Acta Materialia 136 (2017) 39–48

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Hall-Petch relationship for austenitic stainless steels processed by large strain warm rolling

Z. Yanushkevich [a], S.V. Dobatkin [b, c], A. Belyakov [a, *], R. Kaibyshev [a]

[a] Belgorod State University, Belgorod, 308015, Russia
[b] A.A. Baikov Institute of Metallurgy and Materials Science of RAS, Moscow, 119991, Russia
[c] National University of Science and Technology "MISIS", Laboratory of Hybrid Nanostructured Materials, Moscow, 119049, Russia

A R T I C L E I N F O

Article history:
Received 11 April 2017
Received in revised form
5 June 2017
Accepted 28 June 2017
Available online 29 June 2017

Keywords:
Stainless steels
Thermo-mechanical processing
Grain refinement
Strain hardening
Structure-property relationship

A B S T R A C T

The deformation microstructures and their effect on the yield strength of austenitic stainless steels processed by large strain warm rolling were studied. The samples of 304 L and 316 L type steels were subjected to caliber bar rolling to total strains of 2 at temperatures of 773–1173 K. The structural changes were characterized by the development of continuous dynamic recrystallization. A decrease in the rolling temperature resulted in significant grain/subgrain refinement and an increase in the yield strength at room and elevated temperatures. A power law function was obtained between the deformation grain and subgrain sizes with a grain size exponent of 0.3. Therefore, the yield strength could be expressed by a modified Hall-Petch relationship including a term of substructural strengthening, which was evaluated using the obtained size relation. The numerical factors normalized by shear modulus for both structural and substructural strengthening terms depended quite weakly on tensile test temperature in the range of 293–873 K that suggested the deformation mechanisms being invariant up to 873 K. On the other hand, the thermally activated mechanisms led to the yield strength decreasing much faster than shear modulus as the tensile test temperature increased above 873 K.

1. Introduction

Studies on dynamic recrystallization (DRX) are of particular importance for thermo-mechanical processing technologies, because DRX may provide the desired microstructure in various steels and alloys directly during warm to hot rolling [1–3]. Depending on processing conditions, two types of DRX, i.e., discontinuous and continuous, have been observed in austenitic stainless steels [3–5]. Discontinuous DRX readily develops during hot working, when the new DRX grains cyclically nucleate and grow out consuming work hardened grains [6,7]. The size of DRX grains decreases with a decrease in deformation temperature and/or increase in strain rate and can be related to the flow stress through a power law function with a DRX grain size exponent of about −0.7. Remarkable structural refinement leading to ultrafine-grained microstructure with a grain size below one micron can be achieved in austenitic stainless steels by warm working at temperatures close to approx. half of melting point [5,8]. Under conditions of warm working, the structural changes in austenitic stainless steels are characterized by the development of continuous DRX after sufficiently large strains, when the new grains result from progressive evolution of deformation substructures that are associated with a gradual increase in misorientations among the strain-induced subboundaries and transformation of the latter ones into grain boundaries. In such a case, the grain size exponent in the power law relationship between the DRX grain size and flow stress is about halved and comprised approx. −0.3 [3,5]. The grain refinement through continuous DRX upon large strain deformation offers attractive mechanical properties including high yield strength and high ultimate tensile strength [3,9], although the strengthening mechanisms in DRX materials have not been studied in sufficient detail.

The structural strengthening is commonly considered in terms of Hall-Petch relationship, which predicts a linear increase in the yield strength with inverse square root of the grain size [10,11]. The Hall-Petch relationship that has been initially used for evaluation of strength of annealed (statically recrystallized) materials was then validated for strain hardened (pre-strained) materials [12]. It

* Corresponding author. Belgorod State University, Pobeda 85, Belgorod, 308015, Russia.
E-mail address: belyakov@bsu.edu.ru (A. Belyakov).

http://dx.doi.org/10.1016/j.actamat.2017.06.060
1359-6454/

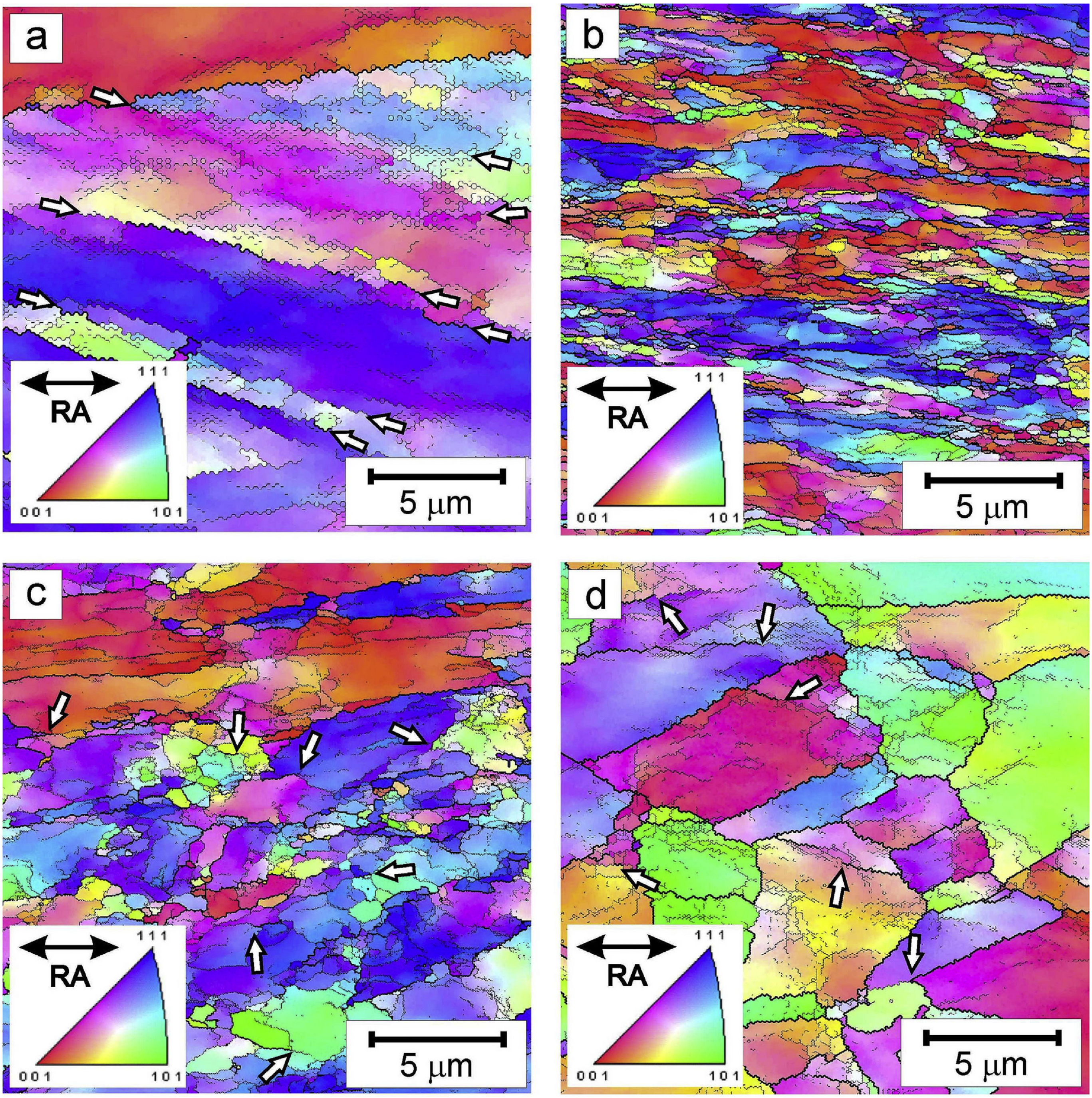

Fig. 1. Typical deformation structures and substructures developed in a 304 L-type stainless steel during warm rolling at 773 K, $\varepsilon = 0.5$ (a), 773 K, $\varepsilon = 2$ (b), 973 K $\varepsilon = 2$ (c), 1173 K, $\varepsilon = 2$ (d). High- and low-angle boundaries are indicated by thick and thin black lines, respectively. The inverse pole figures are shown for the rolling axis (RA).

should be noted, however, that Hall-Petch-type relationship was successfully used for materials subjected to relatively small strains, which are attainable upon conventional tensile tests at ambient temperature. The steels and alloys processed by large strain deformation, e.g., warm-to-hot rolled semi-products, are characterized by complex microstructures including well developed dislocation substructures and large internal stresses and are rather difficult to be treated by a simple Hall-Petch equation. Several approaches were proposed to evaluate the strengthening due to thermo-mechanical processing [13–18]. The most of them considered the subgrain size as the major strengthening contributor similar to the grain size in Hall-Petch relation. Various subgrain size exponents in the range of −1 to −0.5 depending on the test temperature and subboundary strength were suggested to evaluate the structural strengthening [13,19–22]. Following original Tailor consideration, a square root of dislocation density was also successfully used to estimate the flow stress even at rather large strains [23,24]. Another promising approach implies the grain boundary strengthening and the dislocation strengthening as independent and linearly additive contributors [25,26]. Accordingly, the yield strength can be evaluated by a modified Hall-Petch relationship, which includes an additional term for the dislocation