

Effect of the grain shape on the q-value evolution of steel sheets*

Q Xie¹, Y Wang¹ and A Van Bael²

¹The State Key Laboratory for Advanced Metals and Materials, the University of Science and Technology Beijing, 10083, China

²Department of Metallurgy and Materials Engineering, KU Leuven, B-3000 Leuven, Belgium

E-mail: Qingge.Xie@ustb.edu.cn; YdWang@mail.neu.edu.cn;
Albert.VanBael@mtm.kuleuven.be

Abstract. Two polycrystalline plasticity models, namely the ALAMEL model and the viscoplastic self-consistent (VPSC) model were used to study the effect of the grain shape on the evolution of plastic anisotropy. The latter was characterized by the q-value in this paper. The two models both predict the evolution of grain shape and texture and then can predict the effect of the initial grain shape on the texture. The final anisotropy of the materials was also assessed with the help of these models. Data of tensile tests in three directions for three low carbon steel sheets with either equiaxed or a pancake grain shape were used to evaluate the model predictions. Both models give the same trend of the grain shape effect on the evolution of the q-values. Results demonstrate that the effect of the grain shape can be clearly reflected in the x-value distribution as defined and discussed in this paper. But it is not so obvious in the predicted textures for the investigated three materials according to both models.

1. Introduction

For steel and aluminium sheets used in automotive and packaging applications, the evolution of the q-value (the contraction ratio proposed by Bunge [1]) profile is used to characterize the anisotropic plastic property of a sheet. The q-value is defined as the ratio of plastic strain rate in the width direction to the plastic strain rate in the tensile direction during a uniaxial tensile test. It also corresponds to the slope of a tangent line of the yield locus for a given material. The importance of an accurate determination of the q-value in metal forming is that it is closely related with the deep drawing property of a material. A high q-value retards necking in sheet metal forming processes whereas its variation with the tensile test direction in the sheet plane correlates well with the earing tendency of a drawn cup.

Crystallographic texture is known as the main source of this plastic anisotropy. Other sources of anisotropy, such as the grain shape, directional substructure and uneven distribution or a non-equiaxed shape of the second phase may also play a role. In this paper, we employed two crystal plasticity models: ALAMEL [2] and VPSC [3], to study the initial grain shape effect on the q-value evolutions for three low carbon steel sheets. Similar studies have been given by Chung and Cho [4, 5] and by Delannay [6-8]. However, the former mainly focused on the experimental evidence and the emphasis of the latter was on the initial q-value affected by

* Most of the work reported in this paper was done when Qingge Xie did his PhD research at the department of MTM KU Leuven in Belgium.



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

the grain shape. This paper did investigations on not only the effect of the grain shape on the initial q-value, but also the effect of the grain shape on the evolution of the q-values.

The ALAMEL model assumes that each grain ‘sees’ its single neighboring grain. Through compensating relaxations along the common grain boundary between two neighboring grains, the shear stress equilibrium at the grain boundary is achieved by adopting the generalized Schmid law. These additional relaxations (induced by grain interactions) along the grain boundary satisfy the continuity of the velocity at the grain boundary and they vanish somewhere in the grain (cf. [9]). The grain shape in the ALAMEL model is indirectly reflected by the orientation distribution of the grain boundary. The VPSC model assumes that each grain is an inclusion embedded in an equivalent medium, the property of which is the weighted average of that of all consisting grains in the aggregate. The VPSC model employs the Eshelby tensor to take the aspect ratio of each grain into account. These two models use two different methods to calculate the q-values (cf. [10]), which were proved to be equivalent by Van Houtte (cf. the appendix in [10]) for materials with orthorhombic symmetry. The textures in the studied materials in this paper indeed feature orthorhombic symmetry.

2. Results and discussion

The weighted average of the aspect ratios of the three low carbon steel sheets are 1.53:1.19:0.55 (RD: TD: ND) for T52 and 1.28:1.19:0.65 for both T57 and T61. In the model, all grains are considered to have the same shape and the same size but a different lattice orientation. To understand the effect of pancake grain shape on the q-value evolution of tensile tests, for both ALAMEL and VPSC, two types of simulations were carried out: one that uses a (hypothetical) equiaxed microstructure as initial material, and one that uses the measured non-equiaxed (‘pancake’) structure as initial material. Each time the experimentally measured textures were used as initial texture of the simulations, with a representative volume element (RVE) consisting of 5000 grains. The present study assumes isotropic hardening at the level of individual grains. Fig. 1 gives the evolution of the q-values calculated by the two models. Besides that, the model proposed by Delannay [8] which captures the grain shape/size effect in each grain by introducing a back stress τ_b^α on the critical resolved shear stress (CRSS) of potential slip system is also adopted here (cf. equation 3 in [8]). The mean-free path of mobile dislocations within the grain is a physically sound reason of this model by considering the fact that grain shape may cause individual slip systems to strengthen differently. Following the method described in [10], the CRSS of slip system is calculated by equations (1)-(3).

$$\tau_c^\alpha = \tau_{sat} - (\tau_{sat} - \tau_b^\alpha) \exp(-\Gamma) \quad (1)$$

$$\Gamma = \int \sum \dot{\gamma}^\alpha dt \quad (2)$$

$$\tau_b^\alpha = \tau_0 \left(1 + \frac{0.02}{d_l^\alpha}\right) \quad (3)$$

τ_b^α is the back stress term of slip system α . τ_0 is a reference parameter. d_l^α is related to the grain shape effect and it can be calculated following equations (8)-(10) in [8]. τ_c^α is the CRSS of slip system α . τ_{sat} is the saturated value of the CRSS of the slip system in the studied material. Γ is the total slip in a given grain on all potential slip systems. This model was introduced into the VPSC model in this paper. It was named as ‘VPSC-pancake adapted’ in Fig.1 and only the case of initially pancake grain shape is given (the effect of this new approach is only obvious when the grain shape deviates from the equiaxed one before the work hardening saturates).

The q -value of the real material declines with the strain in all cases in Fig.1. Clearly, according to both models, this declining trend is induced by the initial pancake grain shape. Interestingly, the ‘VPSC-pancake adapted’ gives the best predictions for T52. In the meantime, the predictions for T57 and T61 did not become worse. This new approach almost does not affect the quality of the texture evolution and the evolution of the x -value distribution (as discussed in the next paragraph). It is easy to be understood that by introducing a back stress term on the CRSS of each slip system, the yield locus of each grain is changed. This further on affects the shape of the yield locus of the whole aggregate. Fortunately, by using suitable model parameters as given in equations (1)-(3), the q -value prediction seems to be slightly improved.

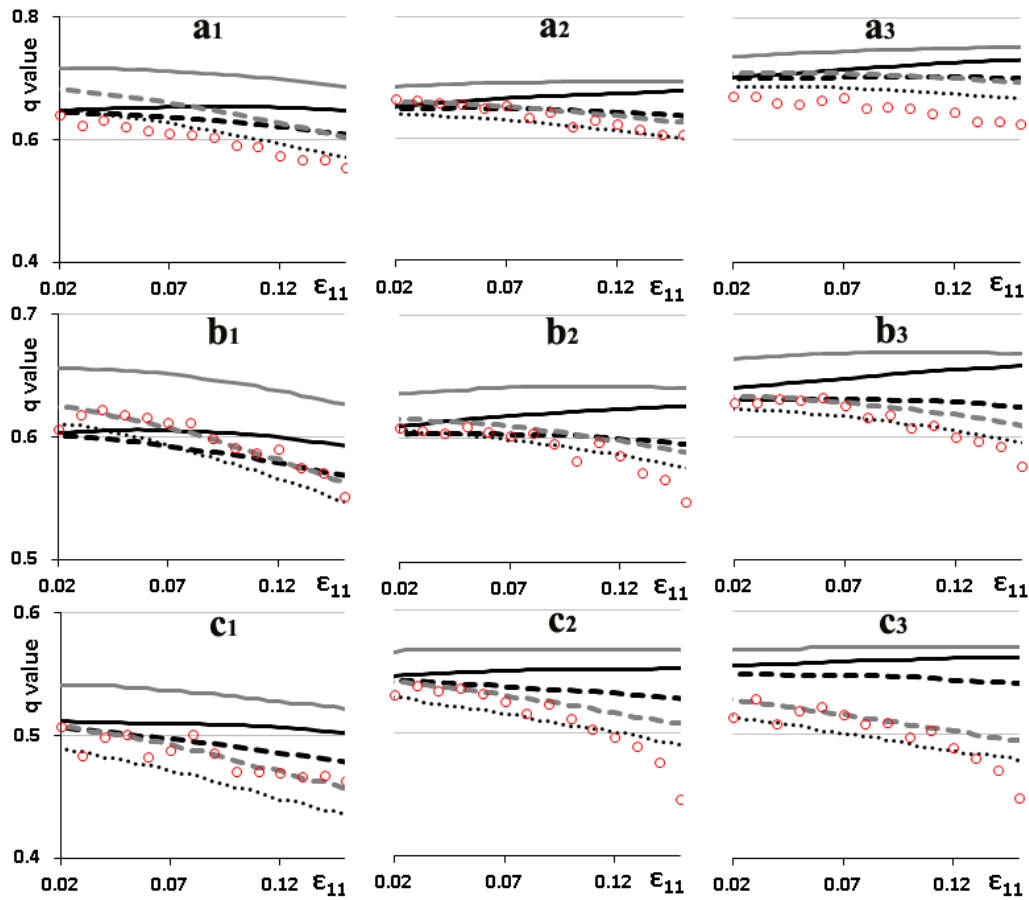


Fig.1 The q -value evolution for tensile tests of a_1 T52-0°, a_2 T52-45° and a_3 T52-90°; b_1 T57-0°, b_2 T57-45° and b_3 T57-90°; c_1 T61-0°, c_2 T61-45° and c_3 T61-90°.

Experiments (open circles), ALAMEL-equiaxed (black full lines), ALAMEL-pancake (black dashed lines), VPSC-equiaxed (grey full lines), VPSC-pancake (grey dashed lines), VPSC-pancake-adapted (black dotted lines).

An interesting difference between these two models is the strain rate distribution calculated for each grain in the aggregate. Hereby, we plot the distribution of the ratio x defined in equation (4).

$$x = \text{sign}(\mathbf{d}_{||} : \mathbf{D}) ||\mathbf{d}_{||}|| / ||\mathbf{D}|| \quad (4)$$

$\mathbf{d}_{||}$ is the component of the tensor \mathbf{d} (the local strain rate in a given grain in a polycrystal) which is parallel with the imposed strain rate \mathbf{D} . The similar method was already used in [11].

'sign' indicates the sign of the double dot product between $\mathbf{d}_{||}$ and \mathbf{D} . The x -value of a given grain can indicate the local strain rate deviation from \mathbf{D} in the direction of \mathbf{D} . The distribution of the x -value can reflect the strain rate distribution in a polycrystal (i.e. deformation homogeneity in a polycrystal in the direction of \mathbf{D}) and can also indicate the size of the relaxation for both soft ($x > 1$) and hard ($x < 1$) grains in the direction of \mathbf{D} . The corresponding figures were given in Fig.7 and Fig.8 in [10]. We found that the x -value distribution is sensitive to the initial grain shape. The pancake grain shape can make the x -value distribution narrower than the case of an equiaxed structure (i.e. materials with pancake grain shape feature more homogeneous strain rate distribution in the direction of \mathbf{D} than that with initially equiaxed structure.). Throughout the tensile deformation, the change of the x -value distribution is small.

The texture prediction by using the VPSC model and the ALAMEL model with and without considering the initial grain shape was studied too. We found that the effect of the pancake grain shape on the deformation texture is small according to both models.

Currently employed models can already give very good q -value predictions. In reality, the dislocation substructure developing within the grains hardens the slip systems differently. Accounting for this additional source of anisotropy may improve predictions further.

3. Conclusions

The comparison between experimentally observed q -value evolutions during the tensile tests for three materials with the predicted q -value evolutions by two models suggests that the grain shape has a clear effect on the q -value. The pancake grain shape affect the strain rate distribution in the polycrystal (reflected by the x -value distribution), which further on affect the evolution of the q -values. Both the ALAMEL model and the VPSC model can give a good estimation of the initial q -value and its evolution in most cases. The model proposed by Delannay [8] was also used in this paper and it seems to be able to improve the q -value predictions further.

The effect of the initial grain shape on the texture evolution was also studied. This effect is quite small for the studied three materials according to both models.

Acknowledgements

This research was carried out under the project number M41.2.08307/M41.10.08307 in the framework of the Research Program of the Materials innovation institute M2i (www.m2i.nl). Y Wang and Q Xie also thank the financial support from National Science Foundation of China (NSFC) (Grant No. 51231002), the Fundamental Research Funds for the Central Universities (Grant No. 06111020), and the fundamental research fund at the State Key Laboratory for Advanced Metals and Materials (2014Z-01).

References

- [1] Bunge H J 1970 *Kristall und Technik* **5** 145
- [2] Van Houtte P, Li S, Seefeldt M, Delannay L 2005 *Int J Plasticity* **21** 589
- [3] Lebensohn R A and Tomé C N 1993 *Acta metal Mater* **41** 2611
- [4] Chung Y H, Cho K K, Han J H and Shin M C 2000 *Scripta Mater* **43** 759
- [5] Cho K K, Chung Y H et al 1999 *Scripta Mater* **40** 651
- [6] Delannay L and Barnett M R 2012 *Int J Plasticity* **32–33** 70
- [7] Delannay L, Melchior M A, Signorelli J W, Remacle J F, Kuwabara T 2009 *Comp Mater Sci* **45** 739
- [8] Delannay L 2012 *Mater Sci Forum* **702–703** 182
- [9] Xie Q 2014 Ph. D. Thesis KU Leuven
- [10] Xie Q, Eyckens P, Vegter H, Moerman J, Van Bael A, Van Houtte P 2013 *Mat Sci Eng A-Struct* **581** 66
- [11] Sarma G B, Dawson P R 1996 *Int J Plasticity* **12** 1023