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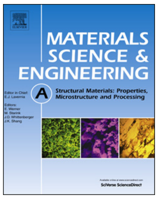

Influence of morphology and structural size on the fracture behavior of a nanostructured pearlitic steel

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ABSTRACT

Subjecting pearlitic steels to severe plastic deformation is known to transform the original colony structure to a nanostructured pearlite with the microstructural constituents aligned parallel to the deformation direction. Besides a huge increase in strength due to an enormous reduction of the interlamellar distance, other mechanical properties such as fracture toughness are deteriorated especially when the crack propagation is parallel to the shear deformed structure. Post-deformation heat-treatments up to 600 °C were applied to modify the oriented nanostructured pearlite after applying high pressure torsion to a micro-duplex structure of ultrafine grained ferrite with spherical cementite dispersoids. Already moderate annealing led to a pronounced increase of the fracture toughness accompanied only by a slight drop in strength. Nevertheless, at those low annealing temperatures the deformation structure was partially present which crucially influenced the crack propagation behavior and thereby the mechanical anisotropy. By raising the annealing temperature it was possible to produce a fully spheroidized microstructure and in further consequence mechanical isotropy was achieved. The decrease in strength due to microstructural coarsening is balanced by a remarkable gain in fracture toughness.

1. Introduction

Severe plastic deformation (SPD) has attracted much attention over the last 15 years due to its capability of generating bulk ultrafine-grained (UFG) and nanocrystalline (NC) material. This novel material class exhibits unique mechanical as well as physical properties, like ultrahigh strength [1], excellent fatigue behavior [2], extremely low magnetic coercitivity [3] and high electrical conductivity in combination with high strength [4]. An additional practical application of SPD is that this technique can be used to study the material behavior under extreme service conditions like the heavily-deformed topmost nanostructured layers of rails under rolling–sliding contact [5–8] with the big advantage of well known deformation parameters. In the rail–wheel contact a combination of high tangential loads (which is the product of the vertical load times the traction coefficient) and localized slip transforms near-surface regions of the rail (and the wheel) to a nanostructured pearlite. Under certain contact conditions rolling contact fatigue cracks, the so-called Headchecks, may initiate at the surface of the rail during service [9–11]. As those cracks emanate from the heavily-deformed surface layer the mechanical properties as well as distinctive microstructural features of the nanostructured pearlite are of great interest. Besides rolling contact fatigue wear is mainly affecting the in-service behavior. As wear occurs at the top surface the nanostructured surface layer is closely linked to the wear process as well [8]. Previous studies of Wetscher et al. [5] and Hohenwarter et al. [12] were devoted to the fracture behavior of SPD-deformed fully pearlitic steel used in railway applications by means of equal channel angular pressing (ECAP) and high pressure torsion (HPT) respectively, which are two of the numerous existing SPD-methods. At very large strains the initially randomly oriented pearlitic structure is transformed to a nanostructured composite of ferrite and cementite or cementite like amorphous layers [13], which are perfectly aligned with respect to the shearing direction. By performing fracture toughness tests on samples with three different crack propagation directions, each perpendicular to each other, a different fracture behavior was noticed which was related to the microstructural anisotropy caused by the alignment during HPT. It is especially the strong deterioration of the fracture toughness, reported in [12], from an initial value of around 33 $\mathrm{MPa}\sqrt{\mathrm{m}}$ to approximately 4 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for the largest degree of deformation when tested along the shear direction, whereas the contrary is observed for the two

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other directions where the fracture toughness remained high. The aim of the current study was to generate an UFG-composite of ferrite and cementite with isotropic mechanical properties, in particular isotropy regarding the fracture behavior and simultaneously keeping the strength up as high as possible. Several ways exist to produce such a micro-duplex structure, like ECAP of eutectoid and hypereutectoid steel at high temperatures [14,15], subsequent annealing of a low-carbon steel after ECAP [16], warm compression tests of martensite with eutectoid composition [17], advanced thermomechanical processing of a C–Mn steel [18], cold rolling of a dual-phase steel with subsequent annealing [19] or HPT with additional tempering of an eutectoid steel [20]. For the current study the approach of an additional annealing treatment after the HPT-deformation was chosen to transform the nanostructured lamellar pearlite to an equiaxed and spherical one. The idea was that by modifying the shape the high strength should be kept almost constant due to a change of the hardening mechanism from boundary strengthening to second phase strengthening. The question which now arose was whether the fracture toughness would be improved by this morphological change or not.

2. Experimental

To obtain this micro-duplex structure consisting of globular cementite dispersoids in an UFG ferritic matrix a two step process was chosen. Firstly, a fully pearlitic rail steel, R260, with the chemical composition given in Table 1 was subjected to HPT similar to the experiments described in Ref. [12]. The HPT-disc was deformed under a nominal pressure of 5.6 GPa at room temperature for three revolutions resulting in a shear strain $\gamma=28$ at a radius of 10 mm according to

$$\gamma = \frac{2\pi n r}{h} \tag{1}$$

Pure metals, like iron or copper, and some alloys like austenitic stainless steel or aluminum alloys reach a saturation regime at a certain amount of strain. In the saturation regime the deformation induced refinement is in equilibrium with the deformation induced coarsening by grain boundary migration. At this point no further microstructural refinement and change in mechanical properties occur, see [21]. For the pearlitic steel we have not reached the saturation regime. The cementite as a second phase impedes grain boundary migration, hence the refinement continues and shifts the steady state to higher strains. Before this was achieved the hardness of the samples reached the hardness of the deformation tools which made further straining impossible. For this study only samples from the outer part of the disc having the highest degree of deformation were considered for further treatment. Slightly oversized compact tension (CT) samples for linear elastic fracture mechanics (LEFM) testing were extracted from the disc periphery with the expected crack propagation direction parallel and perpendicular to the shear direction as can be seen in Fig. 1. Subsequently, heat-treatments were performed under an oxidizing atmosphere at different temperatures for 2 h. The aim of these heat-treatments was to modify the aligned lamellar microstructure to a fully equiaxed one with spherical cementite dispersions in it. After final sample preparation the CT-specimens had a width $W=5.2$ mm and a thickness $B=2.6$ mm. The fatigue pre-crack was generated by cyclic compression–compression loading. Finally the fracture toughness tests were carried out on a testing machine from Kammrath & Weiss at a constant crosshead speed of 2.5 μm/s at room temperature in accordance with ASTM E-399. The microstructure as well as the fracture surfaces were studied in a scanning electron microscope (SEM) from Zeiss at an accelerating voltage of 5 kV.

Table 1
Chemical composition of the fully pearlitic standard rail grade R260. The numbers given are in weight percent.

C	Si	Mn	P	S	Fe
0.76	0.35	1	0.017	0.014	Balance

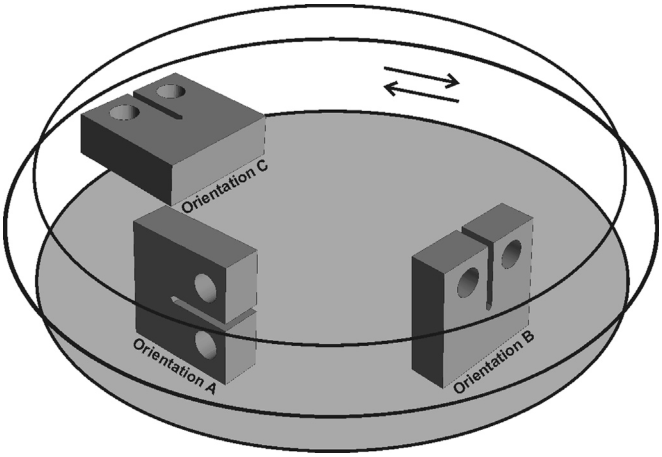

Fig. 1. Schematic illustration displaying possible sample orientations with respect to the shearing direction (indicated by the arrows) in an HPT disc for linear elastic fracture mechanics testing. The sample denominated as Orientation A shows a configuration where the crack propagation direction is parallel to the shear direction, whereas for samples of Orientation B and C the propagation direction is perpendicular to the shear aligned microstructure.

3. Results

3.1. Microstructure

The HPT-deformation led to a significant change of the initially randomly oriented pearlitic colony structure to a nanostructured lamellar aggregate of alternately arranged ferrite and carbon enriched areas [12,13] which were aligned with respect to the shear direction, as can be seen in Fig. 2(a)–(c). Additionally, the SPD-process led to a microstructural refinement where the initial cementite interlamellar distance of an average value of 200 nm was reduced by a factor of ten to roughly 20 nm at a strain of $\gamma=28$. Concurrently the regions of the initial cementite lamellae decreased to a few nanometers. A direct effect of this refinement is an enormous increase of strength which the hardness measurements confirmed as can be seen in Fig. 3. Up to an annealing temperature of 420 °C and a holding time of several hours no marked microstructural changes compared to the SPD-state occurred which the hardness measurements additionally confirmed. However, from that temperature on, morphological changes of the microstructure were observed. On the one hand the SPD-deformed ferrite lamellae started to coarsen and became equiaxed and on the other hand the carbon enriched areas began to spheroidize. Both resulted in a marked softening. With increasing temperature further coarsening took place. An evolution of the microstructure with progressive heat-treatments can be seen in Fig. 4. Detailed microstructural characterization was done for four heat-treatment conditions by SEM micrograph analysis. Several hundred ferrite grains as well cementite particles were individually measured grain by grain, and the average value and the standard deviation of the ferrite and cementite structural size were determined and are given in Table 2 along with the corresponding hardness. Depending on the chosen heat-treatment (temperature and time) a continuous transition from a partially