Analyses on TRansformation Induced Plasticity under non-conventional loading, and plasticity decomposition via full-field FE modelling

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Abstract

In many wide-spread technologies, such as welding of structural elements or thermo-mechanical forming processes, as well as some quickly developing others like additive manufacturing, steels are subject to the mechanical consequences induced by solid-solid phase transformations. As such, the improvement of our knowledge and predictive capabilities on this matter continues to be paramount. Here we investigate the effects of non-conventional loading conditions during TRansformation Induced Plasticity (TRIP) tests on 35NiCrMo16 steel specimens, with the goal of attaining a better and broader understanding on how this affects the change in plastic strain resulting from micro-structural changes. For that purpose, these tests are performed with focus on varying the intensity of the applied external force, but also, and most importantly, the instant during continuous cooling when such a force is applied. Thereby, we are able to see certain indications of the impact these conditions generate, as well as some interesting results on the final extensive-plastic-strain-norm in relation to the corresponding TRIP-norm. These tests also allow to gather information about the change of the phases' mechanical properties depending on temperature, which then enables for a more faithful modelling of the phenomenon. On another side, the models of Leblond and Taleb-Sidoroff, derived from the mechanical equilibrium in the model case of the Greenwood-Johnson mechanism for diffusive transformations, and whom to this date remain the most predictive, (both quantitively and qualitatively), simple-to-use analytical models of TRIP, are known to yield good results when used to predict scenarii which comprehend conventional loading conditions. However, recent evidence shows a quantitative improvement of predictions, when some additional considerations explored via full-field Finite Element modelling of diffusive transformation on 100Cr6 steel had been followed. Since modelling solid-solid phase transformations via (FE) simulations eliminates any supposition about the mechanical equilibrium of the phases, it leaves aside crucial hypotheses upon which rest the aforementioned models. This enables to verify through the numerical results, the extent to which those hypotheses do or do not hold for the analytical models that propose them. Finally, using the mechanical properties identified from the tests on 35NiCrMo16 steel, its structural transformation is simulated in order to confirm the model's capability to reproduce experimental observations.

Key words: TRIP / diffusive transformations / steel / non-conventional loading / plasticity by phases

1 Introduction

Prediction of residual stresses as result of heat treatments or high-temperature manufacturing operations in steels, (some very well-known such as welding, hot rolling and hot forming, or some more recent ones like additive manufacturing), is a subject of great interest due to its direct link with the end-quality lifetime of a part or component. All these previously listed industrial processes pose a scenario where a high-temperature thermal field couples with an external stress field. Hence, all of them share the commonality of conducing steels to endure thermal, metallurgical and mechanical phenomena all at once. As one would expect, these phenomena are not uncoupled and so they are interacting and influencing upon each other. An effect resulting from this triangle is how a temperature-driven solid-solid structural transformation (metallurgical phenomenon), happening in conjunction to a very mild external stress, is solely enough to generate a macroscopically measurable plastic strain (mechanical phenomenon) on a steel.

The mechanical consequence thus entailed is known as TRansformation Induced Plasticity (TRIP). TRIP is defined as a permanent macroscopic strain caused by an external equivalent-stress, much lower than the yield stress of the softest phase present. As a general description, it happens that the aleatory local stress fields that are induced during a phase transition, are channeled along the preferential direction imposed by an external stress [**1**], [**2**], even if its Von Mises equivalent is of very low intensity. Furthermore, TRIP is not the only consequence of these thermal-metallurgical-mechanical interactions, as Hardening Transmission between phases (amongst other) has also been observed [**3**]. The models [**4**]–[**7**], [**8**] that to present date remain as a reference due to their simplicity of usage and predictive character, are known to miss-predict the phenomenon when used for complex loading scenarii [**3**]. For these reasons, interest still arises into better characterizing and modelling it.

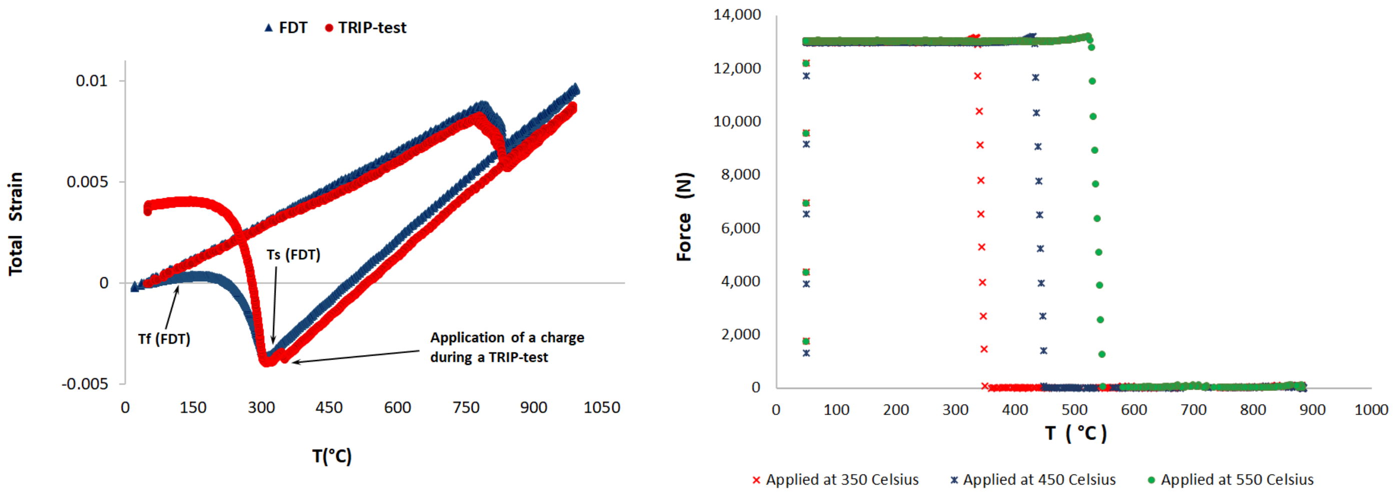
In order to extend the knowledge on TRIP behavior under complex loading, we investigate here the effects of non-conventional loading conditions for tests performed on 35NiCrMo16 steel specimens. This is done by imposing the external stress on our TRIP-tests at temperatures which could favor the appearance of viscous effects in the material. Different stress intensities are used, one for each group of tests. The results gathered during these experiments will serve to simulate TRIP in a context where the mechanical properties of the phases are considered as temperature dependent. After this, plasticity decomposition by phases will be used to investigate from a local perspective, the observations obtained from these experiments. Numerical analyses are to be published in a following article.

2 Experiments: means, test protocol and material properties

2.1 Description of experimental means

Thin-wall cylindrical specimens are used to ensure on one hand, uniform shear stress throughout the wall in the case torsional loading is imposed, and on the other, an accurate control over the imposed heating rate and the yet more important (for these tests) cooling rate. This last one is chosen according to the microstructure (martensite, bainite, pearlite or some combination of them) desired to be obtained after transformation depending on the steel studied. Phase transformation of the specimens is thermally achieved by means of an induction coil for the heating part of the cycle, and a nitrogen flow passing along and through their center during the cooling part of it. They are enclosed in an inert gas (argon) atmosphere to protect them from oxidation. Extended details about the entire experimental device used for these tests can be found in [**9**], [**10**], and details for a similar device can also be found in [**11**].

Two types of tests are performed one right after the other as presented in **Fig. 1a** right below. The first is a Free Dilatometric Test (FDT), during which a specimen undergoes just a thermal cycle alone (heating followed by cooling). This test allows to learn about the kinetics of transformation: transformation start temperature (T_s), transformation end temperature (T_f), the transformation strain ($\Delta\varepsilon_{\alpha\gamma}$), average thermal expansion coefficients of each phase (ζ_γ and ζ_α), and finally the volume fraction of product phase as a function of temperature z=f(T). The second test (TRIP-test) exerts both a thermal cycle identical to the first one plus a mechanical stress *conventionally* applied a few degrees before T_s and maintained throughout the transformation. This stress is kept at constant intensity and direction, but one may also conceive it to be variable. With the combination of these 2 procedures, TRIP during cooling can be macroscopically measured in steels. Mechanical properties of the phases such as Young modulus E and yield stress σ^y, non-linear isotropic/kinematic hardening coefficients Q,b/C,Ɣ and Norton's law parameters K and n, are respectively obtained through monotonic tensile tests, charge-discharge single-cycle tests and relaxation tests [**10**], [**12**], [**13**].



a) ***b)***

Fig.1: ***a)*** Example of the types of thermal cycles performed on the specimens. ***b)*** Graphical representation of the experimental protocol followed. Each curve represents a separate test that makes part of the same group. During a given test the external stress is applied at a different temperature than the other two. The same stress intensity is applied for all three of them.

2.2 Experimental protocol

During this study we use a medium-carbon medium-alloy steel which, according to its Continuous Cooling Temperature (CCT) diagram, possesses self-tempering capabilities. This means that the microstructure obtained under a wide range of cooling rates (even for natural convection air-cooling) will be martensitic. The heating rate imposed on the 35NiCrMo16 steel specimens is 5°C/s, whereas the imposed cooling rate is -8°C/s. They are heated above the austenitizing temperature up to 880°C, where they are kept during 5s. The maximum value for the applied stress intensities (which are described further ahead in the following paragraphs) is attained in each of the tests in an interval of 2 to 2.5s approximately.

With the purpose of observing the impact of *non-conventional loading* conditions on TRIP, three groups of TRIP-tests have been carried out, two of which are presented further ahead in the results section. The *conventional procedure ensures* that the macroscopic plasticity observed after transformation will effectively be consequence of the underlying metallurgical phenomenon (the interaction between coexisting phases) and nothing else. This is what makes it possible to refer to such macro-plasticity as TRIP. On the other hand, our *non-conventional* approach (**Fig. 1b**) consists of a group of three separate tests in which the same tensile stress is applied at a different temperature during each test, and before the γ-α transformation. Hence, during one of the tests composing a group stress is applied in a *conventional* fashion. This means it is applied a few degrees (350°C in our tests) before the identified T_s temperature of the steel (which was ~326°C in our case). For the other two however, it is applied at 450°C and 550°C respectively; therefore, considerably distanced from T_s. During each test, stress is kept constant until discharge at ambient temperature. During the first group of tests the applied stress was 74MPa. This stress intensity represents about 31% of this steel's σ^y at the reference temperature of 350°C. Similarly, the remaining two groups of tests followed the same protocol but applying stress intensities of 150MPa for one and 165MPa for the other (respectively 62.50% and 68.75% of this steel's σ^y at 350°C). Compressive tests were also performed besides the tensile ones for these last two groups, whereas the tests at 74MPa were only performed under tension. The results section presents the findings for the tests performed under 74MPa and 150MPa of stress. They serve to reveal the general trend found in this work.

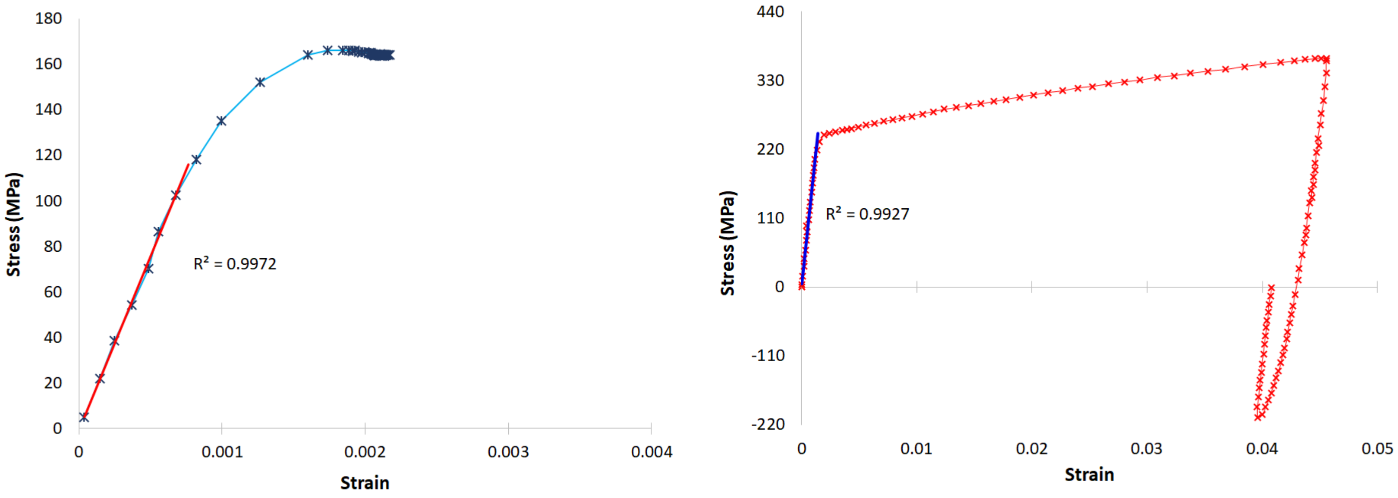
2.3 Mechanical properties of the phases

Since tensile and single-cycle tests have not yet been performed for all testing temperatures (450°C neither 550°C to be specific), material properties at such temperatures are identified and chosen based on a combination of literature references along with the data available from our tests, to characterize the martensitic and austenitic phases prior to their interaction while forming a mixture. TRIP-tests where the external stress is kept constant after its application and during a considerable time interval before T_s, may essentially be viewed as Creep-tests performed on the austenitic phase (γ), provided these two conditions are met: **a)** The (ε_i,σ_i) data points to be analyzed are taken during the time interval before T_s: $t < t(T_s)$. **b)** ε^{th} (the thermal strain) at each t, is accounted for and subtracted from ε^{tot} (the total strain measured) to only leave us in hand with ε^{mec} (the strain of mechanical nature). This is expressed according to the following:

$$\varepsilon^{mec}(t) = [\varepsilon^{tot}(t) - \varepsilon^{th}(t)] - \varepsilon^{tot}(t_0)$$

$$\varepsilon^{mec}(t) = \left[\varepsilon^{tot}(t) - \zeta_\gamma \Delta T(t)\right] - \varepsilon^{tot}(t_0) \quad ; \qquad \zeta_\gamma \Delta T(t_0) = 0\,, \qquad t_0 \leq t \leq t_n$$

This way we are able to build σ–ε curves for the temperatures of 450 and 550°C using the available data from their respective TRIP-tests, and then use these curves to identify the properties that will later be used in our simulations. Since the maximum stress imposed is attained over a short period of time, the properties thereby identified are taken to be representative at the temperature when the charge is applied. Additionally, we were able to perform a charge-discharge single-cycle test on our steel at T=350°C (it seems to be in accordance with the one on [**14**]) which allows for material properties identification at this temperature. However, this task is somewhat cumbersome to perform at higher temperatures, when the material becomes too rate-sensitive. The σ–ε curve built from a TRIP-test where the force is applied at T=450°C, together with the σ–ε curve for the single-cycle test performed at fixed temperature of 350°C, are presented in **Fig. 2** on the next page.



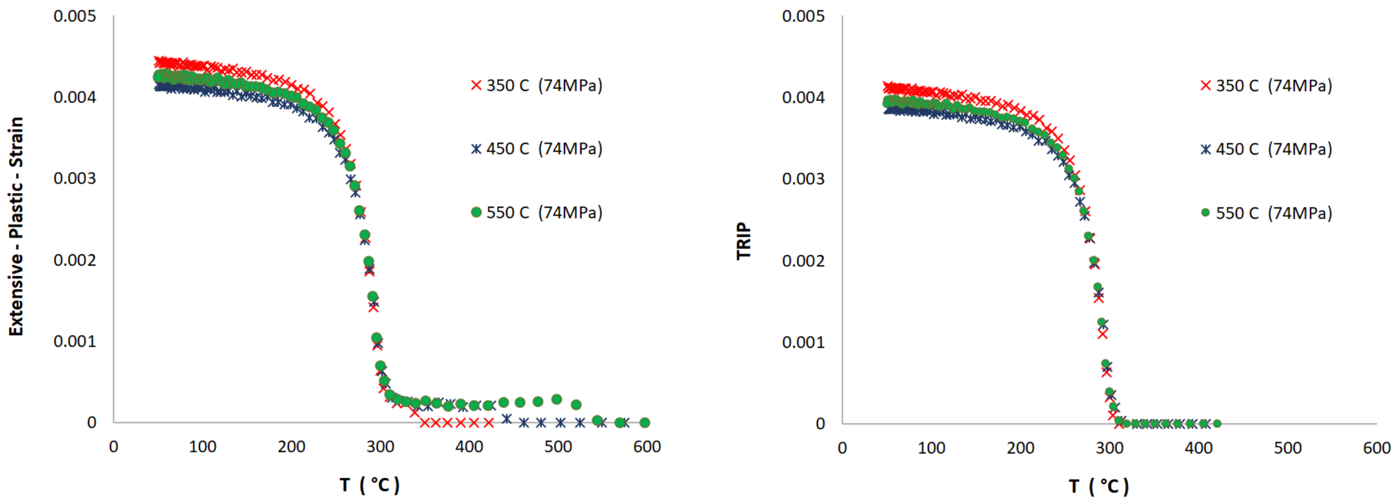
a) ***b)***

Fig.2: ***a)*** σ–ε curve from a TRIP-test where the force was applied at a temperature of 450°C (the specimen was still austenitic). ***b)*** Single-cycle charge-discharge test performed on an austenitic specimen at fixed temperature of 350°C.

3 Results and discussion

As explained in the description of the protocol, one of the main purposes of this study is to understand how the elapsed time under external load before the transformation, may affect TRIP. The results of the tests performed under 74MPa of external load are presented in **Fig. 3** right below. **Fig. 3a** presents the change of the extensive-plastic-strain as a function of temperature. That is, the sum of the visco-plastic strain that could occur due to external loading plus the TRIP strain that occurs due to phase transformation. Looking at the curves in **Figs. 3a** and **3b**, one can see there's an additional amount of plasticity in our specimens relative to their corresponding TRIP norms. This extra plasticity cannot be considered as being a mere product of just the interaction between phases.

We observe that the effect is very similar for all 3 tests. However, the increase in plasticity with respect to TRIP does not seem to happen in monotonic fashion relative to the temperature of application of the load. It is certain that, given its order of magnitude, we may see the proportion of this increase in plasticity as negligible. Except one must consider that the applied stress during these tests was relatively low compared to the yield limit of our 35NiCrMo16 steel while austenitic at the reference temperature of 350°C (240MPa).



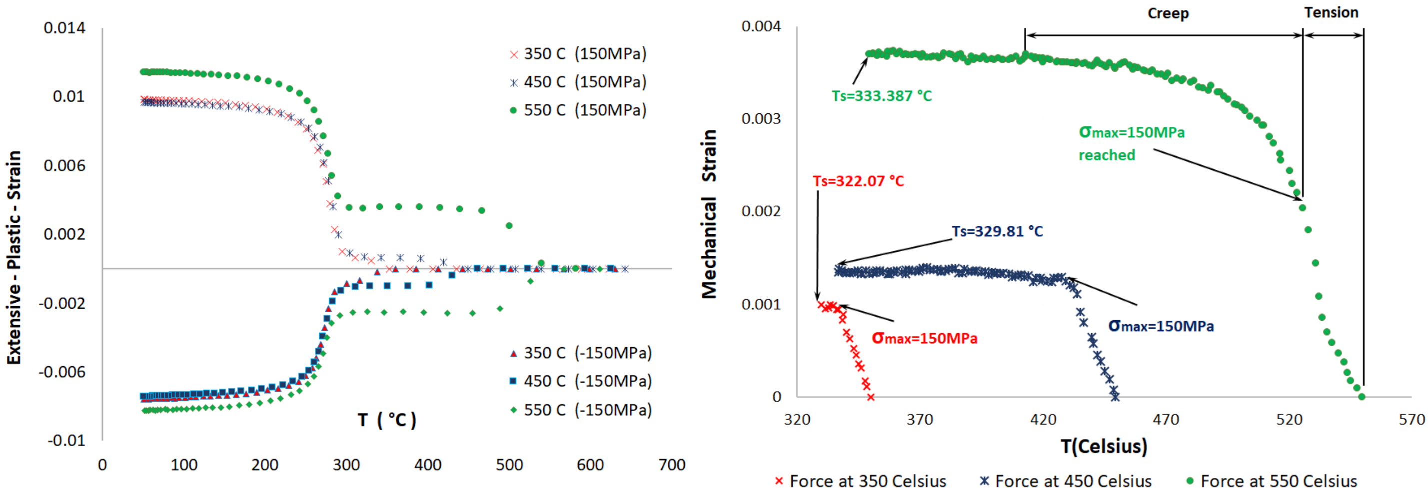
a)

b)

Fig.3: Plasticity results for TRIP-tests on 35NiCrMo16 steel. Axial stress intensity = 74MPa (31% of this steel's σ^y at 350°C). ***a)*** Extensive-Plastic-Strain. ***b)*** TRIP.

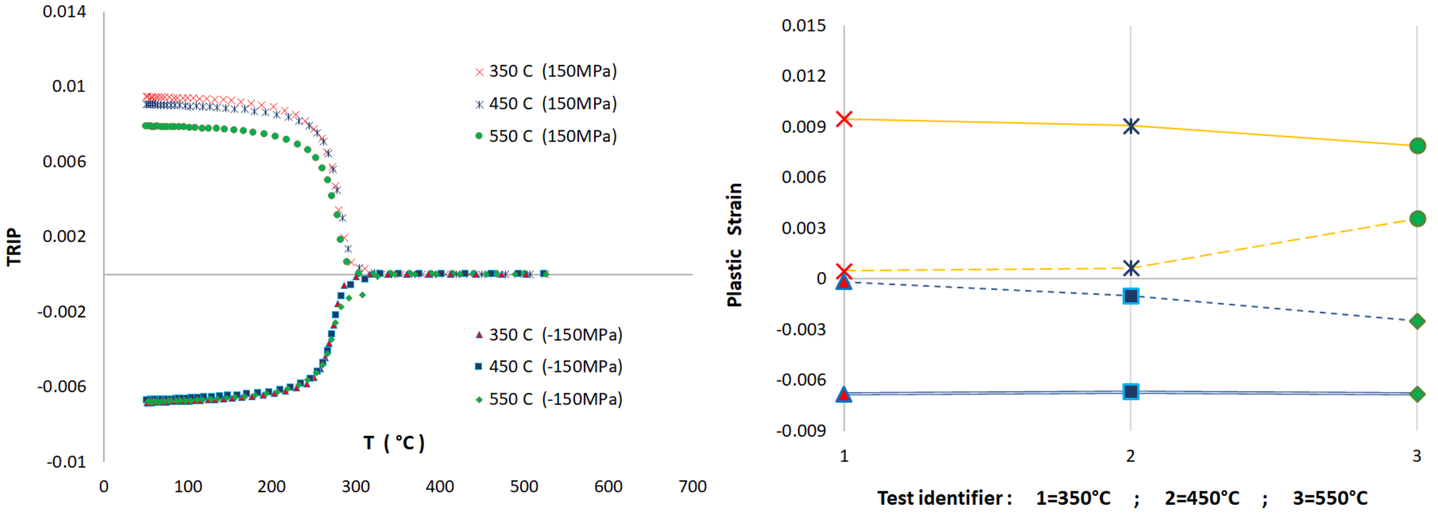
Next, the results of 6 TRIP tests are considered: 3 under compression, 3 under tension. **Fig. 4a** on the following page presents again the change of the extensive-plastic-strain as a function of temperature, this time for the tests performed at 150MPa. It shows that, for this load intensity (which is 62.5% of this steel's σ_y at 350°C), applying the charge either at 350°C or at 450°C does not make a significant difference since both cases attain the same value of extensive-plastic-strain. We can see that the previous remark is valid in tension as well as in compression. However, when the load was applied at 550°C, a much bigger plastic strain was obtained in comparison to the other two cases. The increase on plasticity (**Fig. 4a**) with respect to what we may "safely" denote as TRIP (**Fig. 5a**), cannot be neglected for the case at 550°C, neither for tension nor compression. At this load intensity however, this effect was more important under tension than under compression.

The observed difference on TRIP norm between the three cases, is correlated to the visco-plastic strain generated in each one of them during the external loading period before transformation (**Fig. 4b**). When the load was applied at 350°C or at 450°C, the strain remained at constant value once the maximal loading stress was reached. Based on this, the behavior from this point on can be considered as elastic for these two cases; but when the load was applied at 550°C, a non-linear change in strain is observed during tensile loading, then creep noticeably takes place afterwards. Thus, for this particular case, the visco-plastic strain preceding the transformation produces a significant effect on the TRIP norm, as is resumed on **Fig. 5b** or as may be noticed by comparing **Fig. 4a** with **Fig. 5a**: the scenario with the highest extensive-plastic-strain (550°C), produced the lowest TRIP norm. As mentioned before, this was more remarkable in tension than in compression. Something to also notice for these tests is that TRIP norms turned out to be almost the same when in compression, regardless of the temperature at which the load was applied.



a) *b)*

Fig.4: Plasticity results for TRIP-tests on 35NiCrMo16 steel. Axial stress intensity = 150MPa (62.50% of this steel's σ^y at 350°C). ***a)*** Extensive-Plastic-Strain. ***b)*** Change in *mechanical strain* as a function of temperature for the tests performed under tension. When the load is applied at 350 and 450°C, strain remains constant after the maximal value of external load is reached. When applied at 550°C, two strain regimes are distinguished: a visco-plastic strain corresponding to the applied stress, then creep once the maximal value is attained and kept constant.



a) *b)*

Fig.5: Plasticity results for TRIP-tests on 35NiCrMo16 steel. Axial stress intensity = 150MPa (62.50% of this steel's σ^y at 350°C). ***a)*** TRIP. ***b)*** Effect on TRIP norm when visco-plastic strain precedes a transformation: continuous lines are TRIP-norms; dashed lines are visco-plastic strains right before the transformation starts.

A direct comparison between the tests at 74MPa presented in **Fig. 3b** and the 3 tests at 150MPa under tension in **Fig. 5a** reveals something interesting. In **Fig. 5a** we see a monotonic decrease of TRIP (*contrarily to the inexistent pattern observed for the tests made at 74MPa of intensity*) as a function of the temperature of application of the load. Or strictly speaking, as function of the visco-plastic strain produced prior to a transformation.

4 Conclusions and Perspectives

4.1 Conclusions

- ☐ No visco-plasticity happens before the transformation starts and no remarkable effect is observed on TRIP norm when the applied external stress is <=74 MPa (this is 30% of this steel's σy at 350°C). The latter is true no matter how much time under charge has passed before the transformation starts.

- ☐ With 150 MPa of external stress (62.5% of this steel's σy at 350°C.), visco-plastic strain is observed in the cases where the load is applied at 550°C and 450°C. TRIP norm measured for these tests differs significantly from the observed when the same load intensity is applied at 350°C. This means there is an effect of visco-plasticity on TRIP, but there is not a direct effect of the temperature at which the load is applied (its effect is undirect: it may cause visco-plasticity which in turn influences TRIP).

- ☐ TRIP under compression is considerably smaller (in absolute value) than under tension.

- ☐ Finally, one may remark that: the greater the visco-plasticity had been prior to transformation, the more the TRIP norm seems to decrease. This is observed whether in tension or compression. It's less remarkable under compressive charge. However, with just a slight increase on the intensity of the applied charge (as was done in the tests performed for 165MPa: just a 10% increase from the 150MPa used at first) we have observed that this effect becomes very clear in compression as well.

4.2 Perspectives

Regarding the numerical TRIP simulations to follow, model MH2MH-PN from [**15**] will be used on a first stage. The suitable portion of our TRIP-tests and the single-cycle test performed at 350°C, will be used to estimate the mechanical properties of the austenitic phase (γ) at three different temperatures: 350°C, 450°C and 550°C. Next, observing the single-cycle curve in **Fig. 2** of ***section 2.3***, one can see that the change in plastic strain is *almost entirely driven* by a *kinematic* type of *hardening*. Hence, a non-linear kinematic hardening law will be used for modelling the phases' mechanical behavior, whereas *isotropic* hardening will be considered *constant*.

As for the material properties of the martensitic phase (α') only its ambient-temperature values will be used, in the absence of more data at higher temperatures for the 35NiCrMo16 steel in martensitic state. These material properties are to be taken from the σ–ε curve in **fig.9** of [**16**]. Therefore, material parameters *will not change with temperature* for this phase, for the moment, but rather participate in the mixture with fixed ambient-temperature values.

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