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Outstanding impact toughness of low-alloyed steel with fine lamellar microstructure

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ABSTRACT

A low-carbon low-alloyed steel subjected to tempforming exhibited high strength and outstanding impact toughness (KCV). The latter surprisingly increases from 412 J cm^{-2} at room temperature to 426 J cm^{-2} at 183 K. Such an unusual behaviour is attributed to delamination toughness, which is provided by the ultrafine lamellar microstructure. Namely, the rapid delamination crosswise to the impact direction blunts the crack and significantly increases the impact toughness.

1. Introduction

Low-alloyed high-strength steels are one of the most demanded structural materials owing to their high strength, sufficient ductility and reasonable cost. However, these steels possess a common drawback, which is associated with relatively high temperature of ductile to brittle transition that limits their engineering applications at lowered temperatures [1]. Recently, Kimura et al. have proposed a beneficial approach (tempforming) to increase the impact toughness of medium carbon steels at low temperatures that involves large strain warm rolling of quenched and tempered steels [2,3]. Tempforming results in the elongated ultrafine grains with finely dispersed second phase particles. The fine grained lamellar-type microstructure with a strong fibre of ⟨011⟩ along the rolling axis results in high anisotropy of the coherency length of {001} cleavage plane, which is maximal along the rolling direction and minimal in the transverse one, that promotes the delamination crosswise to the impact direction and increases the impact toughness. The mechanical properties of tempformed steels have been fairly clarified for steels with carbon content of 0.1% to 0.6% [4], whereas low-carbon steels have not been studied. The aim of the present study, therefore, is to illuminate the influence of tempforming on the strength and the impact toughness of a low-carbon low-alloyed steel.

2. Materials and methods

A low-carbon steel with the chemical composition of 0.03C-0.23Si-1.54Mn-0.19Cr-0.12Mo-0.02Al-0.04Nb-0.02Cu-0.2 V (all in wt%) was annealed at 1423 K for 1 h followed by water quenching. Then, the steel samples were annealed at 923 K for 1 h and rolled to total strain of 1.5. An equilibrium phase content was estimated by ThermoCalc v. 5 software with FE6 database. The microstructures were studied using a Quanta Nova Nanosem 450 scanning electron microscope (SEM) equipped with an electron back scattering diffraction pattern (EBSP) analyzer incorporating an orientation imaging microscopy (OIM) system and a JEOL JEM-2100 transmission electron microscope. The grain size (D) was evaluated as average distance between the high-angle boundaries with misorientations of $\theta \geq 15^\circ$, and the dislocation density (ρ) was estimated by Kernel Average Misorientation (θ_{KAM}), setting maximal misorientation of 15°, as $\rho = 2\,\theta_{KAM}/(b\,h)$, where b and h are the Burgers vector and OIM step size, respectively [5], using TSL OIM Analysis 6 software. The tensile tests were carried out by using an Instron 5882 testing machine with specimens of 12 mm gauge length and 3×1.5 mm^2 cross section with the tensile direction parallel to the rolling direction. The impact toughness was evaluated on standard Charpy V-notch specimens using an Instron 450 J impact machine with an Instron Dynatup Impulse data acquisition system at temperatures of 183 K to 293 K. The impact direction was parallel to the normal direction (ND) of the rolled steel plate.

3. Results and discussion

The initial microstructure after quenching consists of acicular-type ferrite with an average grain size of 11 μm (Fig. 1a). The dislocations are mainly collected in dislocation subboundaries (Fig. 1b); the

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dislocation density is 3.7×10^{14} m^{-2}. Warm rolling to total strain of 1.5 results in the pan-caked microstructure with the transverse grain size of 2.9 μm (Fig. 1c). The inverse pole figure for ND indicates strong bimodal fibre texture consisting of ⟨1 1 1⟩//ND and ⟨0 0 1⟩//ND. The latter suggests the maximal coherency length of {0 0 1} cleavage planes along the rolling plane that is similar to other studies on delamination toughness [3,4]. The uniform distribution of θ_{KAM} in Fig. 1d indicates the regular dislocation distribution in the tempformed steel sample. The dislocation gradients that can be observed as relatively large values of θ_{KAM} create rich net in the tempformed microstructure and look like typical deformation substructure. The calculated dislocation density comprises 11×10^{14} m^{-2}. Note here that the dislocation density is somewhat underestimated, because statistically stored dislocations are not taken into account by the used method for calculation. However, the density of statistically stored dislocations is much lower than that of geometrically necessary dislocations arranged in strain-induced subboundaries [6] and, therefore, should not affect the calculated values remarkably.

The longitudinal boundaries of highly elongated grains after tempforming are mainly represented by high-angle boundaries as shown in Fig. 2 (revealed by Kikuchi-diffraction under converged beam). The dislocations are distributed as dislocation tangles and separate dislocation subboundaries with low-to-medium misorientations. ThermoCalc predicts 0.17 vol% and 0.05 vol% of VC and NbC, respectively. An example of such particles uniformly spaced throughout with an average size of d = 30 nm is shown in Fig. 2c. The large strain warm rolling during tempforming could be responsible to loss any rational orientation relationship between the observed particles and ferrite matrix.

A series of tensile stress – elongation curves obtained at indicated temperatures is shown in Fig. 3a. In contrast to medium-carbon steel, the present low-carbon steel was substantially strengthened by tempforming. The yield strength increased from 465 MPa to 780 MPa without remarkable degradation in plasticity. Uniform elongation of 8–10% and total elongation of 13–17% are observed for the tempformed samples. The yield strength in the initial as-quenched state is evaluated as $\sigma_{0.2} = \sigma_0 + \Delta\sigma_D + \Delta\sigma_\rho$. Here, σ_0 is about 50 MPa [7], $\Delta\sigma_D = k_y\, D^{-0.5}$ is the grain size strengthening, and $\Delta\sigma_\rho = \alpha G b \sqrt{\rho}$ is the dislocation strengthening. Taking the shear modulus of $G = 81000$ MPa [8], $k_y = 0.24$ MPa m$^{0.5}$ [9], and $\alpha = 0.9$ [7], the calculated yield strength of 472 MPa is almost the same with experimental one. Takaki et al, suggested that the strengthening of work hardened steels is solely governed by the evolved dislocation density, which in turn depends on the grain size [7]. Namely, the dislocation strengthening incorporates the grain size strengthening and, therefore, can be used for strength calculation, ignoring the grain size strengthening [7]. Thus, the yield strength should be a sum of σ_0, $\Delta\sigma_\rho$, and the dispersion strengthening, $\Delta\sigma_{Or} = 0.4MGb\ \ln(0.82d/b)/(\pi\lambda\sqrt{(1\text{-}\nu)})$, where M is the Tailor factor, λ is the particle spacing, and ν is the Poisson's ratio [10]. Therefore, $\sigma_{0.2} = 767$ MPa calculated for the tempformed steel is close to experimental one.

The principal advantage of tempformed samples is an increase in the impact toughness at low temperatures (Fig. 3b–d). Similar to tensile behavior, the tempformed steel samples are characterized by higher maximal load and that of general yield as compared to the initial state.

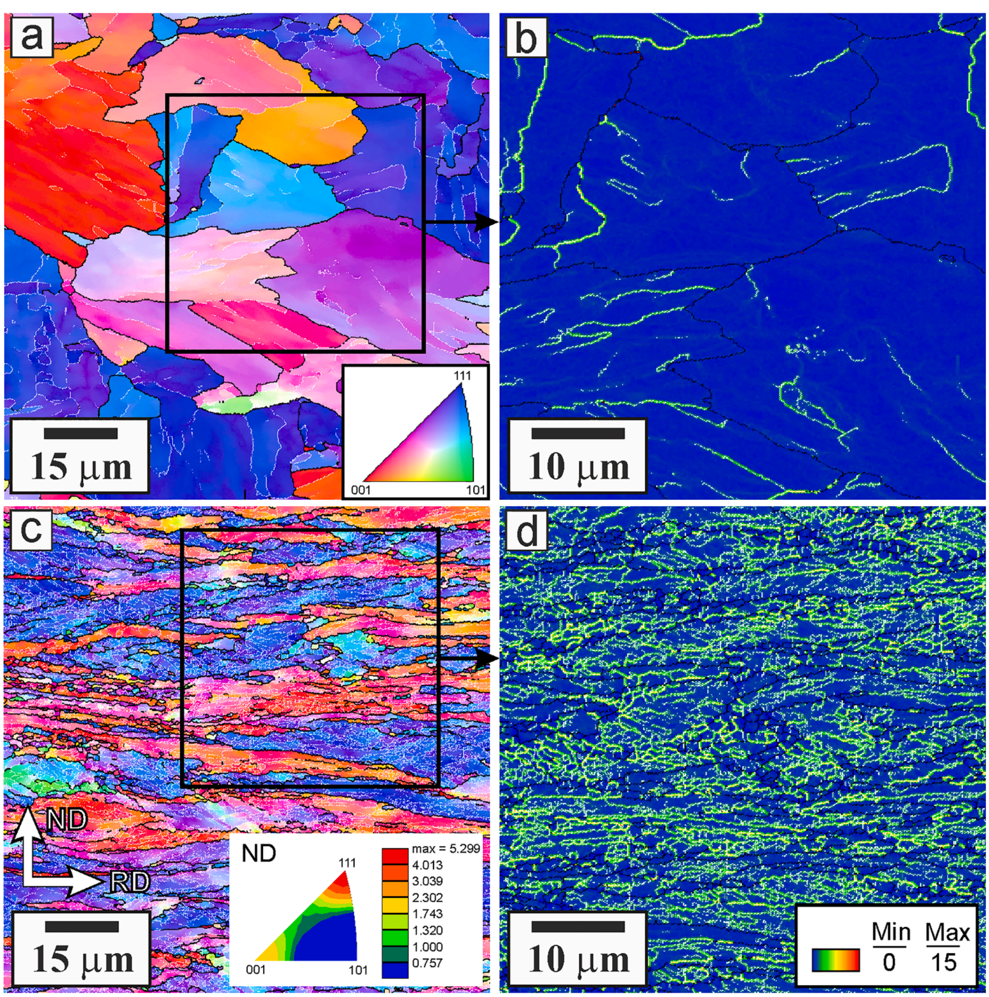

Fig. 1. Typical microstructures of a low-alloyed steel in the as-quenched state (a, b) and after temforming (c, d). Colors in (a) and (c) indicate the crystallographic direction along ND. Inserts enlarged in (b) and (d) show respective distributions of kernel average misorientations.

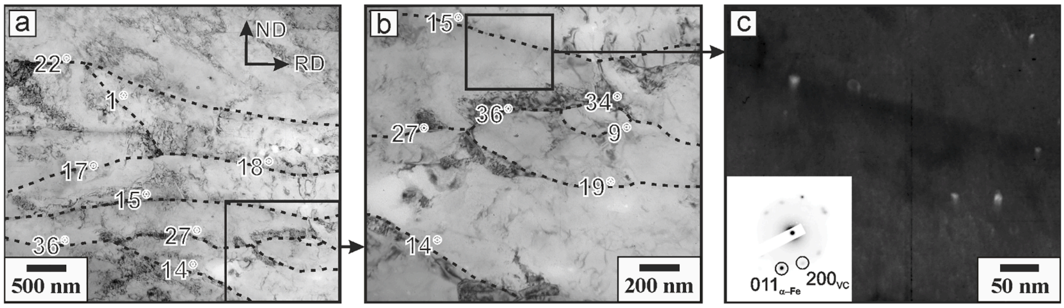

Fig. 2. Fine microstructure (a, b) and dispersed carbides (c) in a low-alloyed steel subjected to tempforming. The values in degrees in (a) and (b) correspond to misorientations of indicated grain/subgrain boundaries.

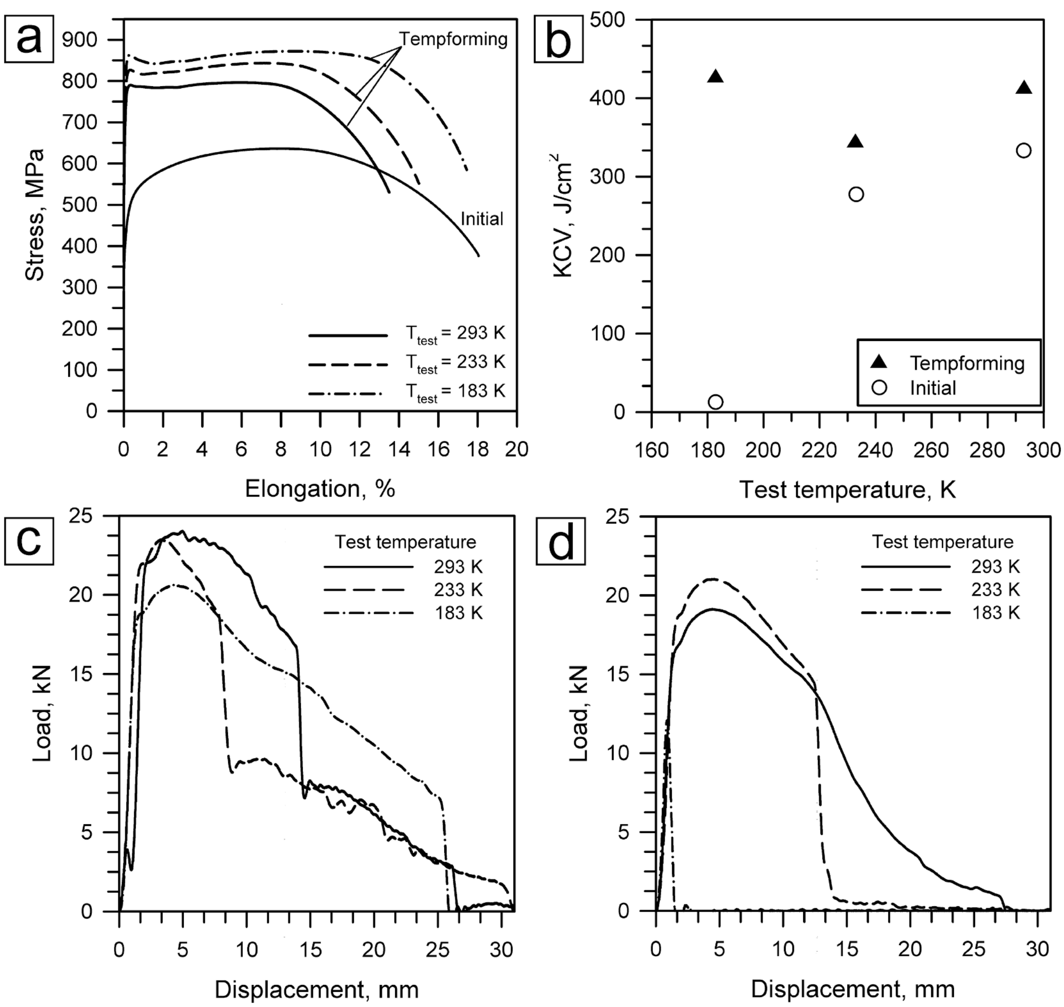

Fig. 3. Engineering stress – elongation curves (a), impact toughness (b) and corresponding load displacement curves for tempformed (c) or quenched (d) low-alloyed steel.

Moreover, in contrast to the initial state, the tempformed steel experiences crack arrest following rapid crack propagation that increases the impact toughness at 233–293 K. At rather low temperature of 183 K, the tempformed specimen exhibits pronounced stage of stable crack propagation increasing surprisingly the impact toughness well above 400 J cm^{-2}, while that of the initial steel drops to almost zero.

The impact specimens of the tempformed steel experience delamination as shown in Fig. 4 along with corresponding fracture surfaces. Irrespective of test temperature, two types of fracture can be recognized depending on the crack propagation direction. Typical ductile dimple fracture occurs along the impact direction (Fig. 4b, e). In contrast, brittle fracture takes place along the specimen (Fig. 4c, f). Hence, the delamination surface looks like terraces composed of large areas of brittle fracture and short steps of ductile fracture. The small size of such terraces in the specimen tested at 183 K testifies to easy delamination, which prevents at all the crack propagation along the impact direction and results in the large stage of the stable crack propagation after the maximal load on the load–displacement curve (Fig. 3c).

4. Conclusions

A low-alloyed steel, 0.03C-0.23Si-1.5Mn-0.2Cr-0.12Mo-0.04Nb-0.2

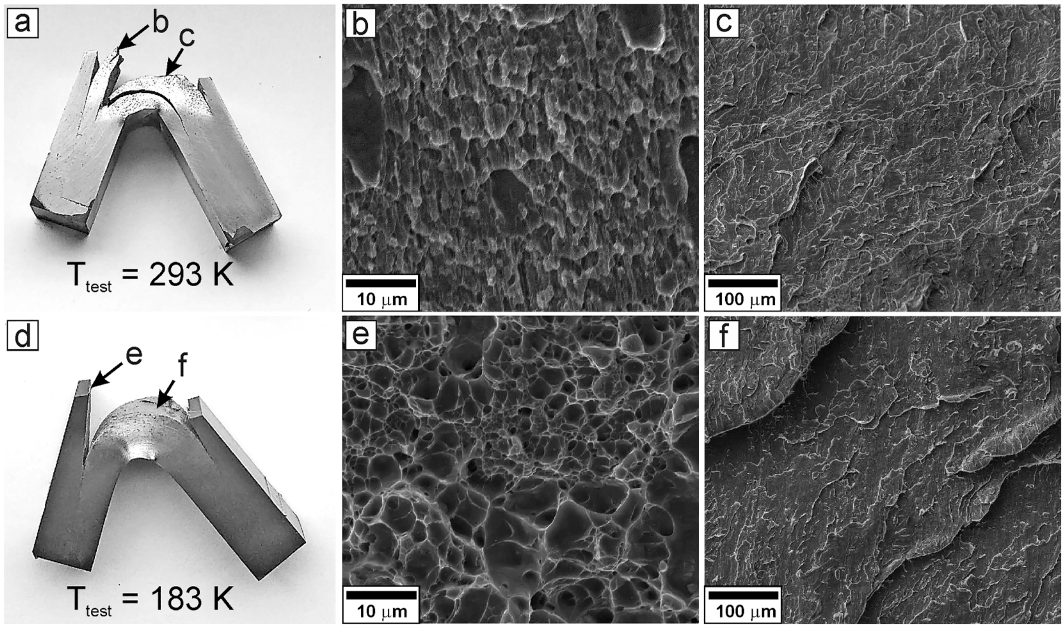

Fig. 4. Impact specimens and characteristic fracture surfaces after tests at 293 K (a–c) and 183 K (d–f) of a low-alloyed steel.

V (all in wt%) subjected to tempforming, i.e., large strain warm rolling following tempering, exhibited high strength and outstanding impact toughness, especially, at lowered temperatures. The strengthening is attributed to the high dislocation density evolved in the fine lamellar-type microstructure, whereas the large impact toughness results from the delamination toughness. The impact specimens with the fine lamellar microstructure located across the impact direction easily delaminate in the plane of the longitudinal direction, which leads to a bluntness of the initial crack, significantly increasing the impact toughness.

CRediT authorship contribution statement

Anastasiia Dolzhenko: Data curation, Investigation, Formal analysis, Visualization. **Rustam Kaibyshev:** Supervision, Resources, Project administration. **Andrey Belyakov:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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