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EFFECT OF STRESS AND STRAIN ON MARTENSITIC TRANSFORMATION IN A  
Fe-Ni-Mo-C ALLOY WITH A HIGH  $M_s$  TEMPERATURE

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**Abstract** - The interactions between stress and martensitic transformation are studied for a low alloyed steel (60NCD11) with a  $M_s$  temperature of 230°C. For tensile tests carried out at temperatures just above  $M_s$ , the transformation doesn't exhibit the stress-assisted behavior expected for athermal martensitic transformation. In contrast, for "static" tests,  $M_s$  is enhanced even at low stresses, but this enhancement is cooling-rate dependant. A comparison has been made with an Fe-Ni-C-Cr alloy obtained by adding Nickel to the 60NCD11 steel and an Fe-20 Ni - 0.5 C alloy. For these two alloys  $M_s$  is below room temperature. A classical scheme with stress-assisted martensite and strain-induced martensite is observed for the Fe - 20 Ni - 0.5 C alloy but an intermediate behaviour is obtained for the Fe-Ni-C-Cr alloy.

The influences of stress and strain on martensitic transformation of steel have been studied by many authors (1-5) both F.C.C.  $\rightarrow$  B.C.C. and F.C.C.  $\rightarrow$  H.C.P.A of these studies however indicates, that most were carried out at below room temperatures.

An interest in the interactions between stress and phase transformation, particularly concerning alloyed steels in common use where martensitic transformation occurs at rapid quenching, led us to study the effect of tensile stress on a steel whose composition is Fe - 0.6 C-2.5 Ni-0.4 Cr-1.5 Mo (60 NCD11). The transformation temperature ( $M_s$ ) of this steel is 230°C.

In order to compare the results of this steel with other published data we made an alloy whose  $M_s$  temperature was - 16°C by adding Nickel to 60 NCD11 steel and an Fe-20 Ni-0.5 C alloy whose  $M_s$  temperature is - 6°C, a type widely studied by others (1, 2, 4,5).

**Experimental methods** - The composition of the three alloys studied is given in table 1 (wt %).

Table 1

Alloy elements	C	Ni	Cr	Mo	Mn	Si	V	P	S
60 NCD 11	0.51	2.54	0.41	1.46	0.65	0.45	0.05	0.013	0.007
Fe Ni C Cr	0.46	17.26	0.71	0.34	0.45	0.44	0.13	0.012	0.015
Fe Ni C	0.48	19.29	0.02	0.01	0.25	0.16	-	0.015	0.021

Sample austenitization is carried out at 1050°C for 20 minutes for 60NCD11 steel and at 1000°C for 20 minutes for Fe-Ni-C-Cr and Fe-Ni-C alloys. The  $M_s$  temperature is thus 230°C for 60NCD11 steel, - 16°C for the Fe-Ni-C-Cr alloy and  $M_s$  6°C for the Fe-Ni-C alloy. The austenite grain size is 30 to 70  $\mu$ m for 60NCD11 steel, 25 to 50  $\mu$ m for the Fe-Ni-C-Cr alloy and 30 to 70  $\mu$ m for the Fe-Ni-C alloy.

The tests are performed on a dilatometer which generates rapid variations of temperature and stress (6). Because of its high transformation temperature, the study of 60 NCD11 steel requires a relatively rapid cooling to near the transformation temperature after austenitization to avoid bainitic transformation. At temperature below 260°C, the interaction between stress and martensitic transformation can be effectively studied. These operations must be done rapidly and continuously.

In contrast, the Fe-Ni-C-Cr and Fe-Ni-C alloy samples are first austenitized and water quenched. At this time they are fixed to the dilatometer. The samples are cooled or eventually reheated in baths, to the test temperatures. These latter manipulations are much easier to perform.

For 60 NCD 11 steel, two types of tests were performed :

- a "static" type where a constant load is maintained in the martensitic transformation range, while the temperature decreases.
- a "dynamic" type where the sample temperature is constant, and the load increases. This test is comparable to a tensile test, differing in that we do not regulate the strain rate but the loading rate. For the Fe-Ni-C-Cr and Fe-Ni-C alloys only the second type of test was performed.

The apparatus allows us to constantly monitor sample temperature, length and electrical resistance variations and applied load. In the case of 60 NCD 11 steel the dilatometric variations and the resistance variations allow us to detect transformation. In the dynamic tests a combination of these two variables allows us to say if the transformation is stress-assisted or strain-induced (7).

For the Fe-Ni-C alloys whose martensitic transformation temperature is below room temperature, the transformation is detected by measuring magnetic permeability variations, using a method based on that described by OLSON et al. (8).

## Results and discussion

### 60 NCD 11 steel

$M_s$  temperature variations with applied stress for the static tests are presented in figure 1 ; for two cooling rates ( $V = 0.5^\circ\text{C/s}$  and  $\bar{V} = 5^\circ\text{C/s}$  in the temperature range  $250^\circ\text{C}-20^\circ\text{C}$ ). We observe a linear enhancement of the  $M_s$  temperature with applied stress. However this increase varies with the cooling rate ( $dM_s/d\sigma = 0.07^\circ\text{C/MPa}$  for  $V = 0.5^\circ\text{C/s}$  and  $dM_s/d\sigma = 0.05^\circ\text{C/MPa}$  for  $\bar{V} = 5^\circ\text{C/s}$ ).

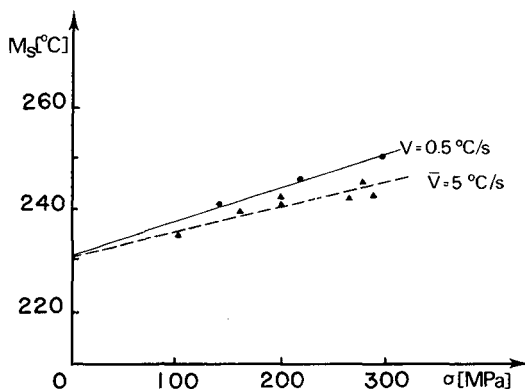


Fig. 1 -  $M_s$  temperature variations with applied stress and for two different cooling rates (60 NCD 11 steel).

In the dynamic tests, Figure 2 shows the stress required to induce transformation as well as the austenite yield stress versus the test temperature.

To determine these values we used the experimental curves  $\sigma = f(\Delta L/L)$  and  $\sigma = f(U)$  where  $U$  is the electrical potential variation proportional to variation in electrical resistance. An increase in length is caused

either by the martensitic transformation or by the plastic strain of the austenite. A divergence of the curve  $\sigma = f(\Delta L/L)$  from the linear path indicates thus a transformation or a plastic strain. The  $\sigma = f(U)$  curves allows us to separate these two phenomena. The transformation is indicated by a drop in resistance ( $- 0.5 \text{ m}\Omega$  variation for a dilatometric transformation amplitude brought to  $10^{-2}$ ) while plastic strain increases electrical resistance ( $+ 0.07 \text{ m}\Omega$  for  $10^{-2}$  plastic strain).

Analysis of the curves of electrical resistance variations with applied stress allows us to define the stress  $\sigma_0$  at which there is austenite yielding. This occurs when the electrical resistance varies from the linear or from a negative resistance variation with the applied stress. The stress required to induce transformation ( $\sigma_t$ ) is thus determined by the curve  $\sigma = f(\Delta L/L)$ . Finally a detailed study of the relationships  $\Delta R/(\Delta L/L)$  allows us to define if the transformation is S.A.M. or S.I.M., and the stress value beyond which a transformation can be induced (7).

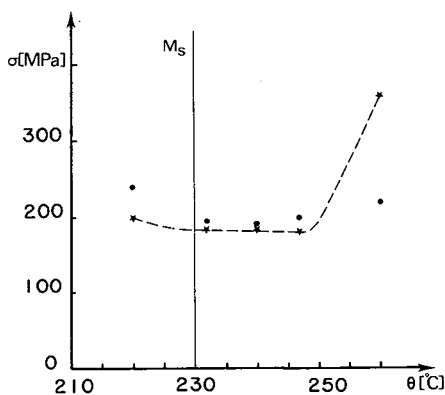


Fig. 2 - Critical stress value (★) needed to induce transformation and yield stress of austenite (●) versus test temperature for 60 NCD11 steel.

The results obtained show that for temperatures slightly higher than  $M_s$  the transformation is induced only for stress values near the yield stress of the austenite. In the range of temperatures from 230°C to 250°C the stress required to induce a transformation is basically constant, and the transformation is strain-induced.

The influence of a prior work-hardening of the austenite was also studied. The steel is pre-strained at 260°C in a way which induces no transformation. Note that in this case the  $M_s$  temperature is slightly lowered by the work-hardening of the austenite.

For a pre-deformation of  $8 \cdot 10^{-3}$  at 260°C with a stress limit of work-hardening of 270 MPa, the stress  $\sigma_t$  required to induce the transformation after cooling to 230°C is thus 230 MPa. In the case of a work-hardening of  $2.8 \times 10^{-2}$ , with a stress limit of work-hardening of 400 MPa, the stress  $\sigma_t$  is 310 MPa. The  $M_s$  temperatures are 223 and 215°C for deformations of  $8 \cdot 10^{-3}$  and  $2.8 \times 10^{-2}$  respectively. We see that work-hardening noticeably increases the stress required to induce the transformation.

In the case of this alloy, we do not observe the classic scheme proposed by OLSON and COHEN (11) in which there are two distinct areas ; one in which the transformation is stress-assisted and the other in which the transformation is strain-induced. In this scheme one observes between  $M_s$  and  $M_s^0$  a linear variation of the stress required to induce the transformation versus test temperature. This variation can be calculated using the PATEL and COHEN model (2).

In our case, a calculation using this model gives a  $dM_s/d\sigma$  value of  $0.13^\circ\text{C}/\text{MPa}$  for values of  $d(\Delta G_{\gamma \rightarrow \alpha})/dT = 1.5 \text{ cal/mol}$ ,  $\gamma_0 = 0.19$  and  $\epsilon_0 = 0.03$ .

In the case of static tests, the linear variation of the transformation

temperature with applied stress is closely observed, but the  $dM_s/d\sigma$  values are weaker than those calculated and, in addition, there is an influence of the cooling rate.

Of the published studies of dynamic tests we have seen, the work of OLSON and AZRIN (9) on TRIP steels at 0.19 wt % C, shows a behavior analogous to ours. These authors attribute this behaviour to the isothermal character of the spontaneous transformation. They established a relation between the critical stress needed to induce the transformation and the temperature (10). The critical stress needed to induce the martensitic transformation does not decrease towards a zero value when one approaches the temperature of the spontaneous transformation.

In order to see if the transformation of our steel was dependant on the cooling rate, the samples were cooled either rapidly to room temperature or rapidly to 280°C and then slowly before  $M_s$  measurements.  $M_s$  temperature values vary from 253°C for the "slow" cooling to 230°C for the rapid cooling. The average cooling rates between 280 and 250°C are respectively 0.17°C/s and 3°C/s.

It thus seems that time has an influence on the beginning of martensitic transformation of this steel. Such a variation of  $M_s$  with the cooling rate could explain the slope variations  $dM_s/d\sigma$  with cooling rate for the static tests.

The same phenomenon could explain the behaviour we observed in the dynamic tests and which is similar to OLSON'S interpretation.

#### Comparison with the Fe-Ni-C-Cr and Fe-Ni-C alloys

Figures 3 and 4 show the stress values required to induce the transformation versus the tensile test temperature for these alloys.

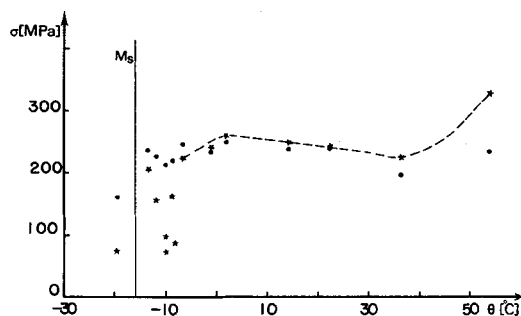


Fig. 3 - Critical stress value (★) needed to induce transformation and yield stress of austenite (●) versus test temperature for Fe-Ni-C-Cr alloy.

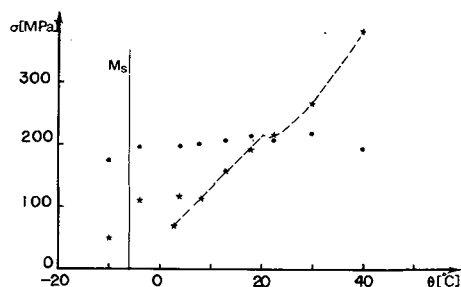


Fig. 4 - Critical stress value (★) needed to induce transformation and yield stress of austenite (●) versus test temperature for Fe-Ni-C alloy.

For the Fe-Ni-C alloy, we observe a linear enhancement with the temperature of the stress needed to induce the transformation. For tests performed at temperature near  $M_s$ , there is a certain dispersion of the critical stress value. The slope of the linear part is 0.14°C/MPa, which is close to values obtained by PATEL and COHEN (2) and other authors studying similar alloys. The Fe-Ni-C-Cr alloy exhibits a

large temperature range during which transformation is induced by strain without a large variation of the critical stress  $\sigma_t$ . In contrast, when temperatures are near the  $M_s$ , less than  $-5^\circ\text{C}$ , there is dispersion of the stress values needed to induce transformation.

Figure 5 summarizes the different kinds of interactions between stress and martensitic transformation that we found for the three alloys. We have plotted the critical stress needed to induce transformation against the difference between test and  $M_s$  temperatures.

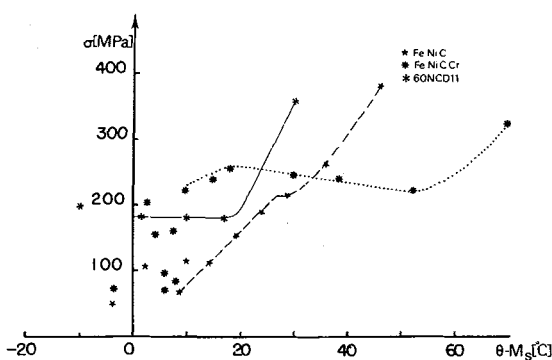


Fig. 5 - Critical stress value needed to induce transformation versus the difference between test and  $M_s$  temperature for the three alloys.

We conclude that :

- the Fe-Ni-C alloy follows the classic scheme whereby the transformation is first stress-assisted (linear stress variation with the temperature between  $M_s$  and  $M_C$ ), then induced by strain. The orders of magnitude are similar to these reported in the literature.

- the 60 NCD11 steel does not show a stress-assisted martensite range under our experimental methods. There does exist, however, a temperature range where the stress needed to induce transformation is more or less constant.

- the Fe-Ni-C-Cr alloys has an intermediate behaviour. It has a temperature range which is more restricted than the Fe-Ni-C alloy where the transformation is stress-assisted. No clear linear relation is observed, and there is a dispersion of the critical stress values. At higher temperatures there is a wide

range where the transformation is strain-induced without a large variation in the critical stress, as with 60NCD11 steel.

Finally for the three alloys at the highest test temperatures we observed a strain-induced martensite range where the critical stress increases relatively rapidly as a function of the tensile test temperature.

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