Effect of Plastic Anisotropy on Shear Localization and Fracture in Automotive Sheets

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Abstract Tensile instability, as characterized by the Considère law, is one of the factors governing formability of metallic sheets. During tensile deformation, material thins in a narrow band due to shear localization, prior to final fracture. Strain rate value within the localized necking band tends to be higher than outside it and final fracture is governed both by the nature of the shear localization as well as the strain rate differential between the neck and the material outside the neck. This paper reports the dependence of shear localization and fracture on plastic anisotropy of the material. Three types of automotive sheet materials, namely IF steel (BCC structure), AA5754 aluminum alloy (FCC) and AZ31 magnesium alloy (HCP) are examined. Digital image correlation is used to follow the development of deformation pattern during tensile tests. The results show that both narrowing and thinning of the tensile sample occur in IF steel, while only thinning occurs in AA5754 and only narrowing occurs in AZ31. These differences arise from the differences in the plastic anisotropy of the three materials, as measured by their r-values. Even though all three materials exhibit ductile fracture, the damage and fracture processes in the three materials differ from each other.

Keywords Shear localization, Plastic anisotropy, automotive sheets, r-value, fracture

1. Introduction

In response to the more stringent regulations on fuel consumption in vehicles, lighweighting via the utilization of aluminum and magnesium alloys are being seen to replace steels for automotive body structural applications. Aluminum can reduce the vehicle weight by 20-30% while magnesium 40-50% compared to a full steel vehicle. A 10% weight reduction will save 6-8% in fuel and related GHG emissions. However, formability of aluminium and magnesium sheets is inferior to that of conventional interstitial free (IF) steel. The formability of alloy sheet can be limited either by instability or fracture depending on the operation [1]. The forming limit is usually defined as the locus in uniform strain space required for the onset of localized necking while the fracture limit is defined as that required for material separation. In uniaxial tension strain path, tensile instability or diffuse necking, as characterized by the Considère law, is one of the factors governing formability of metallic sheets. Further, material thins in a narrow band due to shear localization, prior to final fracture. Strain rate value within the localized necking band tends to be higher than outside it and final fracture is governed both by the nature of the shear localization as well as the strain rate differential between the neck and the material outside the neck. This forms the foundation of the so-called Marciniak-Kuczynski (M-K) approach [2] for forming limit diagram (FLD) analysis. While M-K approach has been successfully applied to prediction of FLD of numerous sheet materials including steels and aluminum alloys, it is commonly recognized that the success of such approach for aluminum alloys depends significantly on the selection of yield functions that represent the effect of plastic anisotropy and texture. On the other hand, whether or not thinning occurs in magnesium alloys is challenged by many experimental observations. For example, for AZ31 sheets, it has been reported that very little thinning occurs during uniaxial tension at room temperature [3] and the deformation process becomes more complicated as a variety of deformation mechanisms become activated at different elevated temperatures [4-5].

This paper reports the dependence of shear localization and fracture on plastic anisotropy of the material. Three types of automotive sheet materials, namely IF steel (BCC structure), AA5754 aluminum alloy (FCC) and AZ31 magnesium alloy (HCP) are examined. Digital image correlation (DIC) [6-7] is used to follow the development of deformation pattern during tensile deformation. The role of anisotropy in relation to damage and fracture process is also examined through a variety of surface analysis techniques including optical microscopy, scanning electron microscopy (SEM), electron backscatter diffraction (EBSD) and X-ray tomography.

2. Experimental

The three sheet materials used in the present study were 0.7 mm thick IF steel, 2mm thick AA5754 in O-temper and 2mm thick AZ31 in O-temper. IF steel has a BCC structure, AA5754 FCC and AZ31 HCP.
The initial texture is measured by EBSD using TSL OIM software for all three materials. Uniaxial tensile tests are performed at room temperature using ASTM E-8 specimens. Prior to the tests, an ink pattern is applied to each specimen surface. A commercial available optical strain measuring system, Aramis based on digital image correlation is used for DIC measurements.

Plastic anisotropy of metallic materials is usually represented by the plastic strain ratio, r-value, that is defined as [8]

$$r = \frac{\varepsilon_w}{\varepsilon_t} = -\frac{\varepsilon_w}{\varepsilon_l + \varepsilon_w} \tag{1}$$

where ε_l, ε_w, and ε_t are longitudinal, width, and thickness strains, respectively. As thickness strain is difficult to measure, longitudinal and width strains are usually measured to determine the r-value based on the incompressibility criterion along with the assumption of uniform strain distribution over the gage length [8]. In practice, r-value represents material resistance to thinning. In steels, it is generally accepted that higher the r value, higher the FLD.

However, in materials with small amount of plasticity, r-value is not a sensitive parameter. Another parameter, the contraction ratio, q-value, similar to a Poisson’s ratio in elasticity, has been proposed and defined as [9]

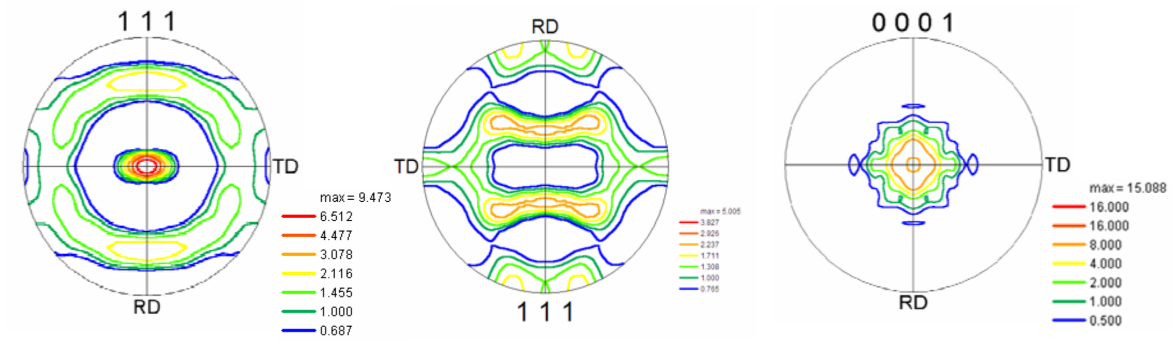
$$q = -\frac{\varepsilon_w}{\varepsilon_l} \tag{1}$$

It is easily seen that $q=r/(1+r)$.

After tensile tests, necked and fractured specimens are collected for damage and fracture observations using optical microscopy, SEM and X-ray tomography.

3. Results and discussion

Fig. 1 shows the initial texture of IF steel, AA5754 and AZ31 sheets, the later having the basal texture while the former sheets exhibit typical rolling texture.



(a) IF steel (b) AA5754 (c)AZ31

Fig. 1 Initial textures of the three alloys

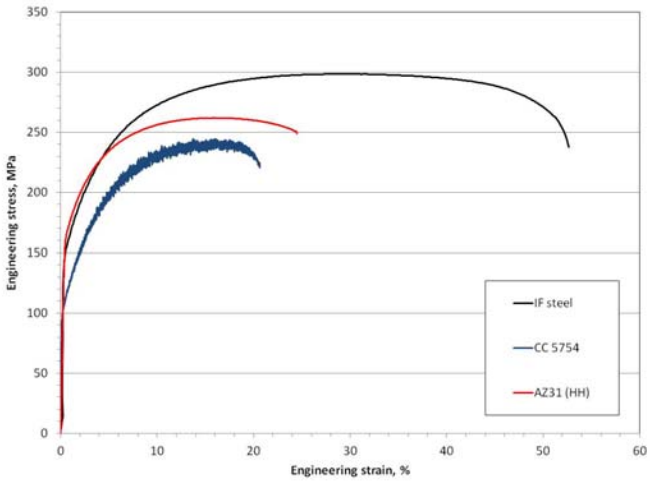
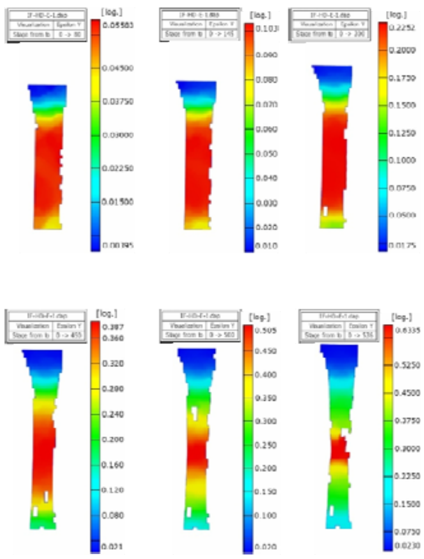


Fig. 2 Engineering stress – engineering strain curves of three alloys

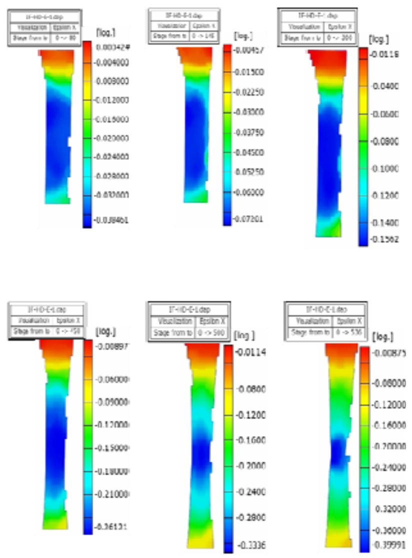
From the engineering stress-engineering strain curves of the three materials (Fig. 2), it is seen that the uniform strain to ultimate tensile stress is 29.6%, 18.0% and 15.8% for IF steel, AA5754 and AZ31, respectively. This is commonly accepted as the strain where diffuse necking is initiated in the materials.

While only diffuse necking can be identified on stress-strain curves, the sequence of deformation occurring during tensile tests, especially the initiation and development of localized necking can be clarified for each material from tensile strain maps obtained from DIC measurements (Fig. 3).

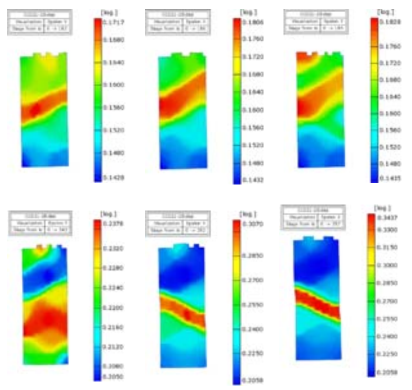
From Fig. 3, it is seen that both thinning and narrowing occurs in IF steel, only thinning in AA5754 and only narrowing in AZ31 following the diffuse neck formation. It is also seen in Fig. 3 (a) and (c) that localized necking occurs in both IF steel and AA5754 before fracture, however, no localized necking occurs in AZ31.



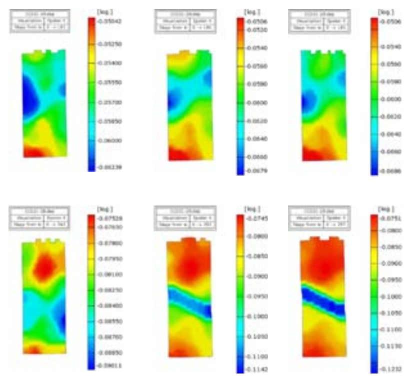
(a) Tensile strain maps in IF steel



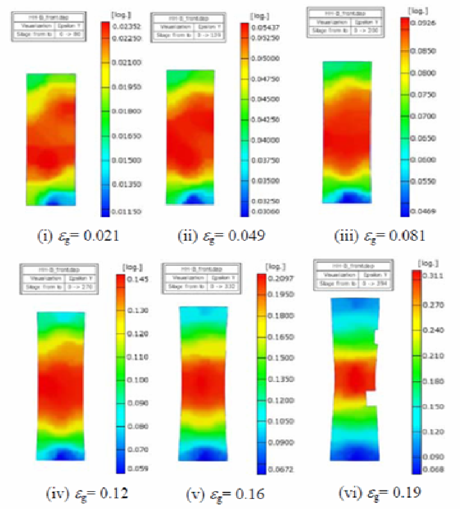
(b) Width strain maps in IF steel



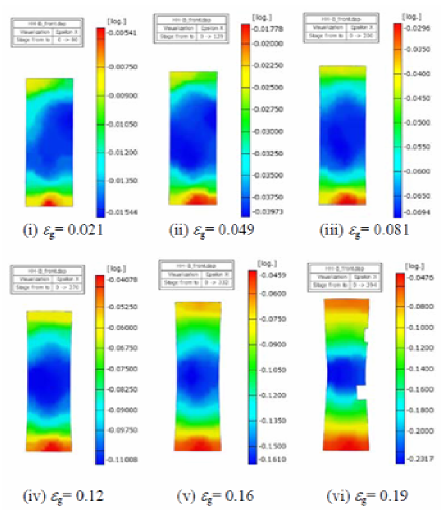
(c) Tensile strain maps in AA5754



(d) Width strain maps in AA5754

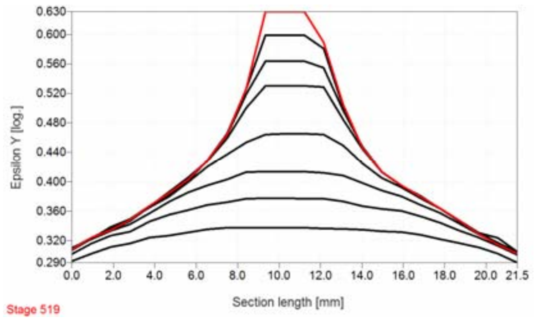


(e) Tensile strain maps in AZ31

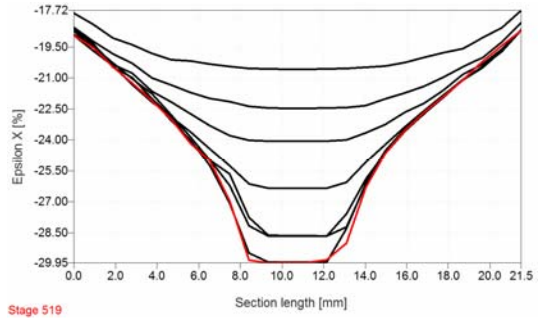


(f) Width strain maps in AZ31

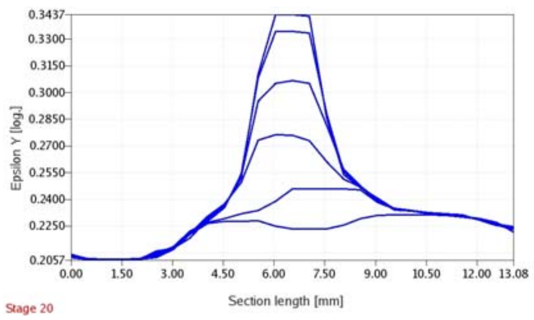
Fig. 3 Deformation development occurring during uniaxial tensile tests



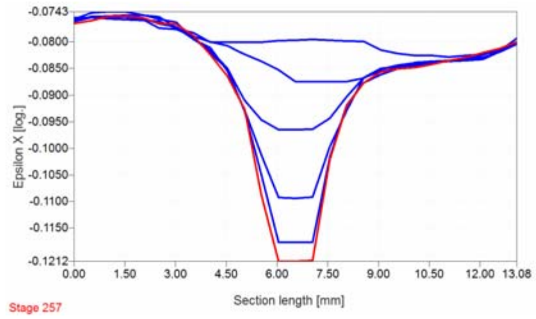
(a) IF steel tensile strains



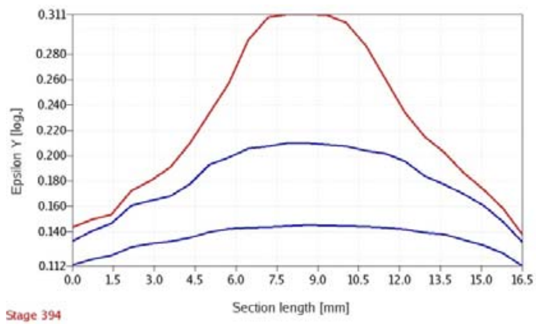
(b) IF steel width strains



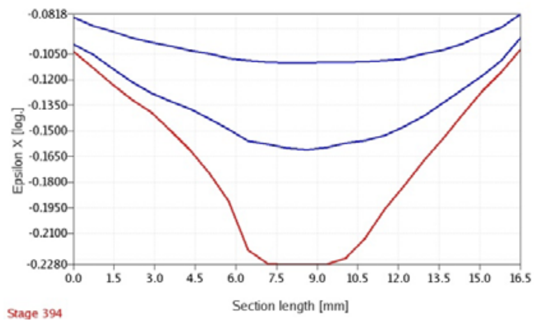
(c) AA5754 tensile strains



(d) AA5754 width strains



(e) AZ31 tensile strains



(f) AZ31 width strains

Fig. 4 Line scan of cross section for post-necking strain development in three alloys

Fig. 4 shows the line scans taken through the strain maps at different stages of the deformation. In Fig. 4 (a) and (c), correspondng to IF steel and AA5754, tensile strains become intense in a more and more narrow band while strain outside this area remains unchanged or even is slightly lowered. These are the typical signatures of localized necking in metallic materials. Together with Fig. 3 (a) and (c), it is concluded that localized necking occurs in IF steel and AA5754 sheet materials. However, when looking closely at AZ31 line scan data in Fig. 4 (e) and (f), one observes that both tensile and width strain keep evolving as the global strain increases. This indicates that no localized necking occurs in AZ31. Instead, it transits directly from diffuse necking into final fracture process [3, 14].

From the local strain development (Fig. 5), it is seen that deviation between local and global strains is more significant in IF steel and AA5754 comparing to AZ31.

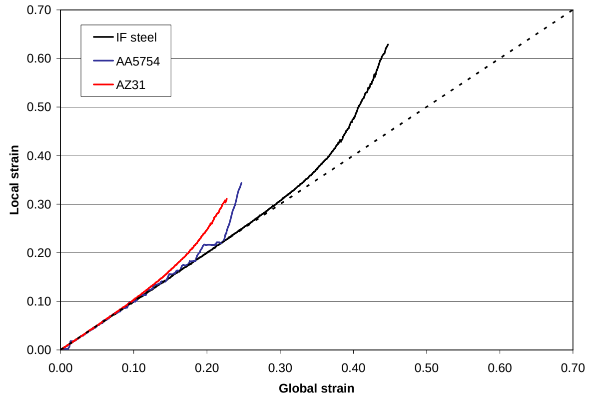


Fig. 5 Local versus global strain in three alloys

It is well known that in AA5754 deformed at room temperature at quasi-static strain rates, premature necking occurs due to the Portevin-Le Chatelier (PLC) effect (e.g. illustrated in the first three maps in Fig. 3 (c)) [1]. A simple model has been established to account for the effect of PLC band strain on reduction of uniform strain to UTS [1]. It is also reported that at a certain combination of temperature and strain rate (e.g. -50 °C and 6×10^{-4}/s), the PLC effect and accompanying premature necking can be removed [1]. It is also reported that the formability of AA5754 can be improved by enhancing specific texture components (e.g. cubic texture) [10]. Traditionally, it is accepted that the higher plastic strain ratio, i.e. r-value, the better formability. In the discussion below, the relationship between plastic anaisotropy and formability is further examined in light of the above observations.

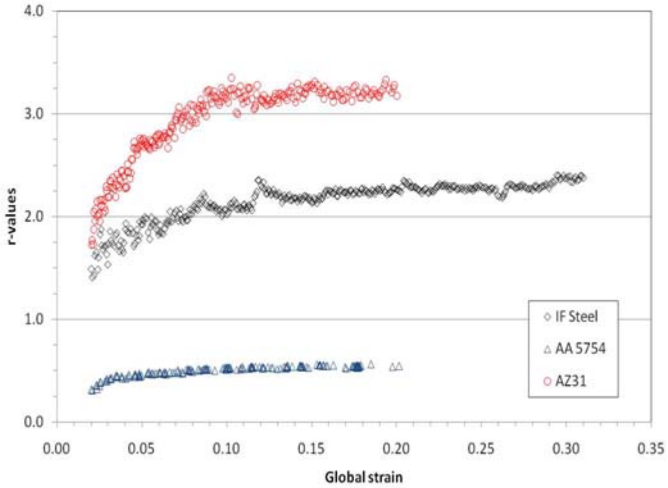


Fig. 6 r-values development in three alloys

When plotting the r-value evolution in the three materials used in the present study (Fig. 6), it is seen that the r-value in AZ31 is the highest (3.2). However AZ31 has the lowest formability in the uniaxial tensile deformation. Eq. (1) is derived with the assumption that material deforms in length, width and thickness directions and when the material deforms more in width direction than thickness direction to produce a higher r-value, it has improved formability. The contribution of each strain component to r-value and q- value may provide insight into the origin of the anomalous relationship between formability and r-value for AZ31. Fig. 7 shows the relationship between the q-value and strain for the three materials.

It is seen in Fig. 7 that AZ31 has the highest q-value, i.e. most of the deformation is actually concentrated in the width direction while AA5754 has the lowest q-values, with least deformation along the width direction.

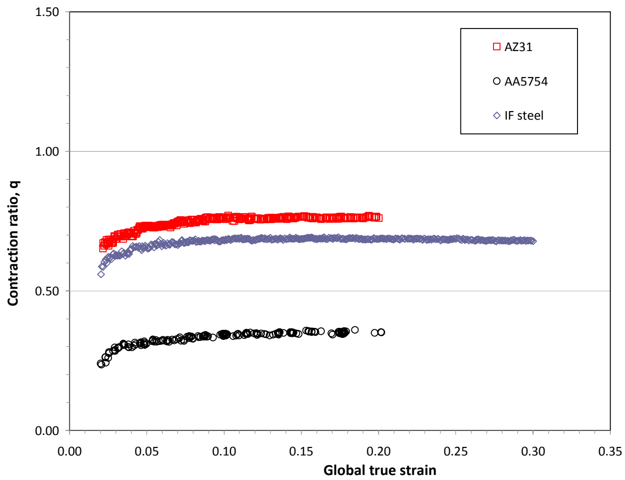


Fig. 7 q-value development in three alloys

Fig. 8 shows the thickness strain in the three materials calculated using the incompressibility criterion. It is clear that there is very little thinning in AZ31, consistent with the q-value results in Fig. 7.

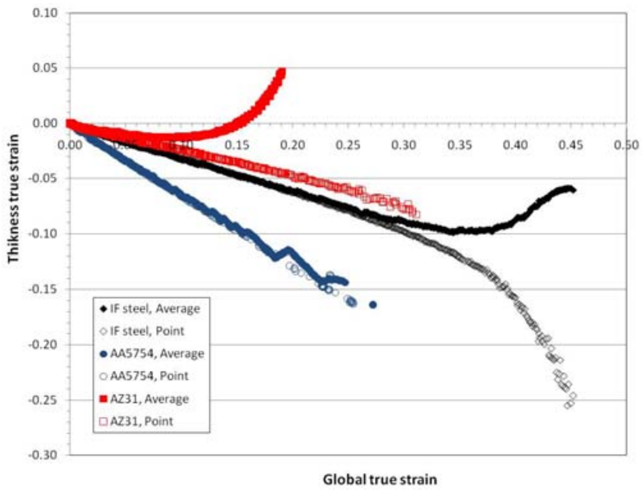


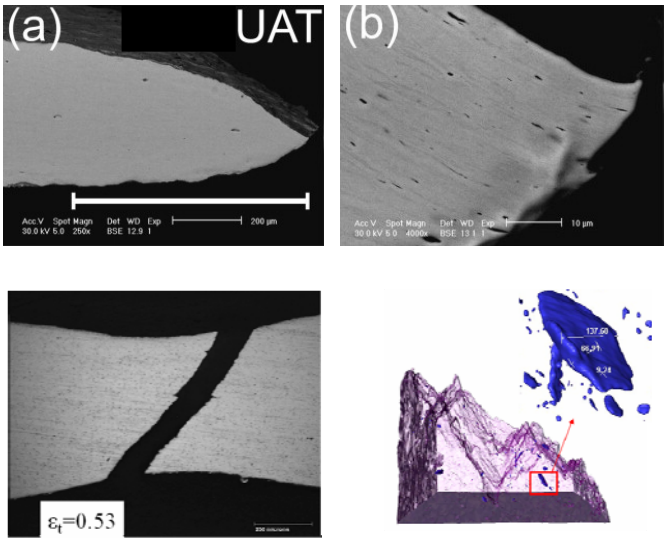
Fig. 8 Thickness strain evolution in three alloys. Note that ‘‘average’’ denotes thickness strain estimated from both tensile strain and width strain from given gage lengths while ‘‘point’’ denotes thickness strain at a point within necked area.

The relationship between damage and shear localization in literature continues to remain ambiguous. Ductile fracture process generally includes three stages, namely void nucleation, void growth and void coalescence. A number of continuum mechanics models have been developed [11-12] to describe this sequence of events. However, the interplay between shear localization and void formation often depends on the materials studied and this effect is not captured in continuum mechanics (macro scale) models. There is very little quantitative data on the development of the complex sequence of damage events in materials such as the ones studied here to ascertain if the existing models can capture any differences in the sequence of events arising from the anisotropic nature of the deformation described above at the microscale.

In IF Steel, limited void growth from aluminum oxide particles has been observed [13] prior to localization in uniaxial tension. It is concluded that damage does not play a role before (or upon) localization, but only beyond localization (Fig. 9 (a) and (b)) [13]. It is in contrast with the observations in other steel alloys [11].

In AA5754, void nucleation is observed only in the very final stage of the tensile deformation and the damage is very localized near the fracture surface [14-16]. This suggests that damage may be a consequence of the fracture process rather than a trigger that determines material ductility (Fig. 9 (c)). Further, it is observed that particle distribution as random particles or in stringers affects the final fracture process. For example, anisotropic distribution of stringers in continuous cast AA5754 sheets significantly reduces the fracture strains [17].

In AZ31, it is revealed by X-ray tomograpghy that microcracks formed at the later stage of diffuse necking (Fig. 9 (d)) contribute to the final fracture without transition into localized necking [18].



(c) (d)

Fig. 9 Damage and fracture in (a) and (b) cross section of a fractured IF steel specimen [13] showing void growth within localized shear bands, (c) cross section of a fractured AA5754 tensile specimen showing no damage or voids just underneath the fracture surface and (d) fracture surface of an AZ31 alloy tensile specimen revealed by X-ray tomography showing microcracks underneath the fracture surface [18].

Clearly, there is a link between the anisotropy in the deformation process and the development of damage and fracture processes in the three sheet materials. Microcrack formation in AZ31 sheets, for example, is strongly related to the twin formation as a result of the inability of textured AZ31 sheet to deform by dislocation mechanisms alone. IF steel on the other hand deforms by dislocation mechanisms which produce vacancies at high strains, leading to void formation which grow and coalesce to drive the material to failure. AA5754 sheets deform by dislocation mechanisms but voids form not from vacancy condensation at large strains as in IF steel but because of matrix-particle interactions in the sheet which then quickly develops to rupture. The above results suggest the need for developing microscale models that account for these differences in the microstructure and deformation mechanisms between different materials. It is expected that the quantitative data provided above can serve as a starting point for linking the anisotropic deformation with damage processes using a multi-scale (micro and macro scale) simulation strategy.

4. Conclusions

In this paper, we report the dependence of shear localization and fracture on plastic anisotropy of three types of automotive sheet materials, namely IF steel (BCC structure), AA5754 aluminum alloy (FCC) and AZ31 magnesium alloy (HCP). The results show that both narrowing and thinning of the tensile sample occur in IF steel, while only thinning occurs in AA5754 and only narrowing occurs in AZ31. These differences arise from the differences in the plastic anisotropy of the three materials, as measured by their r-values. Even though all three materials exhibit ductile fracture, the damage and fracture processes in the three materials differ from each other – mainly void mechanisms arising due to dislocation interactions in IF steel, premature void formation influenced by particle distribution in AA5754 sheets and premature crack initiation caused by twinning in textured AZ31 sheets. The need for micro-macro model development to link material anisotropy with fracture processes is identified for numerical model development.

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References

[1] J. Kang, D. S. Wilkinson, M. Jain, J. D. Embury, A. J. Beaudoin, S. Kim, R. Mishra, A. K. Sachdev, On the sequence of inhomogeneous deformation processes occurring during tensile deformation of strip cast AA5754. *Acta Materialia*, 54(2006), 209-218.

[2] Z. Marciniak, K. Kuczynski, Limit strains in the process of stretch-forming sheet metal, International Journal of Mechanical Sciences, 9(1967), 600-620.

[3] J. Kang, D.S.Wilkinson, R.K.Mishra, W. Yuan, R.S. Mishra, Effect of inhomogeneous deformation on anisotropy of AZ31 magnesium sheet. Materials Science and Engineering A (in press, http://dx.doi.org/10.1016/j.msea.2012.08.117).

[4] Z. Gao, D.S. Wilkinson, J. Kang, Microstructural stability of magnesium alloys during high

temperature deformation, in: K. U. Kainer (ed.), Proceedings of 8th International conference on magnesium alloys and their applications, Wiley-VCH, Weinheim, 2009, pp.745-750.

[5] H. Watanabe, T. Mukai, M. Mabuchi and K. Higashi, Superplastic deformation mechanism in powder metallurgy magnesium alloys and composites. Acta Materialia, 49(2001), 2027-2037.

[6] Aramis v6.02 manual, GOM, Braunschweig, Germany, 2001

[7] J. Kang, D. S. Wilkinson, J. D. Embury, M. Jain, Local strain measurement in a strip cast automotive aluminum alloy sheet. SAE Transactions: Journal of Materials and Manufacturing, 114 (2005), 156-165.

[8] ASTM Standard E517-00, in: ASTM Standard Annual Book vol. 0.3.01, West Conshohocken, PA, USA, 2010.

[9] Hosford and Backofen, Strength and plasticity of textured metals. In: Fundamentals of deformation processing, Proceedings of the 9th Sagamore army materials research conference, Syracuse University Press, Syracuse, 1964, pp.259-292.

[10] K. Yoshida, T. Ishizaka, M. Kuroda, S. Ikawa, The effects of texture on formability of aluminum alloy sheets. Acta Materialia, 55 (2007) 4499-4506.

[11] Viewpoint Set No. 6: Shear bands. Scripta Metall 18(1984), 421.

[12] A.L. Gurson. Continuum theory of ductile rupture by void nucleation and growth. I. Yield criteria and flow rules for porous ductile media. Journal of Engineering Materials and Technology, 99(1977), 2–15.

[13] C.C. Tasana, J.P.M. Hoefnagelsb, C.H.L.J. ten Hornc, M.G.D. Geersb, Experimental analysis of strain path dependent ductile damage mechanics and forming limits. Mechanics of Materials, 41 (2009), 1264–1276.

[14] J. Kang, D. S. Wilkinson, M. Bruhis, M. Jain, P. D. Wu, J. D. Embury, R. K. Mishra, A. K. Sachdev. Shear localization and damage in AA5754 aluminum alloy sheets. Journal of Materials Engineering and Performance. 17(2008), 395-401.

[15] J. Kang, M. Jain, D.S. Wilkinson, J.D. Embury, S. Kim, A.K. Sachdev. Effect of strain path change on forming limits of strip cast automotive aluminum sheets AA5754. In: A.S. Khan (ed.), Dislocations, plasticity and metal forming. Neat Press, Fulton, 2003. pp.181–183.

[16] K. Spencer, S.F. Corbin, D.J. Lloyd. Notch fracture behavior of 5754 automotive aluminum alloys. Materials Science and Engineering A, 332(2002), 81–90.

[17] J. Kang, D. S. Wilkinson, D. V. Malakhov, H. Halim, M. Jain, J. D. Embury, R. K. Mishra, Effect of processing route on the spatial distributions of constituent particles and their role in the fracture process in AA5754 alloy sheet materials, Materials Science and Engineering A, 456 (2007), 85-92.

[18] J. Kang, D. S. Wilkinson, R. K. Mishra, J. D. Embury, E. Essadiqi, A. Javaid. Microstructural Aspects of damage and fracture in AZ31 sheet materials. Journal of Materials Engineering and Performance. Journal of Materials Engineering and Performance. (in press, DOI 10.1007/s116 65-012-0399-5).