

# Cooperative micro-mechanisms between recrystallization and transformation during/after dynamic strain-induced transformation in aluminum-containing low-carbon steel



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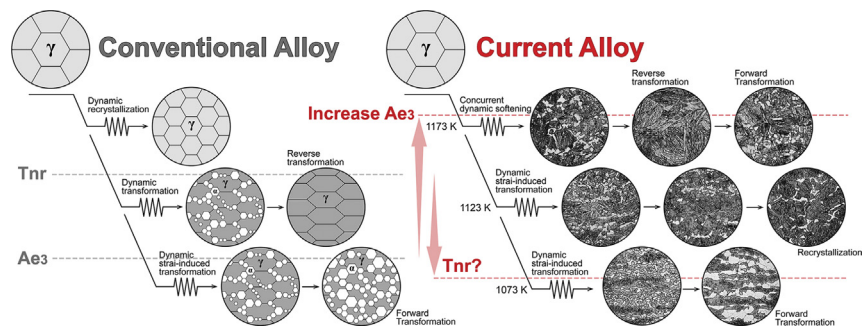
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## HIGHLIGHTS

- Dynamic transformation and dynamic recrystallization were concurrently enabled in the aluminum-containing low carbon steel.
- Recrystallization assisted by reverse transformation was discovered, which breaks the limit of non-recrystallization temperature.
- Transformation crystallography was applied to distinguish the sequence between transformation and recrystallization.

## GRAPHICAL ABSTRACT



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## ABSTRACT

In this work, the cooperative relationships among dynamic ferrite transformation, reverse ferrite transformation, and austenite recrystallization were investigated by using dynamic dilatometry, optical metallography, and electron backscattering diffraction in an aluminum-containing low-carbon steel subjected to hot compressions in the two-phase region. The microscopic mechanism of concurrent dynamic softening was studied based on the analysis of transformation crystallography. Moreover, this analysis method was used to discover the occurrence of reverse-transformation-induced recrystallization. In this microscopic mechanism, new austenite grains formed by reverse transformation can act as seeds for recrystallization. These paths for microstructural control in steels are not common, but they can be enabled by critical thermo-mechanical treatments combined with proper alloy design.

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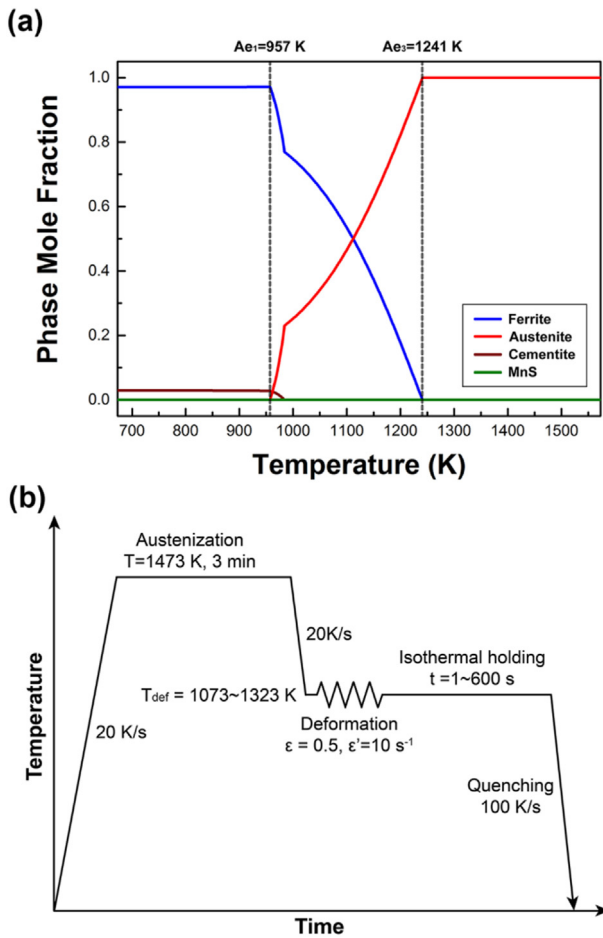
## 1. Introduction

Recrystallization and ferrite transformation are associated with the nucleation and growth of new grains in steels when austenite is deformed during thermo-mechanical processes. Recrystallization

produces new austenite grains; transformation produces new ferrite grains. Fine grain leads to hardening effect due to the Hall-Petch relationship [1,2], while softening process also occurs due to annihilation of blocked dislocations. In steels, both mechanisms are usually regarded as softening mechanisms during a deformation process. Static recrystallization (SRX) or static ferrite transformation (SFT) can occur after austenite grains have been strained. In contrast, the occurrences of dynamic recrystallization (DRX) or dynamic ferrite transformation (DFT) will be accompanied by the accumulation of strain during the deformation of

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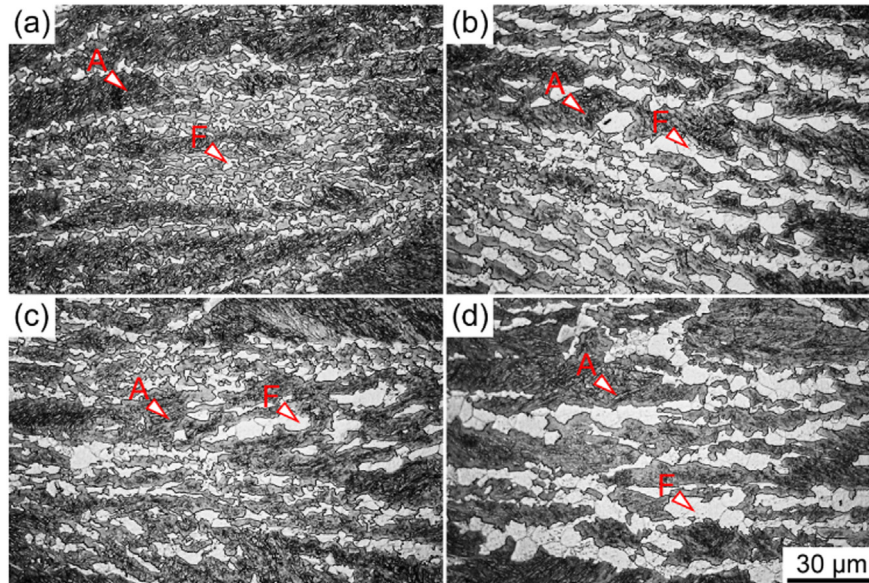
**Fig. 1.** (a) The equilibrium phase diagram of our studied alloy with a composition of Fe-0.16C-2.5Mn-1.17Al-0.97Si (in wt%) and (b) the schematic diagram showing thermomechanical treatments in the dilatometer.

austenite, rather than afterwards as a separate process. In most reports [3–7], these softening mechanisms occur separately or in sequence. Also, they are competitors for strain energy in deformed austenite.

There are few discussions on their interactions or collaborations among these softening mechanisms.

DFT has been frequently used to produce fine or ultrafine ferrite grains since it was first reported by Yada et al. in the 1980s [8,9]. Reactions of DFT can be divided into dynamic transformation (DT) and dynamic strain-induced transformation (DSIT) depending on the deformation temperature. DT is usually conducted by applying a large strain to induce ferrite transformation at a temperature above  $A_{e3}$  [7, 10–20]. Additional driving force for ferrite transformation above  $A_{e3}$  can be obtained during the deformation. Moreover, a critical strain is required for this driving force [3,5,21–23]. Certainly, the deformation-induced driving force also assists transformation at a temperature below  $A_{e3}$ . When DFT occurs at a temperature below  $A_{e3}$ , the reaction is classified as DSIT. It was claimed that DT ferrite had a morphology related to Widmanstätten transformation and that DSIT ferrite had a morphology related to diffusional transformation [6,24–28]. When the deformation temperature is below  $A_{e3}$ , forward ferrite transformation, which is SFT, will continue until equilibrium is achieved. When the deformation temperature is above  $A_{e3}$ , reverse ferrite transformation (RFT) can occur, and the tiny ferrite grains due to DFT diminish in the austenite matrix.

DRX of austenite, which takes place during deformation, can also release the strain energy by producing the nucleation of new austenite grains, followed by grain growth [29–34]. Several studies on the competition relationship between DFT and DRX have been reported, but the results have not been completely consistent. Choi et al. [3] demonstrated that DRX is the predominant softening mechanism when deformation is at temperatures above  $A_{e3}$ , while DSIT is the operative softening mechanism when austenite is deformed at temperatures below  $A_{e3}$ . Yang and Wang [4] also reported that energy from deformation can be fully utilized to induce ferrite transformation, indicating that DRX will not occur, when the specimen is deformed at temperatures below  $A_{e3}$ . In this viewpoint,  $A_{e3}$  temperature is the transition point between two mechanisms. However, by using the double-differential method, Ghosh et al. [5] concluded that the critical strain for DT is lower than that for DRX and that it increases with increasing temperature, while that for DRX decreases with temperature. They further discovered the concurrent operations of both DT and DRX at a deformation temperature above  $A_{e3}$ . Hence, there is no defined transition temperature if they occur concurrently.



**Fig. 2.** Optical micrographs of the middle of the specimens showing the microstructure evolution of the steel, after deformation, isothermally treated at 1073 K, for different time periods (a) 1 s, (b) 10 s, (c) 30 s, and (d) 60 s, followed by quenching.

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