

Transformation plasticity and resulting microstructures for strain-induced martensitic transformation in Fe-Ni-C alloys

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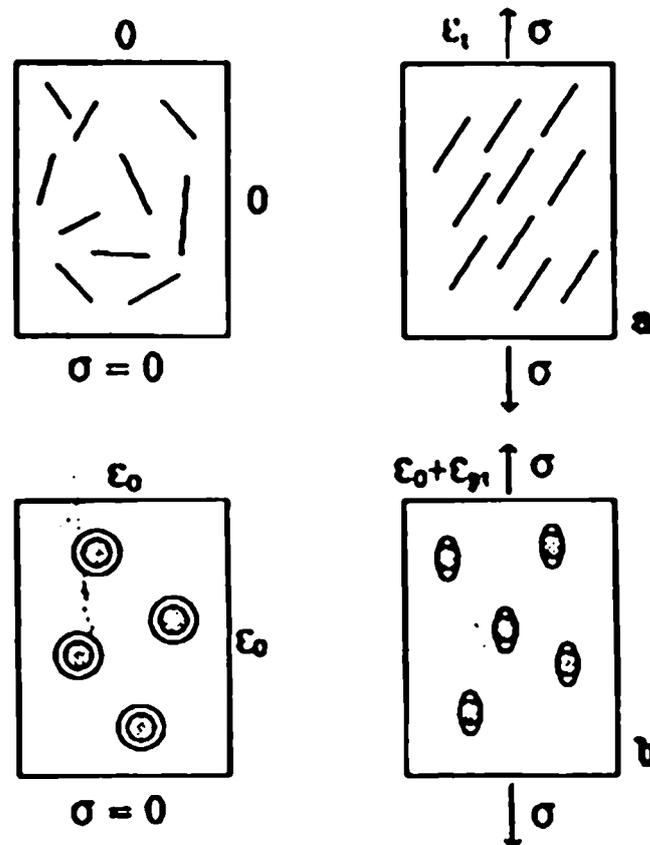
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Introduction

Transformation plasticity deformation occurs when a specimen transforms in a stress field even lower than the yield stress of each constituent of the material. The phenomenon is observed for different transformations, transformations with or without diffusion, or transformations involving shear.

For martensitic transformation, it is generally attributed to two basic mechanisms schematized in Fig. 1.

1) Orientation of the martensite variants by the applied stress. The resulting deformation is reversible when martensite transforms in austenite. This effect is due to the shear component of the phase transformation deformation. It is widely illustrated by superelasticity or shape memory of Cu-Zn-Al alloys or other alloys.



**Figure 1** - Schematic representation of transformation plasticity mechanisms a) only selection of martensite variants orientation ; b) only anisotropic accommodation of volumic transformation strain.

2) Orientation of the plastic yielding around the transforming particles when transformation deformation are accommodated by plastic deformation (Fig. 1b). This mechanism has been essentially studied for diffusional transformation (1-3).

In the case of martensitic transformation of ferrous alloys, these two mechanisms can operate, because that transformation involves large shear deformation ( $\approx 0.2$ ) and volumic variations ( $\approx 0.01$ ) which are often plastically accommodated.

We have experimentally studied transformation plasticity variations versus the progress of the transformation of Fe-20Ni-0.5C alloys ( $M_s = -7$  or  $-16^\circ\text{C}$ ).

Different tests have been realized :

- non isothermal creep tests (or static tests), specimen is cooled from room temperature above  $M_s$  under constant stress ;
- isothermal tensile tests (or dynamic tests), specimen is tensile tested at constant loading rate ( $1.8 \text{ Ns}^{-1}$ ) at constant temperature, between  $M_s$  and  $M_D$ .

The experimental results have been reported and analysed in (4).

The major conclusions from these experiments are :

1) for non-isothermal creep tests, orientation of martensite plates by the applied stress is effective at the beginning of the transformation (martensite content up to 10 %), and for applied stresses as high as the yield stress of austenite. Orientation of plastic yielding occurs certainly, but its contribution must be low ( $\approx 1-2 \%$ ).

2) for tensile tests, orientation of martensite plates by the applied stress is effective, essentially in the plastic deformation range.

For these tests conditions, large transformation plasticity deformation are observed. Normalized to the content of martensite formed, the transformation deformation reaches values up to 0.4-0.6, while for the creep tests, in similar thermomechanical tests conditions regarding the absolute value of the stresses or of the temperatures, the maximal value is 0.12.

These large transformation plasticity deformations obtained for tensile tests can not be explained by only a total orientation of martensite plates.

We will focus here, on the origin of these large transformation plasticity deformations namely how thermomechanical transformation conditions could influence transformation plasticity mechanisms.

## 1 - ORIENTATION OF MARTENSITE PLATES

Martensitic transformation is considered as a deformation process. The energy associated with the transformation of one plate under stress can be expressed by the following relations :

$$\Delta G^0 = \sigma_{ij} \epsilon_{ij} \quad (1)$$

Patel and Cohen (5) have established a general relation relating the applied stress to the deformation measured in the stress direction for one plate of martensite formed :

$$\Delta G^0 = \sigma_A \left( \frac{1}{2} (\gamma_0 \sin 2\theta \cos \alpha + \epsilon_0 (1 + \cos 2\theta)) \right) \quad (2)$$

where :  $\gamma_0$  is the shear strain

$\epsilon_0$  is the volumic variation

$\theta$  is the angle between the stress axis and the normal to the potential habit plane.

$\alpha$  is the angle between the maximal shear direction and the real shear direction

$\sigma_A$  is the tensile stress.

The resulting deformation associated with the transformation of the plate in the direction of the stress is :

$$\epsilon_t = \frac{1}{2} (\gamma_0 \sin 2\theta \cos \alpha + \epsilon_0 (1 + \cos 2\theta)) \quad (3)$$

That deformation will depend on the orientation of the plate with regard to the applied stress. It has a maximal value which is given for  $\tan 2\theta = \gamma_0 / \epsilon_0$ .

In the case of Fe-Ni-C alloy  $\epsilon_{tmax} = 0.11$  with  $\gamma_0 = 0.19$  and  $\epsilon_0 = 0.024$ .

For a single crystal, considering crystallography of the martensitic transformation and neglecting the volume variation component, these relations are :

$$\Delta G^0 = m_i \gamma_0 \zeta \quad (4)$$

Where  $m_i$  is similar to the Schmid factor, and  $\zeta$  is the critical shear stress necessary to induce martensite.

The deformation measured in the applied stress direction is  $m_i \gamma_0$  and variant with maximum  $m_i$  will be formed.

For a single crystal, the resulting deformation from mechanism 1 can be determined knowing the shear and volumic transformation deformations and the crystal orientation.

Also, this deformation due to the plate formation is not dependent on the level of the applied stress nor to the way transformation occurs (i.e. creep tests or tensile tests). The role of the stress is to select the martensite variant.

In a polycrystal, the transformation plasticity deformation will be function of the plate orientation distribution. The way of selection can be considered from an energetical point of view.

Transformation occurs when :

$$\Delta G^C + \Delta G^0 = \Delta G^d + \Delta G^S \quad (5)$$

$\Delta G^C$  is the difference in chemical free energy between the two phases

$\Delta G^0 = \sum \sigma_{ij} \epsilon_{ij}$  is the mechanical energy associated to the transformation occurring under local stress  $\sigma_{ij}$ .

$\Delta G^d = \Delta G^{e+p} + \Delta G^I$

$\Delta G^{e+p}$  is the deformation energy in order to accommodate

transformation strains. This deformation energy can reach high levels. In consequence internal stresses are created during the transformation. These stresses can induce new plates. Also transformation can occur by formation of not only one plate, but a group of self-accommodating plates.

$\Delta G^I$  is an interaction term between transforming plates, plates and grains... which increases when  $X$  increases. This term is related to an internal stress state  $\sigma_I$ , 1) existing during the transformation and partly relieved by forming self accommodated plates, 2) increasing as transformation progresses due to the increasing interaction between plates, plates and grains...

$\Delta G^S$  is the surface energy associated to the formation of the plate.

Also, the plate orientation will be determined by the stress state  $\sigma_{ij} = \sigma_A + \sigma_I$ . If  $\sigma_A$  is large compared to  $\sigma_I$ , the plate orientation will be determined essentially by  $\sigma_A$  and the resulting deformation will lead to large transformation plasticity deformation tending toward  $\epsilon_{tmax}$ . If  $\sigma_A$  is low, plate orientation will be determined by  $\sigma_I$ . Then plate orientation distribution can be more random and resulting deformation in the direction of the applied stress will be lower.

Also one expect a maximum contribution of the plate orientation at the beginning of the transformation, when  $\sigma_A \gg \sigma_I$  and when self-accommodation is not working.

This is the case for the creep tests at large stress levels and at the beginning of the transformation, and for the tensile tests in the plastic deformation range. This mechanism is discussed in (6).

## 2 - ANISOTROPIC ACCOMMODATION OF TRANSFORMATION STRAINS

This mechanisms operates when transformation strains are plastically accommodated.

The transformation strains can be considered as a shear strain and a volumic variation.

When transformation occurs without applied stresses, macroscopic shear strain is mainly self-accommodated.

In this case, the plates microstructure and morphology is not different for the plates self-accommodated or not.

However, the transformation deformation may be accommodated differently when the material is deformed plastically and self-accommodation is less working.

Indeed, observations of martensite formed during tensile tests reveal strong modifications in the microstructure as it is shown in Figure 2 and discussed in (7).

For low stress effects, habit planes are along  $\{225\}_f$  planes and plates growth is stopped along  $\{111\}_f$  planes (Fig. 2a). Long direction of martensite plate growth is  $\{225\}_f$ .

When transformation occurs under stress, during deformation, martensite plates still form along  $\{225\}_f$  planes, but they have large growth direction along  $\{111\}_f$  planes. (Fig 2b - plates D).



a



c



b

**Figure 2** - Electron micrographies of martensite formed under tensile test.

a) Martensite with low stress effect ; Tensile test temperature  $T = M_s + 8^\circ\text{C}$ ;  $\epsilon = 6,4 \%$ .

b) Large stress effects same test as the preceding.

c) C.D.F. image,  $T = M_s + 20^\circ\text{C}$ ,  $\epsilon = 12 \%$ .

Martensite along  $\{225\}_f$  planes is often twinned.

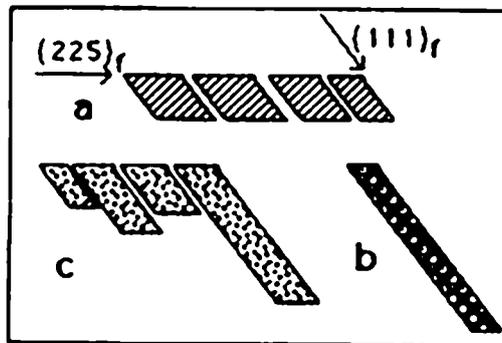
At last, plates with no trace of  $\{225\}_f$  habit planes can be formed in specimen transformed at higher temperatures (Fig. 2c).

In this case, interfaces are curved near  $\{111\}_f$  planes. In figure 3, we show martensite with three branches. The branches have interfaces nearly parallel to three different  $\{111\}_f$  planes.



**Figure 3** - Electron micrography of deformation induced martensites  $T = M_s + 52,5^\circ\text{C}$ ,  $\epsilon = 13,25 \%$ .

This change in morphology is schematically illustrated in Fig. 4.



**Figure 4** - Schematic diagram of the morphologies for a) thermal martensite b) deformation induced martensite and c) is an intermediate state between a) and b).

The change in habit planes can be related to a modification in the transformation strain accommodation mechanisms. Indeed, Tiem (8) calculated such changes in habit planes toward  $\{111\}_{\gamma}$  habit planes when transformation strain (Bain distortion) was accommodated by a plastic deformation in the austenite and when a tensile stress was applied.

Also, if the accommodation by plastic yielding in austenite is favoured, the resulting deformation to accommodate bain deformation may be different, and then, this deformation will be enhanced leading to large transformation plasticity deformations as such observed for tensile tests.

We think that the thermomechanical transformation conditions existing during tensile test allow that locally one reaches the critical stresses in order to activate new austenite slip systems which are more favourable to accommodate these transformation deformations.

As we can observe on the microstructures Fig. 2b, the plates often form with habit plane along  $\{225\}_{\gamma}$  planes and then develop along  $\{111\}_{\gamma}$  planes. The initial habit plane can be considered as unchanged, but the growth of the plate is highly modified.

For these tests, the stress has two effects, one crystallographic effect which is to select the martensite variant by the initial habit plane, and a second effect which is to modify the growth process ; the growth is triggered by the plastic deformation which leads to plates morphology described Fig. 4b.

## SUMMARY AND CONCLUSION

Transformation plasticity deformation is the result of a transformation under stress. Martensitic transformation has been generally considered as a deformation process.

This seems to be the case for the creep tests where the applied stresses are generally lower than the internal stresses generated during the transformation. In this case, the applied stresses do not modify the transformation process. The major role of the stress is to select the martensite variant ; an anisotropic accommodation of transformation strain occurs but its contribution is low because it is essentially the volumic variation which must be accommodated plastically.

For the tensile tests, when the applied stresses are of the level of the internal stresses, and when slip in austenite (as deformation mechanism) is favoured, the transformation is triggered by the deformation not only considering the nucleation mechanism as it has been shown largely in the literature, but also considering the growth process of the martensite plates. As a result, the morphology of the plate is modified and the resulting transformation plasticity deformation is large.

## REFERENCES

- (1) M. De Jong, G.W. Rathenau : Acta Metall 7 (1959) 246 ; Acta Metall 9 (1961) 714.
- (2) G.W. Greenwood, R.H. Johnson : Proc. R. Soc. 283A (1965) 403.
- (3) E. Gautier, A. Simon, G. Beck : Acta Metall 35 (1987) 1367.
- (4) E. Gautier, A. Simon, G. Beck : Proc. 7th Int. Conf. on Strength of Metals and Alloys, Montreal, Canada, Pergamon Press, (1985) 569 ; Proc. ICOMAT The Japan Inst. Metals (1986) 503 ; Proc. Int. Conf. Solid-Solid Phase Transformations, Institute of Metals (1987) 285.
- (5) J.R. Patel, M. Cohen : Acta Metall 1 (1953) 531.
- (6) E. Gautier, X.M. Zhang, A. Simon : Proc. I.C.R.S.2. in the press.
- (7) X.M. Zhang, E. Gautier, A. Simon : Acta Metall 37 (1989) 477; Acta Metall 37 (1989) 487.
- (8) S. Tiem, Thèse de Doctorat, Metz 1987.