

MARTENSITIC TRANSFORMATION INDUCED BY TENSILE STRESS PULSES

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1. INTRODUCTION

The martensitic transformation has been generally classified, according to the observed kinetic behavior, into isothermal and athermal [1]. While the fraction of martensite formed increases with time, at a constant temperature, for the isothermal case, it is considered constant for athermal martensite, in which it is a function of undercooling below M_s . Isothermal martensite was first observed by Kurdjumov and Maksimova [2]. Fe-C, Fe-Ni-C systems tend to exhibit athermal transformation, while Fe-Ni and Fe-Mn-Ni tend to show isothermal transformation. The effect of externally applied stresses on the formation of martensite was first observed by Scheil [3]. In 1953, Patel and Cohen [4] systematically investigated this effect and found that shear stresses help the transformation and normal stresses favor or oppose it depending on whether they are tensile or compressive, respectively. Meyers and Guimarães [5] in 1976

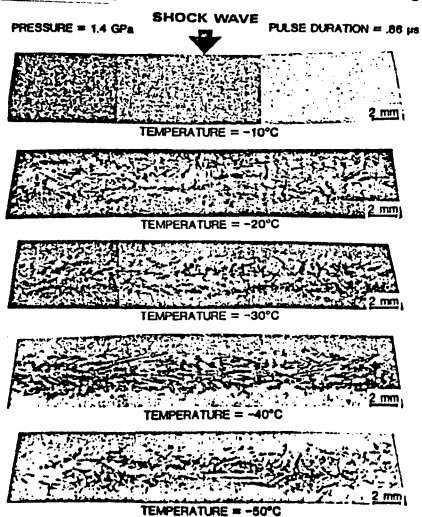


Fig. 1. Micrographs of cross-sections of recovered targets impacted at varying temperatures and constant pulse duration of 0.86 microseconds.



Fig. 2. Micrograph of specimen impacted at -30°C and 1.4 GPa showing martensite stringers running along bands.

found that a tensile pulse produced by a shock wave reflected at a free surface triggered the martensitic transformation. Meyers [6] used this concept to propose a nucleation time for transformation. Kolomytsev et al. [7] applied shock and tensile waves to martensitic transformations. This paper describes a systematic analysis of martensitic transformation induced by tensile pulses and proposes that athermal martensitic transformation is an ultra-rapid isothermal transformation.

2. EXPERIMENTAL TECHNIQUES

An Fe-32wt%Ni-0.035wt%C alloy was used in this investigation. It was cold-rolled to 10.0 and 5.5 mm plates and annealed at 1100°C for 2 hours in vacuum. After specimen preparation (machining) an additional anneal of 750°C for one hour was conducted for stress relief. The M_s (martensite start) temperature was found to be -61°C. Disc-shaped specimens of various thicknesses were prepared and impacted in a one-stage gas gun at SRI-International at temperatures between 20°C and -50°C. The thickness of the flyer plate was always equal to half the thickness of the target, so that the maximum tensile pulse occurred in the central portion of the target. The pressure was kept constant at 1.4 GPa and the pulse durations were approximately 0.2, 0.4, 0.9, 1.3, and 1.8 μ s. These values were established after instrumented experiments using manganin gages were performed, allowing the establishment of the equation of state for the Fe-32wt%Ni-0.035wt%C alloy. The SWAP-7 code was used to establish the stress histories. The martensite fractions were obtained by a point counting technique. Greater details of the experimental procedures can be found in Thadhani [8] and Thadhani and Meyers [9].

3. RESULTS AND DISCUSSION

Experiments were performed as a function of temperature (-10 to -50°C) for pulse durations of 0.44, 0.86, and 1.76 μ s, and at varying pulse durations (0.22 to 1.76 μ s) for the temperatures of -20, -30, -40, and -50°C. Figure 1 shows the sections of the targets impacted at varying temperatures and at a constant pulse duration of 0.86 μ s. The regions transformed to martensite are black. Three important observations can be made:



- (a) As the temperature is decreased, the fraction of material transformed to martensite increases. At zero stress, the temperature at which martensite starts to form is -61°C . Hence, the stress pulse changes the M_s (martensite start) temperature. Analogous photomicrographs at varying pulse durations revealed that the fraction transformed increased with increasing pulse duration.
- (b) The fraction transformed is largest at center, where the amplitude and duration of the tensile reflected pulse are highest. At the impact interface (marked by arrow) no transformation is observed. Thus, the transformation is triggered by the tensile reflected pulse.
- (c) The transformation does not take place homogeneously, but occurs in "stringers", more evident in Figure 2. These stringers were found to occur along previously existing deformation bands produced by the shock wave preceding the tensile reflected pulse. A detailed explanation is given by Thadhani et al. [10].

After quantitative metallography the fractions transformed were determined and are shown in Figure 3 (symbols with error bars). The analysis of the experimental results was made along the kinetic equation of Pati and Cohen [11] appropriately modified. The mean volume per martensite plate was found to be independent of fraction transformed; the "sweeping out" effect of nuclei; represented by $(1-f)$, where f is the fraction transformed, was removed from Pati and Cohen's equation; the resulting equation is:

$$\frac{df}{dt} = \dot{f} = \left\{ \left[n_i + f \left(1 - \frac{1}{p} \right) \right] v \exp \left(-Q_a/RT \right) \right\} \bar{v} \quad (1)$$

where n_i is the total number of available preexisting nucleation sites, f is the fraction of martensite transformed, p is the autocatalytic factor, \bar{v} is the mean volume per martensite plate, v is the nucleation attempt frequency, and Q_a is the activation energy for nucleation. Considering that reaction reaches saturation at values $f_{\max} < 1$, Equation 1 can be manipulated:

$$\dot{f}_0 = n_i \bar{v} v \exp \left(-Q_a/RT \right) \quad (2)$$

$$\dot{f} = 0 \text{ and } n_i + f_{\max} \left(p - \frac{1}{\bar{v}} \right) = 0 \quad (3)$$

$$f = f_{\max} \left\{ 1 - \exp \left[\left(\dot{f}_0 / f_{\max} \right) t \right] \right\} \quad (4)$$



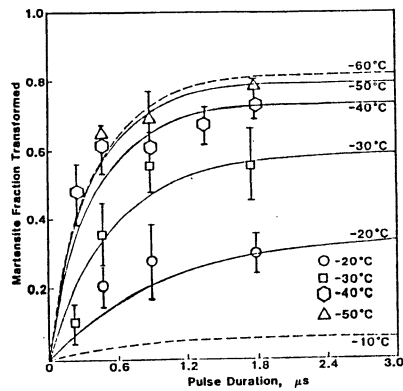


Fig. 3. Agreement between the experimental points and predicted transformation curves for Fe-32Ni-0.035%C alloy, for temperatures ranging between -10°C and -60°C .

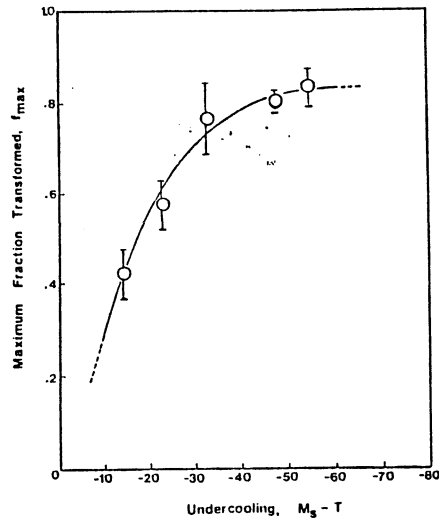


Fig. 4. Maximum martensite fraction (f_{max}) as a function of undercooling ($M_s - T$) at ambient pressure.

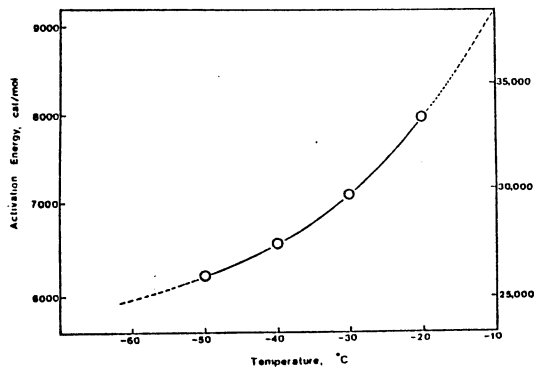


Fig. 5. Variation of activation energy as a function of temperature for Fe-32Ni-0.035%C alloy.

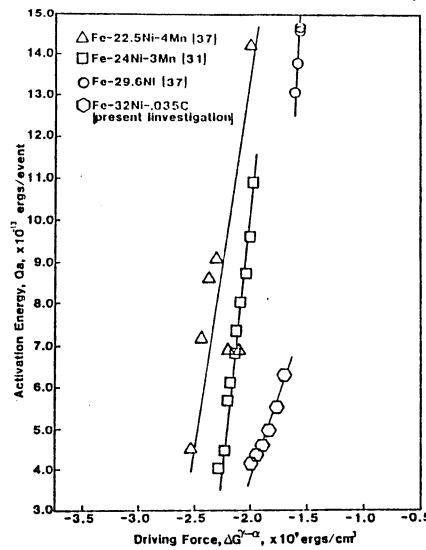


Fig. 6. Activation energy dependence on the total driving force for Fe-32wt% C alloy.

By plotting $\ln(1-f/f_{\max})$ versus t , one obtains slopes that are equal to $-f_0/f_{\max}$. From Equation 2, the initial nucleation rate is given. Hence, the value of the activation energy, Q_a , can be computed if n_i , \bar{v} , ν , f_{\max} are known. The initial number of nucleation sites, n_i , was taken as 10^7 cm^{-3} , from the literature. The nucleation attempt frequency, ν , was taken as 10^{13} s^{-1} . The maximum fraction of martensite, f_{\max} , was obtained from experiments in which specimens were cooled below M_s ; the fractions transformed were measured as a function of temperature and are plotted in Figure 4. By using these values, Q_a was calculated. The results are shown in Fig. 5. By inserting these values into Eq. 1, it was possible to calculate the predicted transformation rates. They are indicated by continuous and broken lines in Figure 3. It can be seen that the agreement between experimental results and prediction from Pati and Cohen's modified kinetic formulation is good, and that athermal martensite is indeed ultrarapid isothermal martensite.

The driving force for the transformation was calculated by considering both the chemical and mechanical terms. The plot of Figure 6 shows the linearity between the activation energy and driving force. This is in accord with classical nucleation theory.

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