

MARTENSITIC TRANSFORMATION INDUCED BY TENSILE STRESS PULSE IN AN Fe-Ni-Mn ALLOY

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Martensitic transformation induced by a tensile pulse, produced by shock-wave reflection at the free surfaces, has been investigated. The tensile stress generated produces a considerable increase in the magnitude of the driving force for martensitic transformation. The alloy chosen for this investigation (Fe-22.5wt%Ni-4wt%Mn) exhibits a sluggish isothermal transformation at zero stress. It was found that the volume fraction of martensite transformed at a constant impact pressure increases with increasing pulse duration at a constant temperature, and with decreasing temperature (-60 to -177°C) at a constant pulse duration. The isothermal kinetics and energetics of the martensitic transformation were obtained and interpreted in terms of the existing theories. The activation volume for nucleation was found to be 65 atoms.

1. INTRODUCTION

Many uncertainties exist regarding the fundamentals of the nucleation and kinetics of martensitic transformation. In this research shock waves were used as a tool to probe into the microsecond and sub-microsecond regime. The martensitic transformation involves primarily a deviatoric ($\gamma = 0.10$) and a dilatational strain ($\epsilon = 0.04$). Patel and Cohen¹ demonstrated that externally applied shear stresses increase the driving force for the transformation while hydrostatic compressive stresses decrease the driving force, inhibiting it. Thadhani and Meyers^{2,3} applied this concept, generating shock-wave-induced tensile pulses to trigger martensitic transformation. By varying the duration of the tensile pulse, they showed that the martensitic transformation in an Fe-32wt% Ni-0.035wt%C alloy was actually isothermal (fraction transformed increasing with time) and not athermal, as previously assumed. The research results de-

scribed herein use the same technique to investigate the transformation kinetics in another alloy, Fe-22.5wt% Ni-4wt%Mn alloy. While the former alloy exhibits burst characteristics (very rapid transformation) the latter has such sluggish transformation kinetics that exposure of one hour at -120°C (the temperature at which the transformation rate is highest) is required for the first perceptible transformation signs. This alloy Fe-Ni-Mn was previously investigated by Korenko and Cohen⁴ who applied magnetic fields to increase the driving force for the transformation.

2. EXPERIMENTAL PROCEDURES

The experimental procedures are described in detail by Thadhani⁵ and Chang⁶. The alloy was homogenized for 72 hours in vacuum, hot rolled to thicknesses required for the targets, and reannealed for 20 minutes at 1100°C. The resulting

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grain size, measured by the linear intercept technique, was 81 μm . The specimens were impacted by 6061-T6 aluminum alloy flyer plates at a velocity of 200 m/s yielding a shock pressure of 2 GPa. The impact experiments were conducted in a one-stage gas-gun at SRI International. This velocity was the maximum velocity at which no significant spalling occurred. The targets were cooled by nitrogen circulated in copper coils attached to the back of the disk supporting the specimen. The SWAP-7 code was used to calculate the stress histories inside the specimens^{5,6}.

3. RESULTS AND ANALYSIS

Figure 1 shows the fractions transformed as a function of time and temperature.

Pati and Cohen's⁷ approach for transformation kinetics was used to determine the activation energy, ΔW_a . Assuming that the mean volume, \bar{V} , of martensite plate is constant with volume fraction transformed, Pati and Cohen's⁷ formulation can be rewritten as

$$\frac{df}{dt} = (P\bar{V}-1) \left\{ f - \frac{n_i \bar{V}}{1-p\bar{V}} \right\} (1-f) \nu e^{\left(\frac{-\Delta W_a}{RT}\right)} \quad (1)$$

where f is the volume fraction of martensite formed at time t , ΔW_a is the activation energy for nucleation at a given temperature, ν is the attempt frequency, n_i is the initial number of embryos, P is the autocatalytic factor, and T is the absolute temperature. Although there are some inherent assumptions in Pati and Cohen's⁷ formalism, such as a single activation energy for all nucleation sites and random nucle-

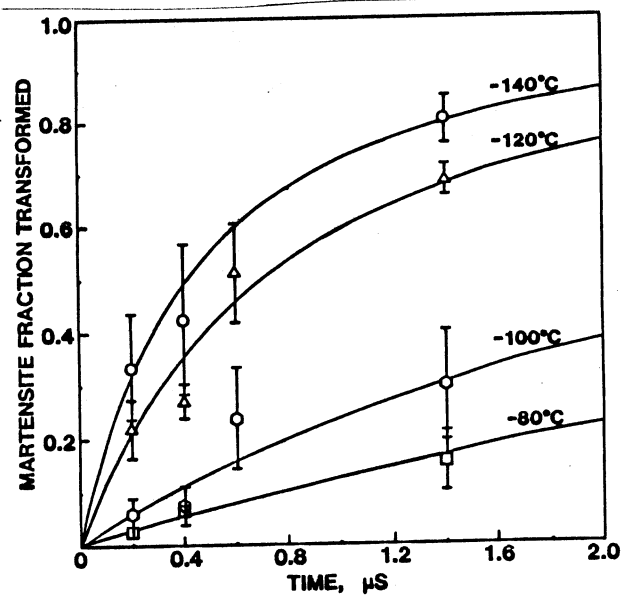


Fig. 1 Martensite volume fraction transformed at tensile stress pulse of 2 GPa as a function of temperature, at different pulse durations of 0.2, 0.4, 0.6 and 1.4 μs .

ation events, one can determine the effective activation energy for nucleation during the entire course of isothermal transformation⁸. Integrating Equation (1) by using the method of separation of variables, a linear equation is obtained as a function of time,

$$\ln \frac{f + \frac{n_i \bar{V}}{P\bar{V}-1}}{f-1} = t \left[(n_i \bar{V} + P\bar{V}-1) \nu e^{\left(\frac{-\Delta W_a}{RT}\right)} + \ln \left[\frac{n_i \bar{V}}{P\bar{V}-1} \right] \right] \quad (2)$$

By substituting experimental values of fraction f versus time t at constant temperature, along with the values of ν (10^{13}s^{-1}), n_i (10^7cm^3), R , and \bar{V} into Equation (2), the activation energy, ΔW_a , was computed. Using the least squares method, ΔW_a was iteratively determined by the value of P which gives the minimum root mean square error.

The martensite fraction transformed as a function of time in the present work is shown in Figure 2. The calculated solid curves (based on Equation (1)) for the martensite fraction transformed with time at constant temperatures of -80° , -100° , -120° , and -140°C are in good agreement with the experimental points.

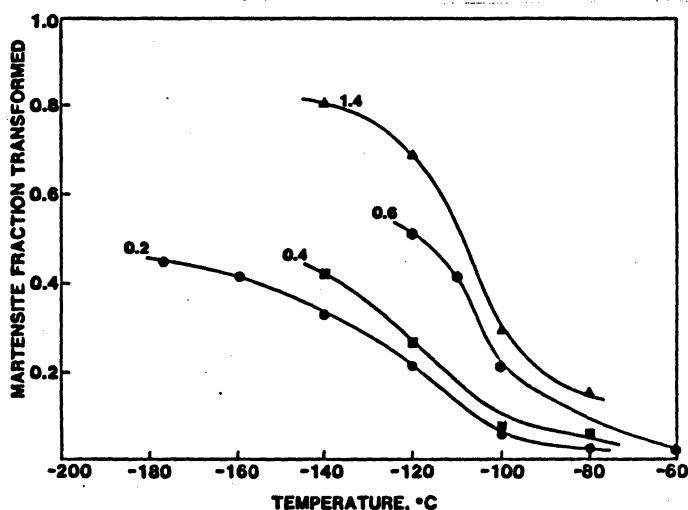


Fig. 2 Experimental points and calculated curves for martensite volume fraction as a function of pulse duration, at different temperatures.

The martensite morphology in Fe-22.5% Ni-4%Mn alloy induced by a tensile pulse of 2 GPa is plate-like which is evidence of the elastic-stress-assisted martensite. Thus, the martensite can be assumed to be formed in the elastic portion of the tensile pulse. In the elastic regime the M_s temperature change in ferrous alloys is proportional to the applied mechanical stress⁹ that contributes a mechanical work term to the overall thermodynamic driving force for the transformation. Since there is no obvious M_s temperature in Fe-22.5%Ni-4%Mn alloy, it is difficult to obtain the mechanical work contribution to the

overall driving force. Thadhani and Meyers² used the change in M_s temperature as a measure of the mechanical work contribution due to the tensile stress pulse, based on Patel and Cohen's¹ rationalization. Extrapolating the M_s temperature change for a tensile pressure pulse of 2 GPa (present work), one obtains an equivalent M_s change of 75.7°C . Since all experiments performed were similar to those in Thadhani and Meyers' work², the M_s change of 75.7°C was used to obtain the mechanical work contribution, adopting Patel and Cohen's expression:

$$W = \frac{d\Delta G_{ch}}{dT} \Delta M_s \quad (3)$$

The value of $d\Delta G_{ch}/dT$ within the temperature range of interest (-60° to -177°C) is 2.33 J/mol K . The chemical free energy change for martensitic transformation in the Fe-22.5%Ni-4%Mn alloy can be expressed as (this is based on an interpolation conducted from values known for Fe, Mn, and Ni):

$$\Delta G_{ch} = 1613.7 + 5.56 \times 10^{-3} T^2 - 8.83 \times 10^{-5} T^3 + 15.22 \times 10^{-8} T^4 \quad (\text{J/mol}) \quad (4)$$

Figure 3 shows the activation energy linearly related to the total driving force for different Fe-Ni-Mn and Fe-Ni-C alloys reported in the literature. The curve for the Fe-22.5%Ni-4%Mn alloy (present work) lies towards the bottom, directly below Pati and Cohen's Fe-24% Ni-3%Mn alloy⁷, and reveals a lower slope, compared to other alloys.

The coefficient B, which is the slope ($\Delta W_a / \Delta G_{tot}$) of the curve in Figure 3,

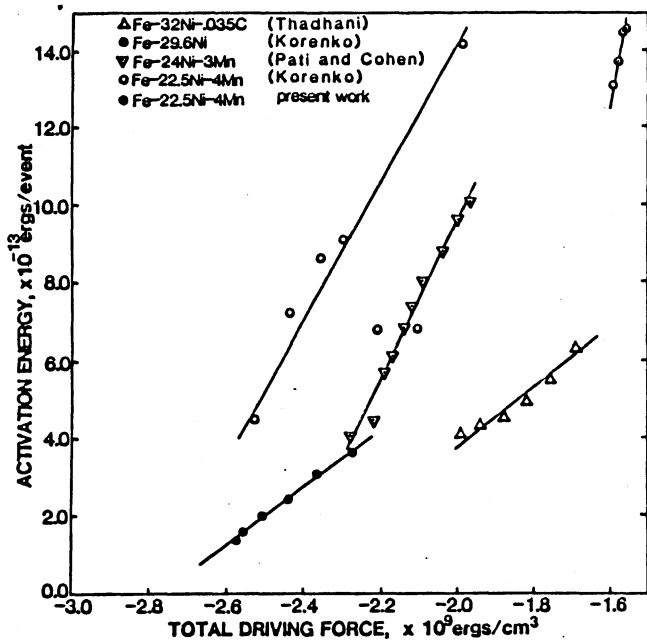


Fig. 3 Relationship between activation energy and total driving force.

corresponds to the activation volume, V^* (volume transformed/event divided by atomic volume of a BCC unit cell). The physical interpretation of the activation volume V^* is, according to Magee⁸, the volume of the embryo at nucleation (peak of ΔG_{tot} versus volume of martensite curve). The activation volumes compared to those reported by other investigations in bulk Fe-Ni-Mn alloys are the following: 65 atoms (present investigation); 100 atoms (Korenko)⁴; 190 atoms (Pati and Cohen)⁷. This decrease in the activation volume at the high driving forces imparted by the tensile pulses is consistent with the trends postulated by Olson and Cohen¹¹. The physical underpinnings for such a decrease in V^* as ΔG_{tot} increases are that the nucleation is controlled by motion of the austenite-martensite (embryo) interface, consisting of discrete dislocation arrays.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation (Grant DMR81-15127) and by the New Mexico Department of Economic Development and Tourism through the Center for Explosives Technology Research.

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