athermal, is indeed an ultra-rapid isothermal transformation. Figure 3 shows the micrographs of cross sections of specimens impacted varying pulse durations, at a temperature of -20°C and constant stress level (1.4 GPa). The fraction of martensite formed at the position of maximum tensile stress duration (center of the target) increases with increasing pulse duration. Similar results were obtained for the Fe-22.5wt%Ni-4.5wt%Mn alloy (Fig. 4). This alloy exhibits very slow transformation kinetics and the first perceptible signs of transformation without any external stimulus require prolonged exposure (over one hour) at the temperature corresponding to the nose of the C-curve (-120°C). This alloy was previously investigated by Korenko and Cohen /11, 12/, who used magnetic fields to increase the driving force for the transformation; they were able to obtain transformation kinetics and found that the maximum transformation rate was obtained at -120°C.

Systematic experiments and quantitative metallography allowed the determination of

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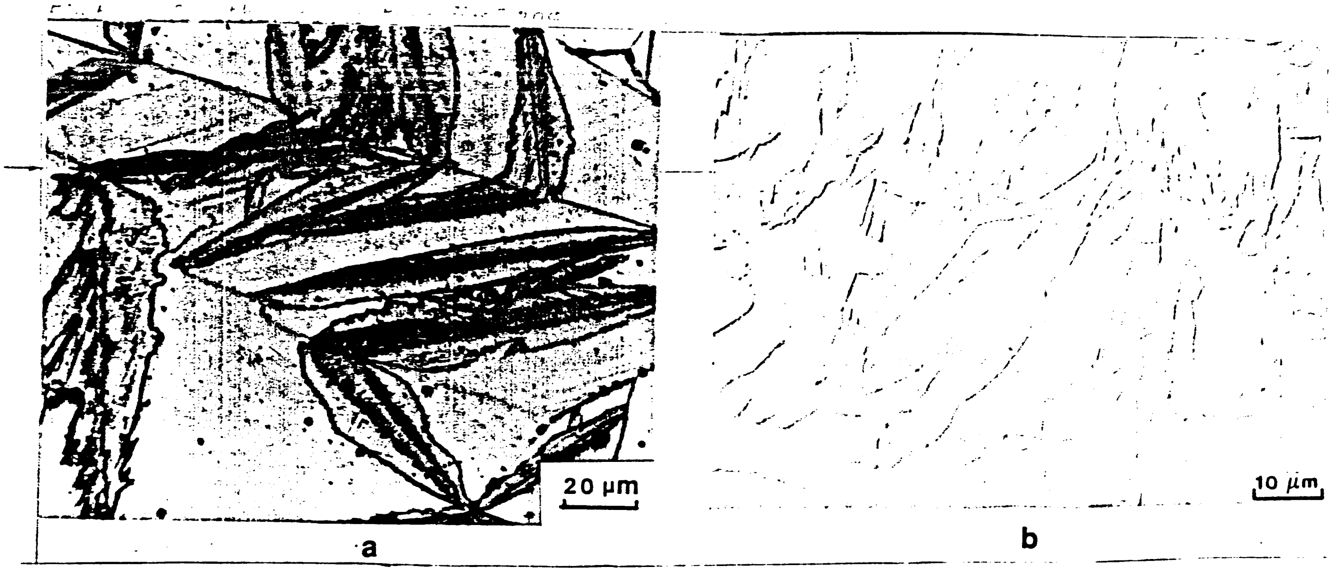

Figure 2. Stress-pulse induced martensite transformation (a) Fe-Ni-C and (b) Fe-Ni-Mn system.

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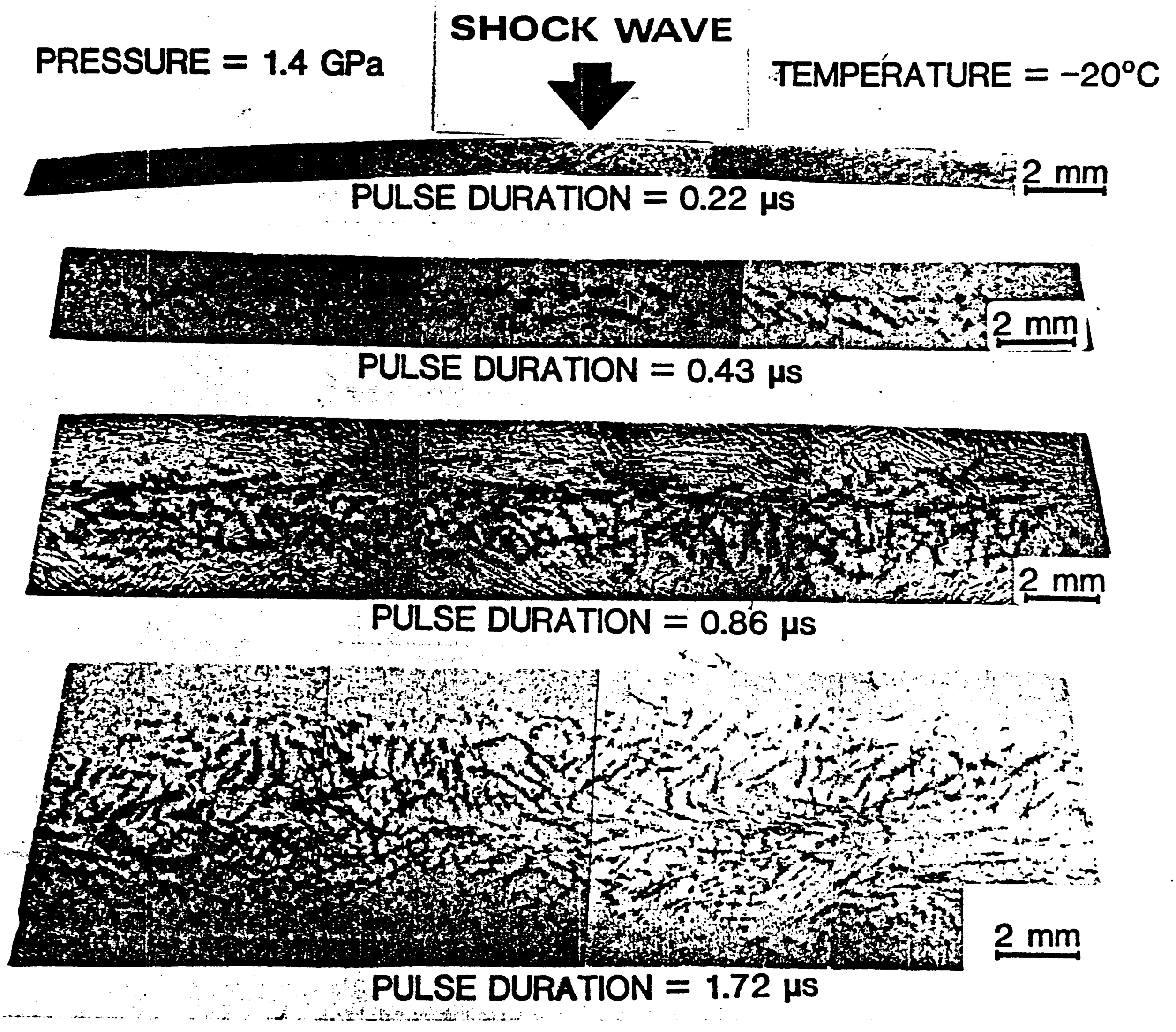

Figure 3. Micrographs of cross-sections of recovered targets (Fe-32wt%Ni-0.035wt%C alloy) impacted at varying pulse durations and constant temperature of $-20^{\circ}C$.

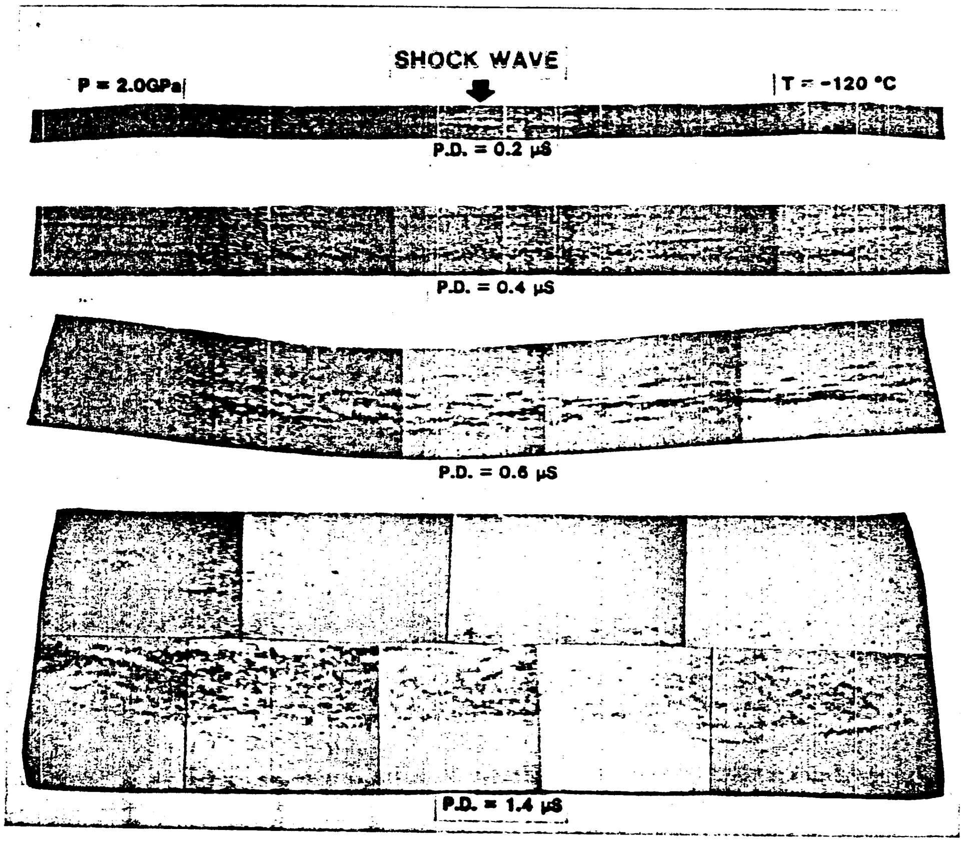

Figure 4. Micrographs of cross-sections of recovered targets (Fe–22.5% Ni–4% Mn) impacted at 2 GPa, -120°C, and varying pulse durations.

the kinetics of the martensitic transformation. Figure 5 shows the quantitative metallography results: for the Fe-32wt%Ni-0.035wt%C alloy, the isothermal nature of the transformation is evident and reaction seems to go to completion within the first microsecond. For the Fe–22.5wt%Ni-4wt%Mn alloy, transformation does not seem to reach saturation at 1.5 microseconds.

The kinetics of the martensitic transformation were analyzed by modified versions of the kinetic equation developed by Pati and Cohen [13]:

$$\dot{f} = df/dt = [n_i + f(p - \frac{1}{\bar{v}})](1-f)\nu \exp(-Q_a/RT)(\bar{v}+N_v \frac{d\bar{v}}{dN_v}) \qquad (1)$$

Here, n_i is the total number of available pre-existing nucleation sites, f is the fraction of martensite transformed, p is the autocatalytic factor, $\bar{v}$ is the mean volume per martensite plate, ν is the nucleation attempt frequency, and Q_a is the activation energy for nucleation.

Equation (1) is based on the assumption of a single activation energy for all nucleation sites and random nucleation events. This equation was modified to accommodate the specific needs of this investigation. If one considers that the mean volume of a martensite plane, $\bar{v}$, is not a function of the amount of transformation, then $d\bar{v}/dN_v$ equals zero. This is the situation observed in the present work for the Fe-32wt%Ni-0.035wt%C alloy, as shown in Figure 5(a). The fact that the transformation reaches saturation at a transformed fraction less than one implies that more sites are consumed than are generated by the new plates through autocatalysis; therefore p is small. Furthermore, the mean volume per martensitic plate is constant and is less than the volume of influence of a nucleation site upon being activated to martensite. These assumptions imply that fewer sites are produced by autocatalysis and that the probability of their falling within the volume of a martensite plate is small. Hence, for p and $\bar{v}$ small and constant, and $(p - 1/\bar{v})<0$, the "sweeping-out" effect represented by the term (1-f) can be reasonably discarded from Equation (1), which becomes:

$$\dot{f} = df/dt \cong \{ [n_i+f(p-1/\bar{v})] \nu \exp(-Q_a/RT)\} \cdot \bar{v} \tag{2}$$

The initial nucleation rate, assuming that the transformation occurs from only the pre-existing nucleation sites (i.e., $\dot{f} = 0$ at t=0), can be expressed as:

$$\dot{f}_o = n_i \bar{v} \nu \exp(-Q_a/RT) \tag{3}$$

Further manipulation of the equations leads to:

$$f = f_{max} [1-\exp(-\dot{f}_o/f_{max}) t] \tag{4}$$

This equation was used to predict the transformation as a function of time and is given by the lines in Figure 5(a).

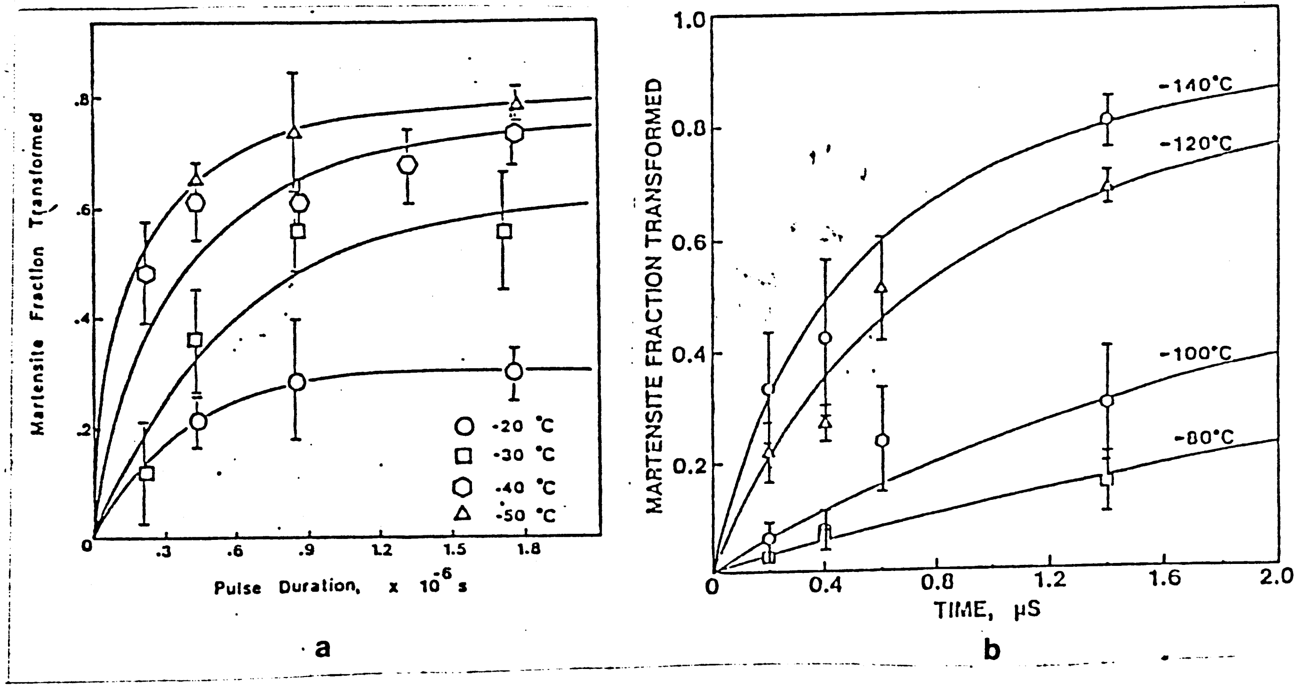

Figure 5. Martensite fraction transformed versus time at various temperature for (a) Fe-32wt%Ni-0.035wt%C and (b) Fe-22.5wt%Ni-4wt%Mn alloys.

For the Fe-22.5wt%Ni-4wt%Mn alloy, the reaction did not reach completion within the time frame of the experiments, and the following form of Pati and Cohen's [13] equation was used:

$$\ln \frac{f+\frac{n_i v}{p\bar{v}-1}}{f-1} = (n_i\bar{v} + p\,\bar{v} - 1)\nu\exp-\frac{\Delta W_a}{RT}\,t+\ln\frac{n_i\bar{v}}{p\bar{v}-1} \tag{5}$$

Application of this equation allowed the prediction of transformation rates shown in Figure 5(b) by solid lines.

Both predictions from Eqs. (4) and (5) were found to be in good agreement with experimental results and led to the establishment of ΔW_a, the activation energy (this was the only adjustable parameter in the computation). The driving energies for the transformations were calculated from the sum of the chemical and mechanical terms. The mechanical terms were obtained from Patel and Cohen's /2/ rationalization:

$$W = \frac{d\Delta G_{ch}}{dT}\,\Delta M_s \tag{6}$$

where ΔM_s is the change in martensite start temperature with stress. The chemical work contribution was found by interpolation from the free energies of the pure elements and from mixing enthalpies. The data are plotted in Figure 6. One can see that a linear relationship was obtained between the activation energy and driving

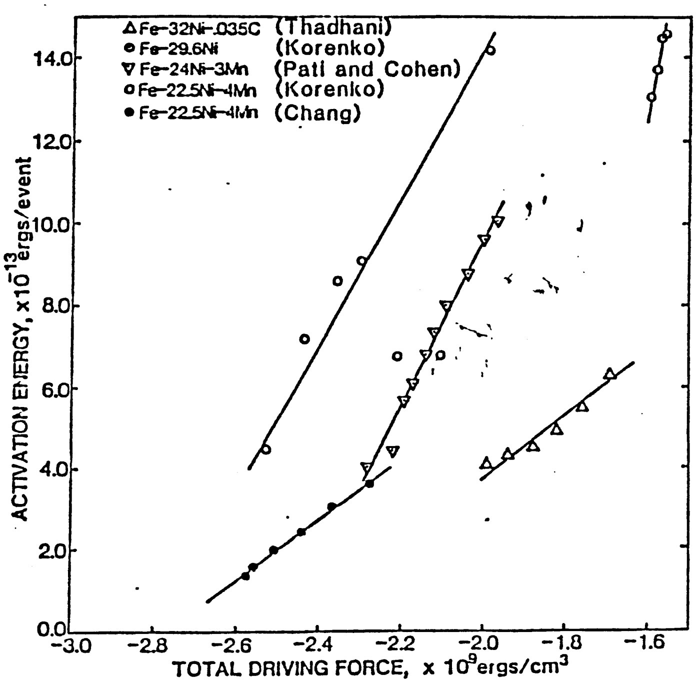

Figure 6. Relationship between activation energy and total driving force: Fe-32%Ni-0.035%C, Fe-22.5%Ni-4%Mn, Fe-29.6%Ni, Fe-24%Ni-3%Mn.

force, in agreement with earlier results by a number of investigators.

These results can lead to fundamental parameters of martensite nucleation. Kaufman and Cohen /15/ developed a model for the isothermal nucleation of martensite based on the existence of an oblate-spheroidal embryo with a semi-coherent interface. This model is based on the Knapp and Dehlinger /14/ approach. Applying Kaufman and Cohen's /15/ analysis, the radius of the most potent embryos was found to be equal to 16 nm for the Fe-32wt%Ni-0.035wt%C alloy. An alternative analysis, based on Magee /16/, established the activation volume, that is, the volume of the embryo at nucleation, directly from the slope of the activation energy versus driving force plot. Both calculations were made. These activation volumes were calculated to be 60 atoms for the Fe-Ni-C alloy and 65 atoms for the Fe-Ni-Mn alloy, indicating that martensitic nucleation in these alloys is interface-mobility controlled.

ACKNOWLEDGEMENTS

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