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Hardening Response of Dual-Phase Steels Under Non-Proportional Strain Path

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***Abstract*:** *The anisotropic hardening behaviors of dual-phase steels under various strain paths are studied. Three dual-phase steels DP500, DP600 and DP780 with different amount of martensite were used in the tests. In order to identify strain hardening and initial plastic anisotropy of the as-received material, standard uniaxial tension test along different directions with respect to the rolling direction (RD) was performed. In addition, two stage tension-tension test was conducted in order to study the anisotropic hardening behavior of dual-phase steel under complex strain paths. The strain path change covers from proportional to near reverse loading, including pseudo cross-loading. The results showed that the dual-phase steels exhibited different hardening behavior under orthogonal and pseudo cross-loading compared with single phase steels. The explanation of their hardening behavior was also discussed.*

Keywords: *Dual-phase steel; Strain path changes; Anisotropic hardening behavior.*

1. Introduction

Metal parts and objects are commonly manufactured by metal forming operations, in which the workpieces are reshaped by plastic deformation. These operations are commonly associated with complex strain paths. In the last decades, sufficient experimental works have been conducted to understand the deformation behavior of low carbon and IF steels under complex strain paths [1, 2]. However, there have been fewer studies on the plastic deformation behavior of dual-phase steel under complex loading paths. In some of the previous experimental works, reversal loading paths have been applied to dual phase steels [3], and it was observed that the Bauschinger effect and permanent softening were taken place for the material. The Bauschinger effect is more pronounced for dual phases than for IF steel. In the work of Tarigopula et al. [4] and Yoshida et al. [5], the two stage loading path have been applied to dual phase steels and they found that almost no cross-hardening effect was observed for the materials in the subsequent loading. Conversely, the reloading stress yields at lower level than that in the monotonic tensile test, which evidently deviates from the behaviors found in IF/mild steels. Their works indicate that the presence of martensite phase in dual phase steels do have an key role on the hardening behavior of the materials subjected to complex strain path. But the physical mechanisms involved in the plastic deformation of the dual phase under complex strain paths are still not completely understood.

The objective of this work is to study the anisotropic hardening behaviors of dual phases with three different amount of martensite under complex strain path and analyze the influence of the second hard martensite phase on their mechanical behaviors under strain path changes.

2. Experimental Procedure

In this study, three dual-phase steels with grades of DP500, DP600 and DP780 were adopted. The microstructure of dual-phase steel is characterized by hard martensite particles and soft ferrite matrix. The hard martensite phase provide substantial strength while the soft ferrite give good formability for this material. The amount of martensite increase with the grade of the material. In this work, several mechanical tests were conducted in order to characterize these materials.

First, monotonic standard tensile tests along the rolling direction, 45° and 90° to the rolling direction from the as-received sheet are conducted to identify strain hardening and initial plastic anisotropy of the material. Then, for the two stage tension test, uniaxial tension is first applied to the as-received material in the rolling direction until strain reaches 0.04 or 0.07 and the material is fully unloaded. Then, sub-size specimens are cut from the pre-strained sheet at two different strain levels by an angle of 0 (proportional loading), 45 (pseudo cross-loading) and 90 (orthogonal loading) degrees with respect to the pre-loading direction. Hereafter sub-size specimens are subjected to another uniaxial tension tests. The tensile tests in three orientations for the pre-strained samples are instrumental in covering a wide range of strain-path changes for this material [4].

3. Results And Discussions

Fig.1-3 shows the results of the monotonic tension tests for the three dual-phase steels, respectively. All the curves exhibit a smooth transition from the elastic to the plastic domain, which is typical of dual-phase steel.

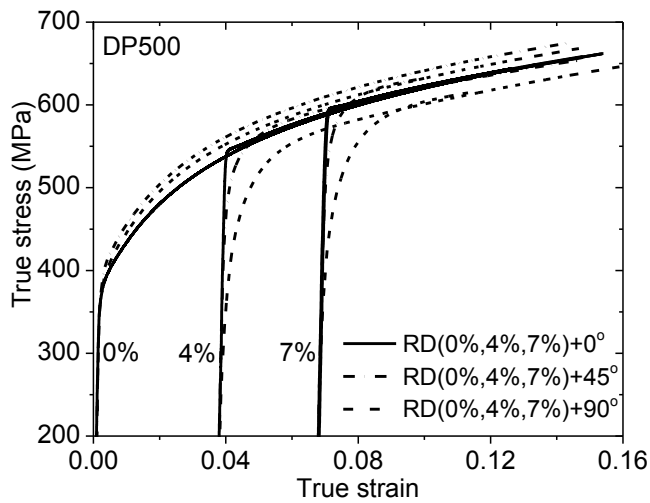

Fig. 1: True stress-strain curve of DP500 under two-stage tensile tests

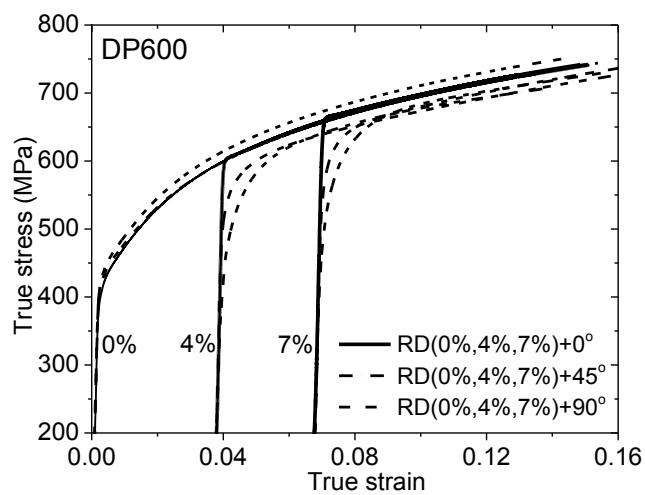

Fig. 2: True stress-strain curve of DP600 under two-stage tensile tests.

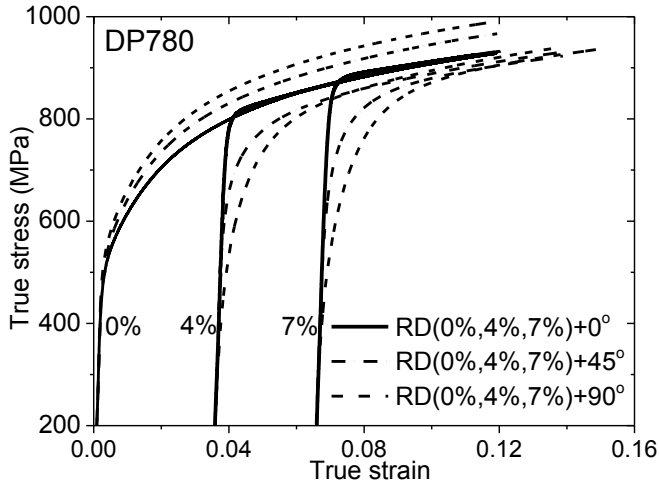

Fig. 3: True stress-strain curve of DP780 under two-stage tensile tests.

The results of two stage tension test is also depicted with the monotonic curves in Fig. 1-3. As seen from the figures, For all the pre-strains of the three steels, the reloading in different strain paths produced transient hardening behavior, i.e. yielding at lower stresses and rapid change of work hardening rate, which is completely different from that observed in single phase steels [3]. For the later, a stress overshoot the monotonic curve is generally perceived for the reloading curve in this kind of test.

The initial yield stress is strongly dependent on the orientation of reloading after pre-straining and the grade of the DP steels. The transient hardening effect is more pronounced for the 90º subsequent tensile orientation, although it's also observed in the 45º direction. Comparing the three dual-phase steels after transverse subsequent tensile orientation, it can be noted that the initial yield stress decreases with the increase of the amount of martensite in the steel, while the length of this transition period increases with increase of the amount of martensite. For the three dual-phase steels after 45º subsequent tensile orientation, i.e. in the condition of pseudo cross-loading condition, it is interesting to note that not only transient hardening effect but also permanent softening are observed for the three DP steels. Both the transient behavior and permanent softening increase with the increase of the amount of martensite and pre-strain.

The different anisotropic hardening behaviors of these steels might be due to the incompatibilities of plastic deformation between soft ferrite matrix and the hard martensite particles. It is deduced that the incompatibility of plastic deformation between the two phase has a direct effect on the activity of the slip systems and favoring the reverse reactivation of slip system during strain path change (Bauschinger effect), which might make a contribution to the decrease of the reloading yield stress. However, further microstructural examination need to be conducted to provide more detailed explanation.

4. Conclusions

In this work, monotonic tension test and two stage tension-tension test were conducted on three dual-phase steels in order to study the mechanical behavior of this kind of steel under monotonic and complex deformation paths. The hardening behavior of these steel under proportional, pseudo cross-loading and orthogonal loading were discussed. The results show that a transient hardening behavior and long-term softening were taken place for all the materials subject to orthogonal and pseudo cross loading path changes. This effect becomes more pronounced with the increase of martensite and pre-strain in the dual-phase steels. The anisotropic hardening behavior of dual-phase steel, which is completely different from that of single phase steel, might due to the incompatibilities of deformation between soft ferritic matrix and the hard martensite particles. Future work will focus on the physic mechanism of the hardening behavior of dual-phase steel under complex strain paths.

5. Acknowledgments

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