Experimental evidence on the coupling between discontinuous plastic flow (DPF) and γ → α’ phase transformation in FCC metals and alloys at cryogenic temperatures

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Abstract

During low-temperature tensile tests of austenitic stainless steels (304, 316, 316LN, etc.) two phenomena may occur: discontinuous plastic flow and γ → α’ phase transformation. Previous investigations have considered separately each of phenomena. The present paper is focused on strong coupling between discontinuous plastic flow and γ → α’ phase transformations at cryogenic temperatures. For the investigated materials- austenitic stainless steel (304), test results indicate that inclusions of new martensitic phase can block the movement of bands slip during deformation at liquid helium temperature (4.2K).

Keywords:

discontinuous plastic flow, DPF, martensitic phase transformation, tensile test at cryogenic temperatures

1. Introduction

Tensile test results for austenitic steel specimens loaded at wide range of temperature prove three distinct domains of the response of materials [1]. Domain I corresponds to the temperature range below T_1 and to plastic flow instability called the discontinuous plastic flow (DPF). Domain II stretches between T_1 and M_d, the latter being the temperature above which the process of plastic strain induced γ → α’ phase transformation does not take place. Inside this domain the plastic flow is smooth and accompanied by transformation from the parent phase (γ) to the secondary phase (α’). The phase transformation leads to a significant increase of the yield stress. Finally, domain III above the temperature M_d is characterized by smooth plastic flow and rather stable behaviour with respect to the phase transformation.

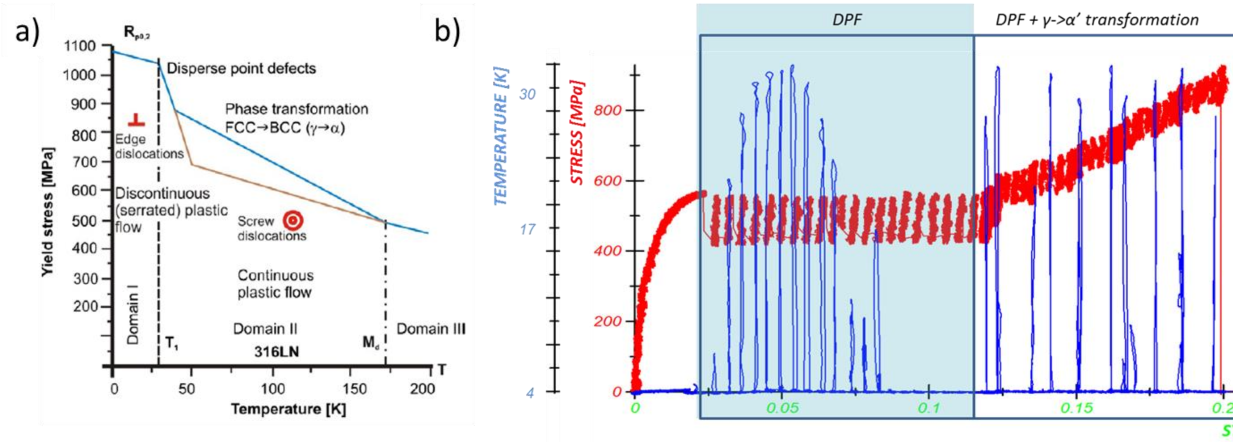


Fig. 1. *(a) Yield point against temperature for austenitic stainless steel [1] (b) Stress-strain and temperature-strain curves obtained for uniaxial tensile test at liquid helium temperature (4,2K) for austenitic steel specimen (304)*

1.1. DPF phenomenon

At very low temperatures (below T_1) and for sufficiently high strain rate, discontinuous plastic flow (DPF) is observed (Fig. 1a). The main feature of serrated yielding consists in frequent abrupt drops of stress as a function of strain during monotonic loading (Fig. 1b). The mechanism of DPF is related with formation of dislocation pile-ups at strong obstacles such as the Lomer-Cottrell barriers. The back stresses of the piled-up groups block motion of newly created dislocations. The local shear stress at the head of dislocation pile-up, proportional to the number of dislocations in the pile-up, may reach the level of cohesive strength and the Lomer-Cottrell lock may collapse by becoming a dislocation. Such a local catastrophic event can trigger similar effects in other groups of dislocations. Thus, the final result is massive, has a collective character and leads to load drops observed in the stress-strain curve [1].

1.2. γ → α' phase transformation

The plastic strain induced γ → α' phase transformation in such materials as 304 stainless steels occurs in a wide range of temperatures below M_d. The process is controlled by the transformation kinetics, represented by the phase transformation curve. Kinetics of the γ → α' phase transformation, developed by Olson and Cohen [2] is reflected by a typical sigmoidal curve defining the evolution of the martensite content as a function of the plastic strain (Fig. 2a). Under isothermal conditions (4,2K) and for a given strain rate, the classical sigmoidal curve has the form shown in Fig. 2b [3].

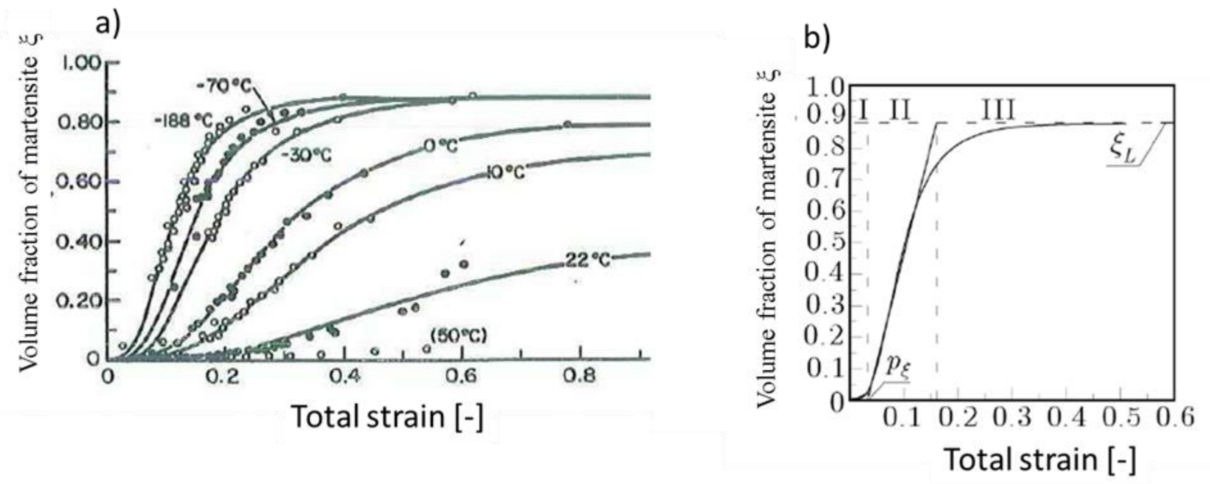


Fig. 2. *Volume fraction of martensite α' versus accumulated plastic strain p,(a) for wide range of temperature [2], (b) for ultra-low temperature [3]*

At very low temperatures, the phase transformation process can be divided into three stages: low rate transformation below the threshold p_ξ (stage I), fast transformation with a high and nearly constant transformation rate (stage II) and asymptotically vanishing transformation with the rate decreasing to 0 and the volume fraction of martensite reaching a maximum L_ζ (stage III).

2. Experimental results

Identification of coupling between DPF and γ → α' transformation implies a significant experimental effort. This section provides results of uniaxial tensile tests at liquid helium temperature (4,2K) for 304 austenitic stainless steel (DIN: X5CrNi1810) , tests were carried out at Cracow University of Technology – experimental set-up is presented in Fig. 3.

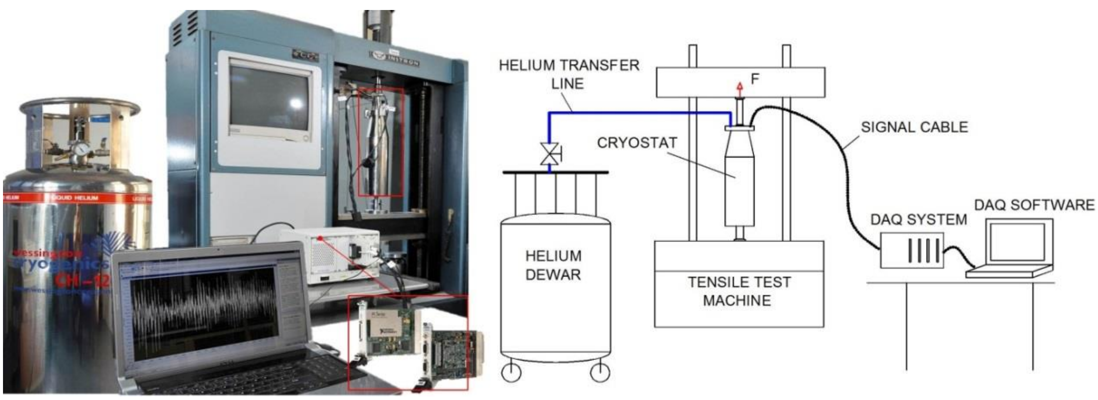


Fig. 3. *Experimental set-up for tensile test at cryogenic temperature*

The gage length of the specimen was equal to 20 mm and the cross-section was equal to 1,5 mm^2. The elongation was measured by using clip-on extensometers mounted on the specimen. Internal piezoelectric sensor, aligned with the specimen, was used. The temperature of specimen was constantly monitored during the test by two Cernox sensors, one (green) was mounted in central part of specimen and second (blue) was mounted near to bottom grip (Fig.4). All tests were kinematically controlled. The stroke speed of crosshead was equal to 0.5 mm/min. The sampling frequency of signals was 1 kHz.

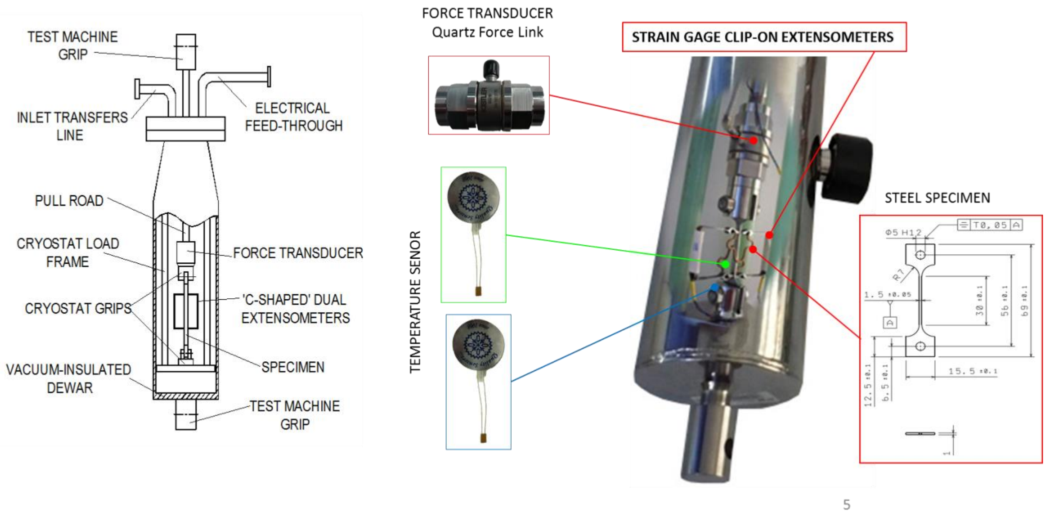


Fig. 4. *Measurement paths for tensile testing at cryogenic temperature. The force is measured by means of piezoelectric sensor, the elongation by clip-on extensometers and special temperature sensor is used for monitoring of specimen temperature*

In order to preform qualitative analysis of coupling between DPF and $\gamma \rightarrow \alpha$’ transformation, special juxtaposition of experimental results was prepared (Fig.5.). Based on presented juxtaposition, determination of slip bands position during uniaxial tensile test is possible both for Domain A (DPF range) and Domain B (DPF + $\gamma \rightarrow \alpha$’ transformation range). In Domain A, the slip band travel “continuously” from one grip to other. The temperature distribution has regular profile which proves easy and regular evolution of slip band between successive serrations. The slip begins near to one grip and travel through specimen to other grip.

While the temperature distribution for Domain B has strongly irregular nature, which proves that slips occurs in “random position” (Fig. 5c). It worth pointing out that Domain B begins when starts hardening process due to $\gamma \rightarrow \alpha$’ transformation. It seems, that new inclusions of martensitic phase determine the slip bands location in the specimen area.

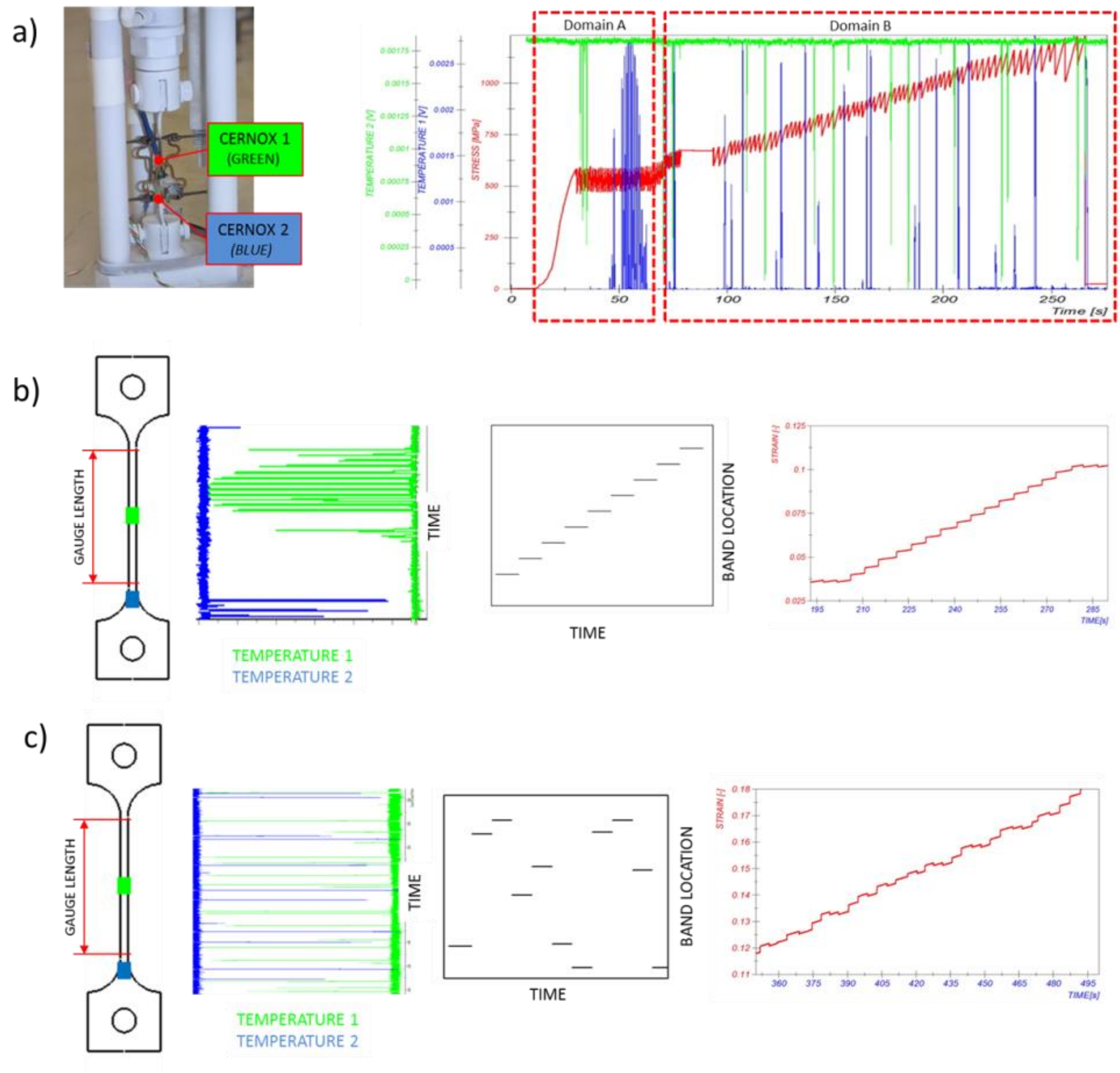
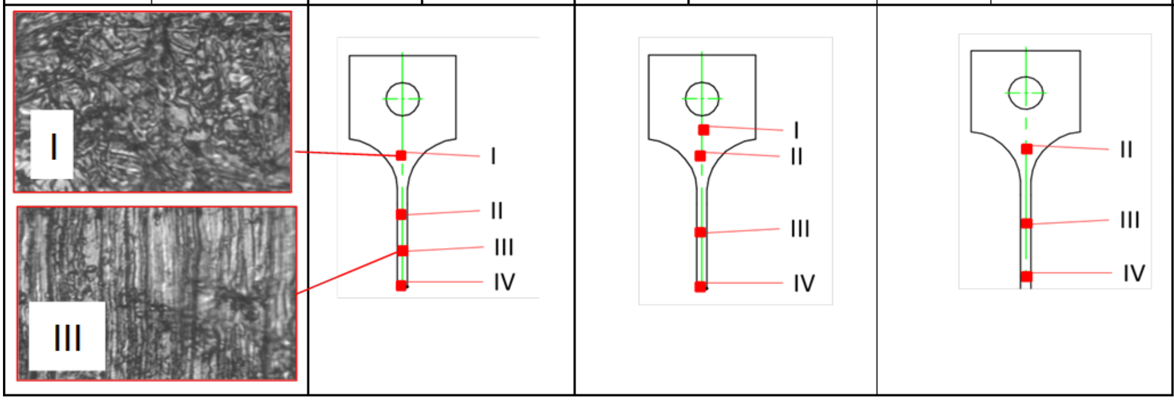


Fig. 5. *(a) Stress (red), temperature 1 (green), and temperature 2 (blue) in time domain for 304 steel specimen during strain-controlled tensile test at 4,2K, (b) schematic of slip band motion and orientation for domain A (DPF), (b) schematic of slip band motion and orientation for domain B (DPF+ $\gamma \rightarrow \alpha'$ transformation).*

In order to preform complete analysis the spatial distribution of new martensitic phase for each cross-section of specimen during each stage of tensile test is required. At the current level of investigations, distribution of martensitic phase in specimens was carried out by means of micro hardness tests (after tensile test). The hardness of martensitic phase is far greater then austenitic phase. The results for defined measurement points are presented in Tab.1.

Measurement points	Number of test	Conditions: After tensile tests at LH		After tensile test at RT		Without tensile test		
I	1	235	244	289	236			
	2	241		205				
	3	257		213				
II	4	490	498	217	226	216	223	HV 0.2
	5	510		226		217		
	6	495		235		236		
III	7	556	542	468	509	219	226	
	8	553		504		221		
	9	517		556		238		
IV	10	558	541	551	498	208	214	
	11	524		502		235		
	12	541		442		199		



Tab. 1. *Results of hardness test for specimen loaded at liquid helium temperature, at room temperature and for specimen before tensile test*

Tab. 1 contains also, microstructure photos obtained for two defined point: I and III. The plastic deformation in area related with point III is much more greater than for point I- specimen geometry influence. Therefore, the volume fraction of martensitic phase induced by plastic strain is greater in point III, which is confirmed by micro hardness test results. It is worth pointing out that during tensile test multi-necking effect is observed (Fig.6). It seems, that new phase of martensitic blocks evolution of slip bands.

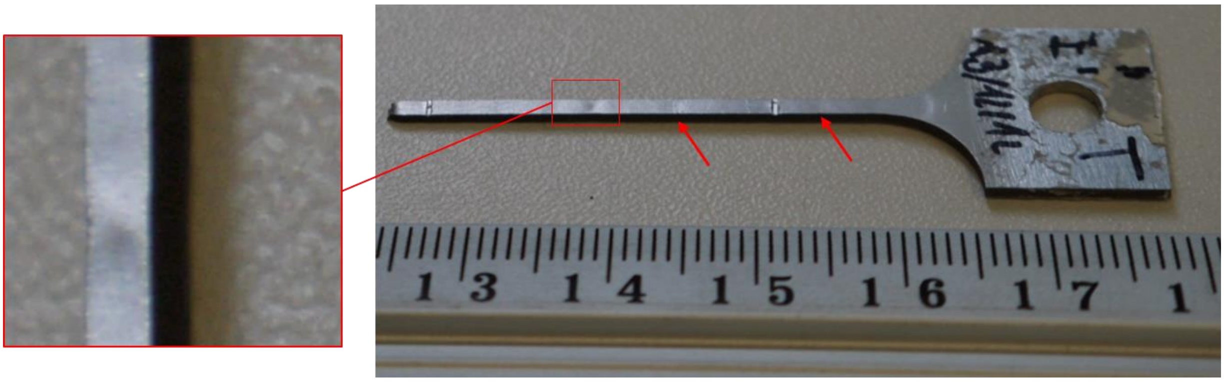


Fig. 6. *Multi-necking effect during uniaxial tensile test of austenitic steel specimen at liquid helium temperature*

3. Conclusion

Experimental results for uniaxial tensile test of 304 steel at liquid helium temperature confirm strong coupling between discontinuous plastic flow (DPF) and $\gamma \rightarrow \alpha'$ phase transformation. When phase transformations starts, regular and easy evolutions of slip bands changes to irregular form- slip bands occurs in random way. It seems that new martensitic phase determines the place where slip bands may occur. In other words new phase of martensite blocks evolution of slip bands (multi-necking effect).

References

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