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A microstructure-based macro-micro multi-scale fine-blanking simulation of ferrite-cementite steels

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ABSTRACT

The fine-blanking process of ferrite-cementite steels was simulated with a macro-micro multi-scale approach. In the macroscopic simulation, the effects of material and blanking clearance were investigated by evaluating the damage work density of the material in the center of the fine-blanking shearing zone. A series of microstructure-based models with different particle fraction and distribution were generated as sub-models for the microscopic simulations. Microscopic damage in the sub-models was predicted with the damage work model. The simulation results indicated that an increase in particle fraction and the existence of carbide banding accelerated the microscopic damage of the material in the shearing zone during fine-blanking. Micro cracks appeared and extended along the carbide band. In addition, an increase in blanking clearance speeded up the microscopic damage accumulation at the microscale and caused early fracture of the material in the shearing zone at the macro scale. The SEM observations of various fine-blanking specimens substantiated the predictions of the simulations and suggested that severe carbide banding would change the macro crack path in the sheets, adversely affecting the quality of the blanking surface.

1. Introduction

Fine-blanking is a sheet-forming process which can produce high-quality and clean-cut components [1]. So far, it has been applied widely in the production of precise parts in the automobile, medical, and other industries [2]. Compared to conventional blanking, fine-blanking is characterized by a smaller clearance and high-pressure at the ejector and V-ring, which create a more compressive stress state in the shearing zone [3–6]. Therefore, the occurrence of macro cracks will be delayed significantly in the fine-blanking process, thus exhibiting a smooth-sheared surface.

At present, carbon steel is the most commonly used material for fine-blanking because of its good mechanical properties and relatively low cost. Normally, hot-rolled ferrite-pearlite steel sheets require further cold rolling and spheroidized annealing treatment to obtain ferrite-cementite steel with globular cementite (θ) embedded in a ferrite (α) matrix. Thus, steel sheets possess better ductility and meet the demands of cold forming processes, such as fine-blanking. However, the rolling process and annealing heat treatment exhibit large diversity in the production process. In addition, microstructural heterogeneity among materials exists and is reflected in certain aspects such as ferrite grain size, cementite size, and their distributions.

For cold rolled ferrite-cementite sheets, microstructure inhomogeneity usually appears in the form of microstructural carbide banding, as observed in the thickness plane of steel sheets, and this banding is generally located at the thickness plane and parallel to the rolling direction. Due to rolling deformation, lamellar pearlites tend to form a band structure along the rolling direction. Even after spheroidized annealing, cementite particles and some retained pearlite will potentially remain at the original band location. The microstructural banding distribution of the constitutive phase and particles causes microstructure inhomogeneity and can potentially affect the mechanical properties of materials, as reported in experimental and simulation results with dual-phase steel (DPs) with banded martensite [7], as well as with AA5474 [8] and SiCp/Al composites [9] with particle stripes.

Microstructural features, such as constitutive behaviors, phase morphology, and distribution play a significant role in the mechanical properties and forming behavior of materials, as reported in relevant publications [10–12]. The representative volume element (RVE) approach is normally employed to correlate the response of the microstructure to the overall material at the macro scale. Under rather simple boundary conditions, the RVE model is usually able to simulate limited deforming types, such as uniaxial tension, shearing, and similar deformations. Recently, a macro-micro multi-scale simulation approach has been developed to

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investigate the effects of microstructure on various metal forming processes. For instance, Hu et al. [10] examined the effects of particle distributions on wrap-bendability and on fuel cap stamping of AA5754 sheets. Similar microstructure-based approaches have been used for characterization of the stretch-flangeability and hole-expansion formability of dual-phase steels (DPs) by Uthaisangsuk et al. [13] and Kim et al. [14], respectively. These simulations have demonstrated the correlation between microstructure features and the material's macroscopic forming properties.

In the fine-blanking process of ferrite-cementite steel, the fine-blanking forming property and the surface quality of the blanking are strongly influenced by microstructure features, such as the spheroidization ratio, cementite fraction, and carbide banding, as reported for a related experiment by Schmidt et al. [15]. However, most research on fine-blanking simulations is limited to the macro scale, and a microstructure-based fine-blanking simulation has been rarely achieved to date.

The present work intends to investigate the effects of microstructure features on the fine-blanking properties of materials by employing a macro-micro multi-scale simulation method. Firstly, a macroscopic fine-blanking simulation of ferrite-cementite steels was conducted using different materials, sheet thicknesses, and blanking clearances. Secondly, microstructure-based sub-models were introduced for microscopic simulation at the center of the fine-blanking shearing zone to investigate the influence of particle fraction and carbide banding on the fine-blanking process. The actual microstructures in the fine-blanking shearing zone were observed for comparison with the simulations.

2. Experimental work

A low carbon steel C15E and a typical high-strength low alloy steel 42CrMo4 were used for analysis in this study. One C15E sheet with 3mm thickness and several 42CrMo4 sheets with 3mm and 6mm thicknesses were obtained for the experiment to compare the results. All of the steel sheets were cold rolled and annealed for spheroidized cementite. To simplify the listing of the properties of all studied sheets and to simplify the modeling process in the subsequent simulation work, one 42CrMo4 sheet with 6mm thickness was selected as the reference 42CrMo4 sheet. In the following work, the properties and modeling of the 42CrMo4 steel refer to this reference 42CrMo4 sheet, unless noted differently. The chemical compositions (in wt.%) of the studied C15E and 42CrMo4 materials are listed in Table 1.

Microstructures of all steel sheets were detected by Optical Microscope (OM) and Scanning Electron Microscope (SEM) from the longitudinally cut thickness plane. Fig. 1(a) and (c) presents the typical microstructure of the spheroidizing annealed C15E and 42CrMo4 steels with the ferrite (α) and globular cementite (θ) phases. In some sheets, carbide banding was evident in the center of the specimen along the rolling direction as shown in Fig. 1 (b) and (d). The microstructures of all steel sheets were evaluated based on the standard SEP1520 in order to determine the differences in microstructures between steel sheets due to microstructure features such as carbide banding and lamellar pearlite remains [16].

Table 1
Chemical compositions of the two steel sheets (wt.%).

	C	Si	Mn	Cr	Mo	P	S	Fe
C15E	0.15	0.26	0.53	0.024	0.007	0.012	0.002	Bal.
42CrMo4	0.39	0.25	0.81	1.01	0.18	0.01	0.002	Bal.

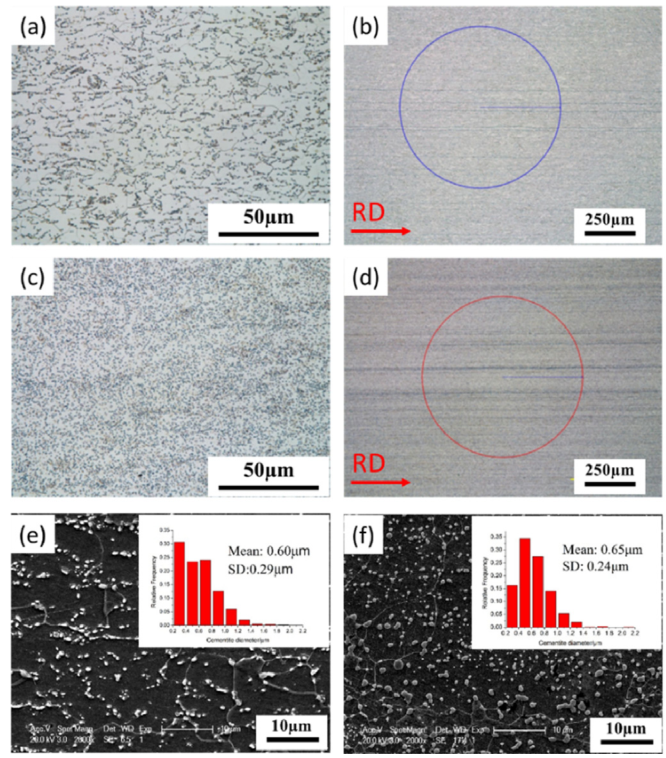

Fig. 1. (a) and (c) OM images of C15E and 42CrMo4; (b) and (d) carbide banding observed in C15E and 42CrMo4; (e) and (f) SEM images of C15E and 42CrMo4 with respective histograms for particle size distribution.

Fig. 1(e) and (f) shows the SEM image of C15E and the reference 42CrMo4 material with a larger magnification. The bright zones are globular cementite dispersed in the ferrite matrix (dark zone). The histograms of the particle size distribution of the cementite for both materials were obtained from the image processing software Image Pro 6. Both histograms depict a distribution that is close to lognormal. The average particle diameter was 0.60μm for C15E and 0.65μm for 42CrMo4.

Standard tensile tests for the C15E and 42CrMo4 sheets were conducted on a Zwick/Roell Z100 testing machine at a strain rate of $10^{-3}s^{-1}$ with dog-bone shaped rectangular specimens obtained along the rolling direction. The tensile specimen was designed with 15mm width by 3mm or 6mm thickness for a rectangular cross section. The nominal gauge length was 37.9mm for 3mm thickness and 53.6mm for 6mm thickness based on the standard ISO 6892-1:2009. The tensile test resulted in yield stress, tensile stress, and elongation of 298.85MPa, 426.69MPa, and 41.6%, respectively for C15E. For 42CrMo4, the respective values were 308.44MPa, 481.98MPa, and 36.1%.

The fine-blanking tests were conducted on a FEIN-fit HFT7000 fine-blanking press. Cylindrical specimens were blanked with the fine-blanking parameters listed in Table 2. The V-ring was set only

Table 2
Parameters of fine-blanking test.

Blanking holding force	750kN for 3mm thickness sheets 1500kN for 6mm thickness sheets	
Counter-top force	350kN	
Fine-blanking material	C15E	3mm
	42CrMo4	3mm and 6mm
Punch round		0.050mm
Blanking clearance		0.015mm (cl15) and 0.050mm (cl50)