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Role of pearlite colonies on the dynamic flow stress of low carbon steel

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ABSTRACT

The dynamic deformation of low carbon steel is examined in two different microstructures; the as-received coarse grained material composed of α-ferrite and pearlite phases, and a heat treated microstructure in the form of carbide particles dispersed within a ferrite matrix. Testing in the dynamic regime is completed using a Split Hopkinson Pressure Bar at strain rates of 10^2–10^4 s^{-1} with testing temperatures of room temperature, 300, 500 and 650 °C. The correlation between strain rate and corresponding flow stress showed a distinct transition delineating the quasi-static regime as dominated by the thermally activated flow stress and that of the dynamic regime. The strain rate and basic characteristics of the thermal and athermal stresses, are studied to determine the mechanisms of deformation as a function of the microstructure, strain rate and temperature. The relative influence of short and long range barriers on the flow stress components is studied in a microstructure in which the pearlite colonies, an effective long range flow stress barrier, are removed. Separation of flow stress components is utilized in a constitutive equation based on thermal activation theory to predict flow stress as a function of strain, strain rate, temperature and explicit microstructure variables including pearlite volume fraction and grain size. Results of this model are compared with those obtained experimentally for both the as-received and heat treated materials.

1. Introduction

Low carbon steel (LCS), is the primary reinforcing phase in civil structures due to its diverse nature of mechanical properties relative to its economical feasibility. Consideration of this material in structural designs must account for its effective properties under conditions resulting in abnormally high loading rates and elevated temperatures. These properties are generally studied utilizing models which incorporate strain, strain rate and temperature dependent parameters. Several models exist for calculating the stress-strain response under these conditions. One of the common models is that of Johnson-Cook (JC) [1] in which the material constants are determined from empirical fitting of experimental dynamic flow stress obtained from at various strain rates and temperatures. These constants do not include microstructure related parameters such as the grain size, phases and dislocation homogeneity and density which are known to influence the material dynamic response [2–5]. Another model is the Zerilli-Armstrong (ZA) that includes the effect of grain size by utilizing the Hall-Petch relationship for both the BCC and FCC crystal structures [6]. A third widely used phenomenological model is the Mechanical threshold stress (MTS) [7,8] which is based on a physical mechanism of thermally activated dislocation motion and focuses on the determination of mechanical threshold stress. The flow stress is expressed in terms of an athermal component due to barriers of thermally activated dislocation motion, the strain hardening due to dislocation accumulation, and strain-rate and temperature dependent scaling factors based on normalized activation energies. The model parameters do not include explicit microstructure dependent terms [9]. DeMange et al. [10] utilized the JC model to simulate the dynamic response of Inconel-718 in the annealed and precipitate-hardened states. The hardening parameter in the model is written as a strain rate independent which could explain the fact that the model outcomes over predict the flow stress response at high strain rates. The model also did not accurately predict the saturation of the flow stress with increasing strain, a feature that was observed in the experimental results. Daridon et al. [11], studied effects of adiabatic shear band spacing on the dynamic response of HY-100 steel and Ti-6Al-4V alloy and concluded that the physically based MTS model was in better agreement with experimental results than that of the JC model. The authors reasoning being that the adiabatic shear bands act as thermal activation barriers for dislocation motion, a physical phenomenon that the JC model does not account for.

Lee and Liu [2] studied the dynamic behavior of different steels with varying weight percent of carbon with respect to effects of

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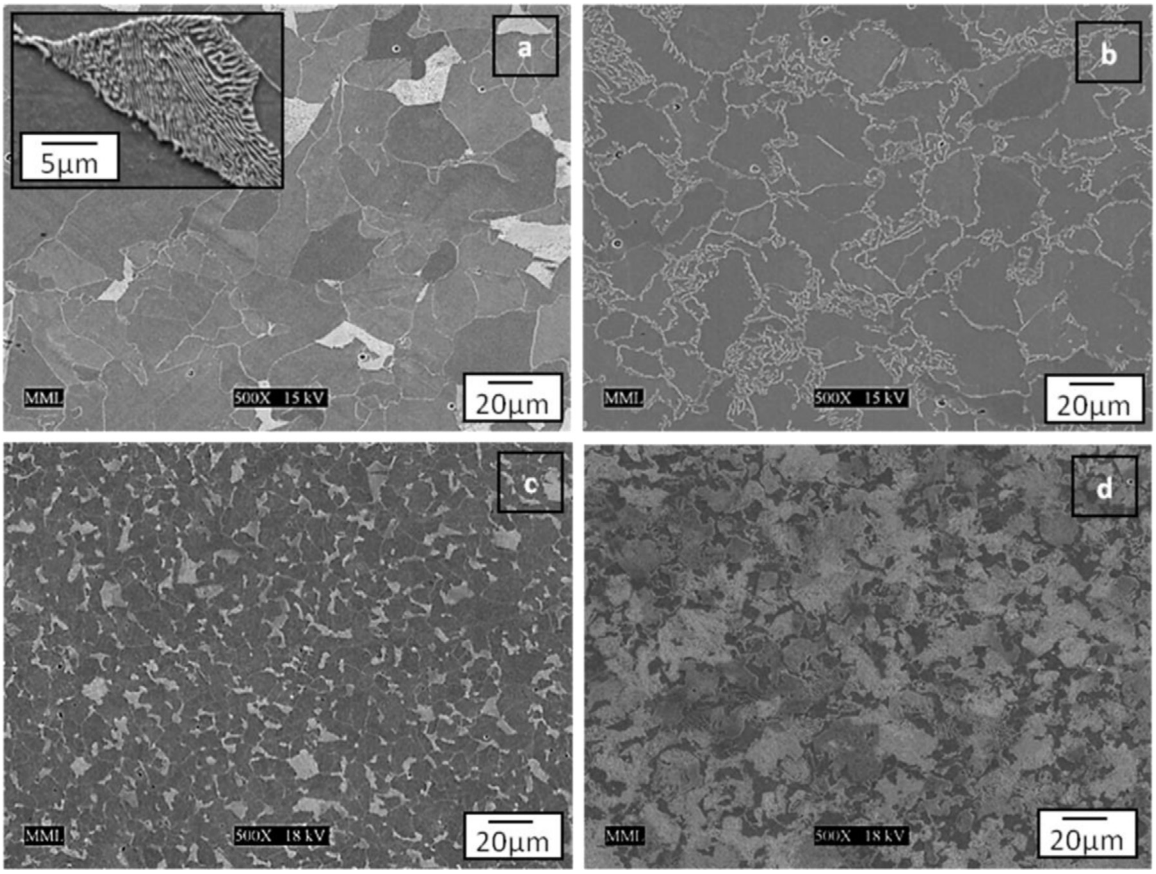

Fig. 1. Micrographs of the microstructures with different pearlite volume fraction being studied: (a) As-received A572 with a grain size of 25 μm, consists of pearlite colonies (dark phase) having a volume fraction of 9% and alpha-ferrite (light phase) equaxied grains. The insert is a magnification of a pearlite colony showing the cementite-ferrite lamella configuration. (b) Heat treated microstructure with pearlite colonies being dissolved and dispersed along the grain boundaries of the ferrite matrix. The grain size is 38 μm. (c) 1018 steel with a 20% volume fraction of pearlite and grain size of 9 μm, (d) 1060 steel with grain size of 7 μm grain size, consists of pearlite colonies shown as light regions with 72% volume fraction and alpha-ferrite phase being the dark regions.

temperature and strain rate. Results of their work showed that the flow stress and temperature sensitivity increase with increasing carbon content. Lee and Lin [3] studied the effect of pre-strain on the 304 stainless steel where results showed that the dynamic deformation response is sensitive to pre-straining. They interpreted this effect in terms of the role of pre-straining in modifying arrangements and density of the dislocation network within the microstructure. Bardelcik et al. [12] studied the effect of cooling rate on the high strain rate response of steel, showing the changes in microstructural phases including martensite, bantite, pearlite and ferrite, had a noticeable effect on the dynamic response of the steel by adjusting the UTS and hardening rate. Odeshi et al. [13] examined effects of the high rate loading of low alloy steel and showed that the plastic deformation is governed by two occurring processes. In the early stage strain hardening, which is strain rate dependent, is dominant. As deformation progresses, adiabatic heating occurs causing thermal softening to dominate. Zhang et al. [14] and Lee and Chen [15] have recently investigated the role that Al_3Sc precipitates have on the dynamic response of the material. It was shown that the secondary particles had a significant effect on the microstructural evolution during dynamic loading conditions. Zhang studied the condition of high speed projectile impacts while Lee and Chen utilized SHPB techniques to characterize the dynamic response. They similarly concluded that the particles had two effects; the first is related to the stabilization of the matrix and the second is due to effect of the particles acting as a major source of dislocations, thus resulting in an increase in the strain-induced hardening. DeMange et al. [10] studied the dynamic deformation response due to blunt projectile penetration, dynamic compression and top-hat dynamic shear testing of annealed and precipitate-hardened Inconel-718. During blunt projectile testing, using plate impacts, the annealed material had a higher resistance to penetration than that of the precipitate-hardened state. During dynamic compression tests, the annealed state resulted in a much lower over-all flow stress than the latter material, but showed considerably superior work hardening than the precipitate-hardened Inconel. The reason for the lowered work hardening in altered state of the Inconel was validated by top-hat geometry dynamic shear tests. Results of these tests showed that the precipitated hardened material readily forms shear bands, leading to localization which lowers the load capacity as compared to the annealed state of the material.

Ogawa et al. [16] studied the high strain rate of low carbon steel employing a model based on the concept of separating the flow stress into two physically-based components. The first is an athermal component which is only a function of strain and is modeled as a simple power law relation. The second is a thermal component that is a function of temperature and strain rate and is modeled assuming that deformation obeys a single thermal activation process. The combined dependence of the stress on strain rate and temperature is based on the Larson-Millar parameter. In a similar approach, Nemat-Nasser et al. [4,5,17] has studied the dynamic response of several metals and alloys including vanadium, tantalum alloys, titanium alloys, aluminum alloys, OFHC copper, molybdenum and niobium and further considered the drag stress as an additional component in the flow stress calculations. The attractive feature of these models is that the different components of the flow stress being derived on the basis of dislocation dynamics as a function of strain rate and temperature would allow the inclusion of microstructure sensitive parameters.

The current work examines the dynamic flow stress of the low