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Quantification analysis of the heterogeneity of microstructure of dual phase steel

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Abstract

Requirements for weight reduction and increased formability in the automotive industry have largely contributed to the development of dual phase (DP) steels, which is a widespreadly kind of high strength steels. Due to the microstructural of dual phase (DP) steels consisting of hard martensite dispersed in a soft ferrite matrix and with different mechanical behaviors of the two phases, the inhomogeneous deformation of the microstructure are generated during the plastic deformation process. In this study, the strain distribution and plastic strain gradient of microstructure is obtained by Point Interpolation Method (PIM). The PIM interpolates a cluster of feature data points to construct its shape function to attain the displacement increments, which shows great convenience and certain precision in computing the strain and gradient distribution of individual phases. A nonlinear function is developed to describe the relationship of individual phases strain and overall material strain. The overall strain of material is greater than the strain of martensite and less than ferrite's. Considering the different stain value of the two phases during the deformation process, the plastic strain gradient is generated to connect the inhomogeneous deformation in the two phases to ensure the deformation compatibility. The average plastic strain gradient is the second derivative of the deformation field of microstructure. The average plastic strain gradient of both phases is built with a power function of overall strain. The results show that greater strain gradient value in martensite phase than ferrite. The effects of grain size on the plastic strain and strain gradient have been studied in this paper. The both of plastic strain and strain gradient of ferrite increase with decreasing of grain size. The grain size has greater impact on strain gradient than plastic strain. The rules of martensite are similar to ferrite and the effects of grain size on martensite are less than ferrite. The grain size plays a critical role in plastic strain and strain gradient of dual phase steel.

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Keywords: dual phase steel; plastic strain; plastic strain gradient; grain size;

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1. Introduction

Due to the excellent combination of high strength and good formability, dual phase (DP) steels have progressively used for various car body parts in automotive industry. These properties are achieved by the microstructures that embedding hard and brittle martensite phase into the soft and ductile ferrite matrix. The macro-mechanical properties of DP steels depend on microstructural characteristics such as martensite and ferrite properties, volume fraction of martensite as well as grain size. In order to research the mechanical properties (i.e. strength and ductility) of DP steel, plenty of researches have been conducted.

The published researches on the properties of DP steels have been predominantly focusing on the stress distribution of two phases, heterogeneous plastic deformation and fracture properties. Jiang et al. [1] proposed a model to predict the stress of martensite and ferrite phase, which shows that the stress of ferrite is affected by the grain size. Zarei et al. [2] created the inhomogeneous and homogeneous two types of finite element models based on SEM images to predict the macro stress. The results show that grain orientations have a strong effect on the inhomogeneity. The evolution of local stress and strain evolution of individual phases was described by the RVEs model. Ghadbeigi [3] studied the local plastic deformation using Digital Image Correlation (DIC) and in-situ tensile testing. Ramazani et al. [4] have researched the failure initiation and characterization using the RVEs combined with the XFEM from the experimental metallographic figure.

The plastic strain and strain gradient distribution of DP steels during the deformation have been extensive investigated as well. Paul [5] studied the plastic strain localization with different loading conditions. Dan et al. [6] investigated the local deformation by the large-strain tensile experiment. Huang et al. [7] obtained the strain field distribution of microscopic metallographic using the point interpolation method (PIM) and built the strain-hardening behaviors. Due to the discrepancy of mechanical behaviors of the two phases, the plastic strain gradient is generated during the process of plastic deformation. Wei et al. [8] introduced the strain gradients in elevating the tip of the crack growth. The microstructures formed under conditions of homogeneous and nonhomogeneous deformation are studied by Hughes et al. [9]. Lyu et al. [10] established the dislocation model with plastic stain gradient and the stress-strain response is obtained from this approach. It reveals a good agreement between experimental results and computed results. However, the quantification analysis of the heterogeneity of the microstructure of dual phase steel is still scarce.

In this paper, the strain distribution and strain gradient of each phase is achieved by the meshless Point Interpolation Method (PIM), which shows great convenience and certain precision in computing the plastic strain and gradient distribution of individual phases. A nonlinear function is developed to capture the strain distribution of individual phases in DP steel. The average plastic strain gradient of the both phases is built with a power function of overall strain. Furthermore, the effect of grain size on the strain and strain gradient is studied in this paper. This study not only makes us better understand the heterogeneity characteristics of microstructure of dual phase steel but also can provide reference for experiments.

2. Materials and experiments

A commercial DP600 steel grade has been used in this study, which is a typical kind of multi-phase high strength steels. The chemical composition of the material is given in Table 1. The sketch map of geometry dimension of experiment specimen is showed in Fig.1. The thinness of specimen is 0.9mm.

Table 1. Chemical composition (wt%) of DP600 steels

Element	C	Mn	Si	P	Cr	Mo	N	Cu
Content(%)	0.05	1.20	0.1	0.04	0.6	0.005	0.006	0.006

The samples were mechanically polished and etched for 5-10s in 4% Nital solution. The in-situ tensile test carried out with a very low load rate (v=0.01 mm/s) at room-temperature by an in-situ uniaxial tensile test platform. The both sides of sample were fixed on the fixtures, which can move at same speed along the opposite directions. A high-resolution CCD camera was located above the middle position of the sample to capture the deformation of microstructure. The microstructure shows a dark martensite islands phase with embedded white ferrite matrix in Fig. 2.

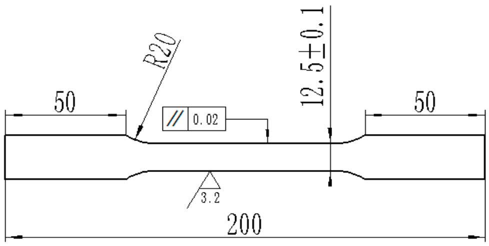


Fig.1. The sketch map of sample for in-situ tensile test (mm)

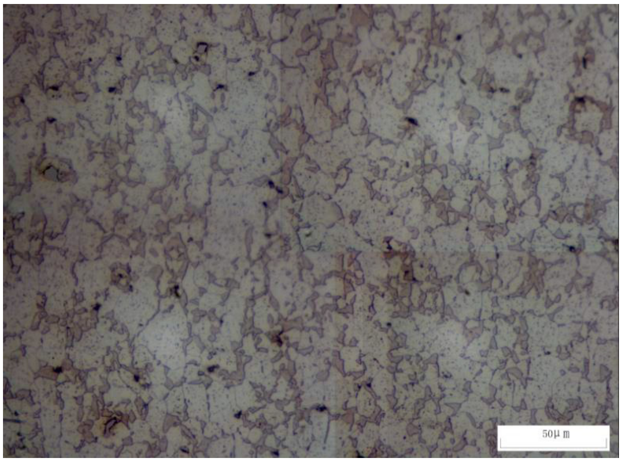


Fig.2 Metallographic figure of DP steel

3. Results and discussion

3.1. Deformation of microstructure

In this paper, the deformation field only considers 2D field and deformation in the depth direction is neglected. Point Interpolation Method (PIM) interpolates a cluster of feature data points to construct its shape function for displacement increments. And it can calculate without dividing grids while satisfying displacement boundary conditions [11, 12]. A continuous surface $u(x)$ by the PIM using polynomial function can be described as

$$u(x)=\sum_{i=1}^{N} p_i(x)\cdot a_i(x)=\mathbf{p}\cdot\mathbf{a} \tag{1}$$

where $p_i(x)$ is monomials in co-ordinates $x^T=[x,y]$ for two-dimensional deformation field, i is the number of feature points, a_i is the coefficient of the $p_i(x)$. $\mathbf{p}$ is the primary function that can be determined by Pascal.

By referencing the previous work [6, 7], the deformation field of 2D microstructure can be expressed as

$$\mathbf{u(x,y)}=\mathbf{p}\cdot\mathbf{P^{-1}}\cdot\mathbf{U} \tag{2}$$

where $\mathbf{u(x,y)}$ is the deformation field of microstructure, $\mathbf{P^{-1}}$ is the inverse matrix of $\mathbf{P}$ which is the i point' coordinates matrix, $\mathbf{U}$ is the i point' coordinates displacements under the deformation.

The derivative and second derivative of the deformation $u(\mathrm{x},\mathrm{y})$ is strain field and strain gradient, respectively.

$$\varepsilon_{ij}=\frac{1}{2}\left(u_{i,j}+u_{j,i}\right) \tag{3}$$

$$\eta_{ijk}=u_{k,ij} \tag{4}$$

where u is the displacement, ε is the strain, η is the strain gradient.

Some typical crystals with different grain size of individual phases are selected to calculate the plastic strain and strain gradient. The relationship of strain of individual phases and overall strain is supposed by Dan [6, 7].

3.2. The plastic strain fields

Due to the different mechanical behaviors of hard and soft phases, the strain characteristic of the both phases is different during the deformation process. The strain of individual phases is calculated based on the PIM approach and the relationship of strain of individual phases and overall strain is built. The micro-strain of individual phases with different grain size is shown in Fig.3. Obviously, the overall strain of material is greater than the strain of martensite and less than the ferrite.

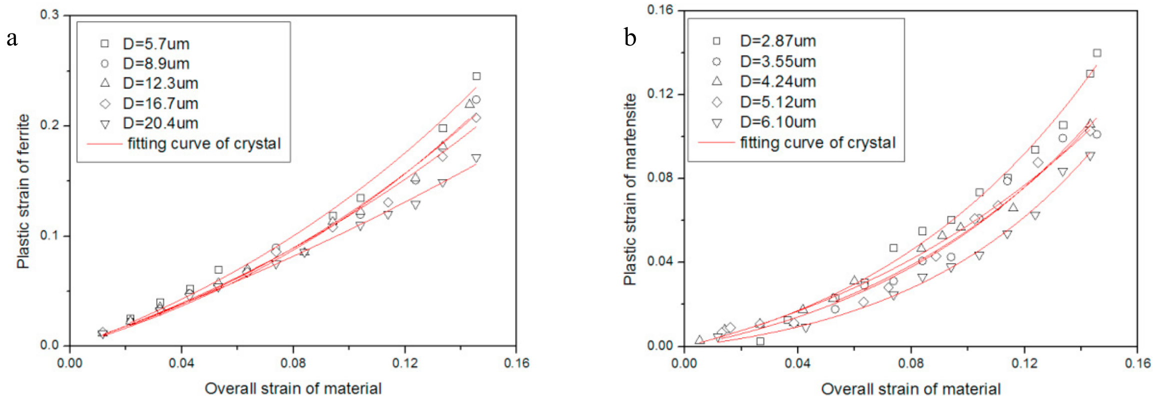
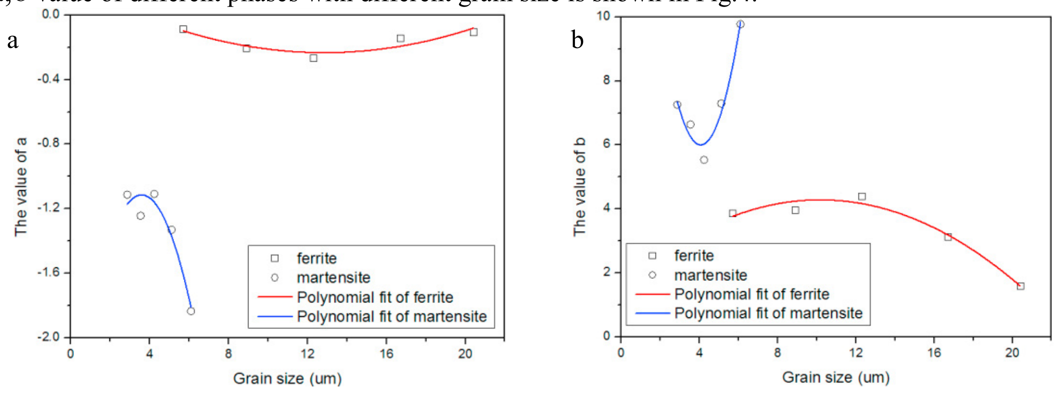


Fig.3. Strain curves of individual phases: (a) ferrite and (b) martensite

With the decreasing of grain size, the plastic strain of ferrite and martensite increased. The effect of grain size on plastic strain is prominent by compared with the grain size. While in the median grain size, the changed trend is not obvious. The strain is fitted by a nonlinear function to describe the variation tendency. The expression is

$$\varepsilon_i = \varepsilon \cdot \exp(\mathrm{a} + b \cdot \varepsilon) \tag{5}$$

where ε_i is strain of ith phase, ε is the overall strain of DP steel, a and b are the parameters of material. The a, b value of different phases with different grain size is shown in Fig.4.



(a) (b)

Fig.4. The value of a , b with different grain size: (a) the value of a , (b) the value of b

The value a , b of ferrite and martensite are fitted by quadratic polynomial function. The relationship of a_f , b_f , a_m , b_m and grain size are built with the expressions as follow

$$\mathrm{a}_f = 0.0027 \cdot d_f^{\,2} - 0.0681 \cdot d_f + 0.2061; \quad b_f = -0.0258 \cdot d_f^{\,2} + 0.5241 \cdot d_f + 1.6182 \tag{6}$$

$$\mathrm{a}_m = -0.1112 \cdot d_m^{\,2} + 0.7999 \cdot d_m - 2.5525; \quad b_m = 0.9342 \cdot d_m^{\,2} - 7.6107 \cdot d_m + 21.5049 \tag{7}$$

where d is the grain size, the subscript f, m denotes ferrite and martensite phase, respectively.

3.3. The plastic strain gradient fields

The average plastic strain gradient of one crystal can be calculated by the second derivative of the deformation. Plastic strain gradient appears due to the mismatch deformation volume of different phases during plastic deformation. The gradient is increased with the increasing strain of material. The calculation accuracy of power function is better than linear fitting. Therefore, the power function is selected to describe the variation tendency of strain gradient. The fitting expression can be described as

$$\eta_i = A_i \cdot \varepsilon^{B_i} \tag{8}$$

where η_i is strain gradient of ith phase, ε is the overall strain of DP steel, A_i and B_i are the fitting parameters of material. The strain gradient of different phase with overall strain is shown in Fig.5.

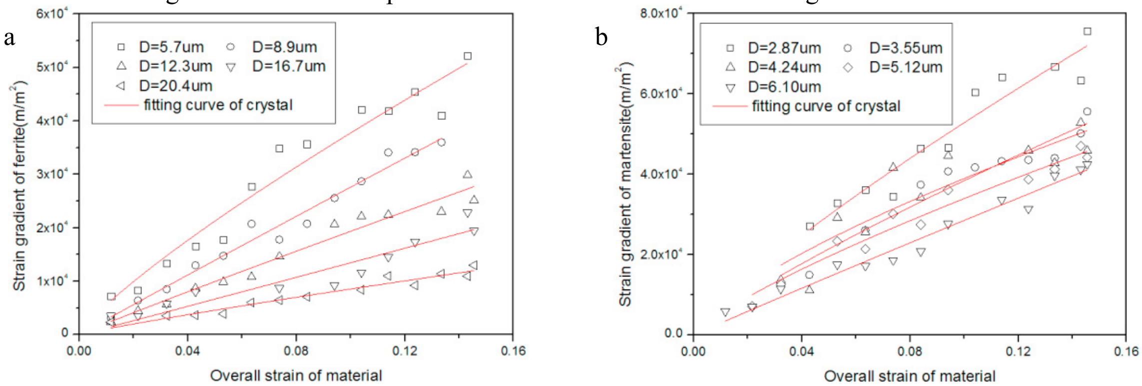


Fig.5. Strain gradient of individual phases: (a) ferrite and (b) martensite

With the decreasing of grain size, the plastic strain of material is increased. The ferrite and martensite phases have the similar change rules. The effect of grain size on plastic strain gradient is more obvious than strain. The rate of increase of strain gradient slows down with the increasing strain of material, which agrees well with Ref. [14].

The value of A_i, B_i and the change law with diverse grain sizes of the two phases is showed in Fig.6.

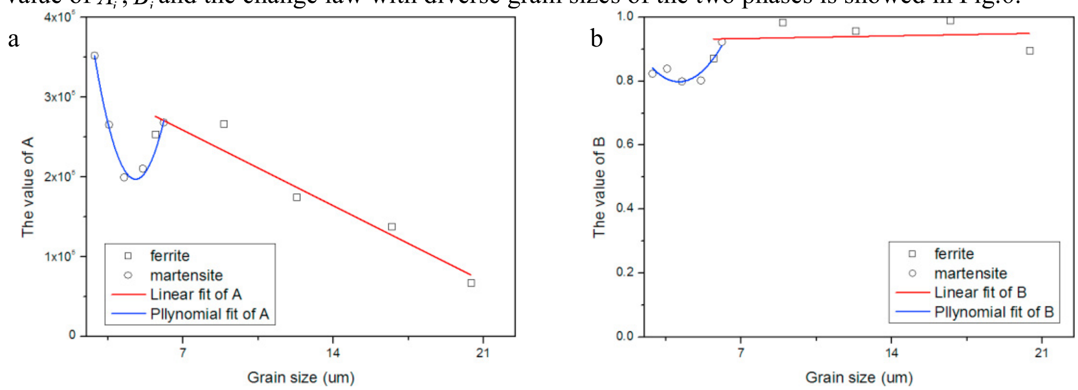


Fig.6. The value of A, B with different grain size: (a) the value of A, (b) the value of B

The value A, B of ferrite are fitted by linear function and the A, B value of martensite are fitted by quadratic polynomial function. The relationship of A_f, B_f, A_m, B_m and grain size are built and described as

$$A_f = -1.3525\text{E}4 \cdot d_f + 3.534\text{E}5; \qquad B_f = 0.002 \cdot d_f + 0.9253 \tag{9}$$

$$A_m = 4.232\text{E}3 \cdot d_m^{\;2} - 4.05\text{E}5 \cdot d_m + 1.165\text{E}6; \quad B_m = 0.0284 \cdot d_m^{\;2} - 0.2326 \cdot d_m + 1.2755 \tag{10}$$

Based on the expression $\rho_G = \eta / b$ in Ref [15], the calculated strain gradient value using the average geometrically necessary dislocations density ρ_G of DP steels in Ref. [16] to divide by burgers vector b is the same orders of magnitude with the measured value in this paper, which is validated the accuracy of this approach.

4. Conclusion

In this paper, the heterogeneity of the microstructure of DP steel is studied. The plastic strain and strain gradient field of DP steel is calculated by the PIM and quantified analysis. This experimental method to calculate the heterogeneity is applied to other steels as well. According to the microstructure deformation investigation and analysis of strain hardening behaviour of material, the major findings are as follow.

1) The overall strain of material is larger than the strain of martensite and less than ferrite.
2) The plastic strain and strain gradient is increased with the increasing the strain and the growth speed of gradient slows down with the increasing the strain.
3) The grain size has more obvious effects on strain gradient than plastic strain by the quantification analysis.

Acknowledgements

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