Heat-Treatable Aluminum Alloys: Three-point Bending

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Abstract

In many applications within the automotive industry, the formability of sheets or extruded material is of great importance. The formability is strongly influenced by the chemical composition and the thermo-mechanical treatment prior to deformation. Grain size and morphology as well as texture and the presence of constituent particles make the material heavily anisotropic and the properties direction dependent. In all cases, shear band formation leads to surface topography during bending and fracture initiates from the grooves. The crack propagation after initiation is, however, dependent on the grain size and the number and distribution of particles.

Introduction

Aluminum sheets and extruded profiles are often formed into more complex shapes by cold deformation. This requires a good combination of strength and ductility from the material as well as good control and understanding of the forming process. In the automotive industry, aluminum material of thicker gauge extrusions may be formed by bending for inner structures, whereas outer skin made of thin sheets has to withstand the extreme deformation during the hemming operation where a 180° bend is obtained (1).

The first theoretical approaches to describe bending of metallic materials were purely mechanical descriptions, e.g. (2-5). According to Wang et al. (6) the understanding of the mechanics and development of mathematical models describing bending were threefold from an industrial perspective. The first was prediction of springback and shape-accuracy control. The second was failure prediction and better understanding of bendability. And last, for estimation of needed forces and strength analysis and design of dies. Compared to a uniaxial tensile test, the bending test is much more complex. In 1960, Datsko and Yang (7) came up with a simple relationship between the reduction in area after tensile testing and the bendability. None of these purely empirical relationships do however take into account the fact that several microstructural features like e.g. work-hardening, constituent particles and texture, influence the bendability. An extruded profile or rolled sheet will not behave in an isotropic way during bending as it is assumed for many of the old models (8). In later years there has been more focus on trying to describe and model what happens in the material during bending from a phenomenological perspective (8-12).

In the following, a brief description of the three-point bending test and its mechanics will first be given. Subsequently different material characteristics, which strongly affect the bendability of heat-treatable aluminum alloys will be presented and discussed.

The three-point bending test

The three-point bending test is included in the international standard ISO 7438 Metallic materials – Bend test (13). The three standardized bend tests are the three-point bending test (bending device with two supports and a former), the cantilever bend test (bending device with a clamp), and bending into a specified angle of shape (bending device with a V-block and a former). Hemming, which is much described in the literature due to the use in automotive body panel forming, i.e. (14-18) may involve all the three bend methods. The industry may require that the test should follow more specific guidelines, which are in accordance to the standard, e.g. the guidelines proposed by Daimler Chrysler (19).

Fig. 1 shows a typical three-point bending test setup, where a universal test machine is equipped with a three-point bending tool. The lower part consists of two supporting rolls and the upper part is the forming tool. The ISO 7438 states that *unless otherwise specified*, the distance between the supporting rolls should be three times the thickness of the test specimen plus the diameter of the forming tool $\pm$ half a specimen thickness. The force is logged as a function of vertical displacement of the upper tool, and the test is stopped as soon as the force-displacement curve shows a drop indicating instability as shown in Fig. 2. After bending when the forming tool is released, elastic recovery (springback) will occur. The angle α in Fig. 3 is manually measured after the test, and the bending angle then corresponds to $180° - \alpha$. This means that the higher bending angle, the better formability.

It is often referred to the bendability of a material. The bendability is not the bending angle mentioned above, but is defined as the ratio between the minimum bending radius (r_{min}) and the thickness (t) of the test specimen without fracture occurring (6, 7, 20-23). Datsko and Yang (7) have proposed an empirical relationship between the bendability and the reduction in area (RA) obtained by tensile testing:

$$\frac{r_{min}}{t} = \frac{C}{RA} - 1$$

where C is an empirical parameter. The lower the r_{min}/t ratio, the better the bendability.

Mechanics of the three-point bending test

During three-point bending test of a strip, the material on the inside of the bend is subjected to compressive loading while the material on the outside of the bend is exposed to tensile loading as schematically illustrated in Fig. 4a. During elastic deformation, the bending strain ε_x may be considered linearly distributed through the thickness of the specimen with the neutral axis coinciding with the center axis of the sheet and with equally large absolute values of the maximum tensile and compression bending strains (6), see Fig. 4b. As the loading continues, plastic deformation is introduced, and the strain distribution through the thickness becomes nonlinear. In the case of sharp bends, the neutral axis moves towards the inside of the bend (24), this is illustrated in Fig. 4c. In a strain state as illustrated in Fig. 4c, the tensile straining on the outside of the bend is larger than the compression straining on the inside, which again results in a thickness reduction of the sheet at the bend section (24). However, in contrast to a uniaxial tensile test, a necking instability is not present in the three-point bending test (11). If the width of the strip is sufficiently large, the strains in the width direction are small and can be neglected, i.e. the bend section is subjected to a state of plane strain (24). The material near the surfaces of the bend experiences stress states close to plane-strain tension or plane-strain compression, although a strain gradient in the thickness direction is present.

Onset of fracture and crack propagation during bending

Failure in metal forming is usually defined as onset of necking or onset of fracture. The onset of necking can be defined as the point when global elastic unloading outside of the neck starts (11). Since the bending specimen is constrained from necking, stable bending deformation is interrupted by fracture caused by shear band formation. Onset of shear banding leads to nucleation, growth and coalescence of microvoids (25, 26) which eventually creates a macroscopic crack surface. Onset of shear banding is likely to initiate at the surfaces of the specimen (11). As fracture occurs on the surface of the tensile side, the crack propagates in the width and thickness direction and the bending resistance of the sheet is significantly reduced. This leads to a drop in the global force level as illustrated in Fig. 2. Shear banding on the compressive side may induce new crack surfaces as shown in Fig. 5. These cracks will, however, not influence the bending resistance since the material is subjected to compressive load.

Material characteristics

In general aluminum alloys do not act isotropic in bending, but depend on the orientation of the bending axis. An example is shown in Fig. 6 where the same material, in this case an extruded AA6060 alloy with a recrystallized grain structure, shows a large deviation in bendability dependent on the direction of the bending axis. To the left, with the poorest bendability, the bending axis is aligned in the same direction as the extrusion direction, and to the right the bending axis is perpendicular to the extrusion direction. Several microstructural features may affect the bendability and enhance the anisotropic behavior. In the following, the most important aspects will be addressed.

Grain size and morphology

Extruded aluminum alloys are typically divided into two classes when it comes to grain morphology; the ones that recrystallize after thermo-mechanical treatments and those that retain the deformed grain structure. The recrystallized ones gain a more or less equi-axed microstructure with deformation free grains as shown in Fig. 7 for a AA6060 alloy. The outermost surface layer usually consists of very fine grains, and right below this surface layer, we find the largest grains, which are a bit larger than the rest of the bulk material (27, 28). The fibrous grain structure, as shown in Fig. 7b, is typically obtained when the alloy contains dispersoids that prevent recrystallization during extrusion. It should be noted that the outermost layer always consist of a recrystallized layer. The thickness of this layer depends on alloy chemistry, die geometry, and processing parameters (29-31).

In the finite element simulations presented by Saai et al. (12) and Mattei et al. (32), it is shown that a larger grain size in a material with equi-axed grains leads to an earlier formation of macro shear bands and an increase in surface waviness. In the work by Lievers et al. (9) the influence of iron content on the bendability has been investigated. Increasing the amount of iron will, however, not only increase the amount of constituent particles, which was their main intent, but it will also influence the grain size, as the increased amount of particles will work as grain refiners. Since these two mechanisms (grain size and particles) counterwork each other, it may be difficult to conclude which of the mechanisms that is the dominating one.

In general the fibrous alloys seem to have a lower bendability compared to the recrystallized ones (8, 33, 34). For the extruded fibrous alloys, the area that experience the largest stresses are the surface layer consisting of recrystallized grains, and this may promote surface roughness. In the experimental study by Snilsberg et al. (33) a 300 µm layer was removed on both a recrystallized and a fibrous alloy. In both cases the average bending angle increased slightly, but it was not concluded whether this was a geometrically effect due sample thinning or due to removal of the recrystallized layer.

If the investigated material is taken from a hollow extruded profile, other artefacts from the extrusion process may affect the microstructure and, hence, the bending behavior. Fig. 8 shows the microstructure of a bend AA6082 alloy taken from an extruded profile, where the geometry of the extrusion tool leaves the seam weld on the middle of the wall of the profile. In this case the bending axis has been aligned directly along the seam weld. Several authors have looked specifically on the tensile and fracture strength of such seam welds (35, 36). But not much has been reported directly on the effect of such a mixed microstructure on the bendability. In the work by Snilsberg et al. (33) two examples are shown for an AA6060 and an AA7003 alloy, but no clear effect of the extrusion weld on the bending angle was found.

Particles

All commercial aluminum alloys contain constituent particles. These particles are typical Fe-rich phases that form during casting and should not be mixed up with the hardening precipitates that are the definition of the heat treatable aluminum alloys. Not only is it difficult to avoid Fe in the material, but the constituent particles also play an important role in microstructure control through the thermo-mechanical process of the alloys, see e.g. Fjeldbo et al. (37) and Engler et al. (38), as well as they influence the work-hardening of the material (9). The constituent particles are also potent nucleation sites with respect to pore formation and are strongly associated with ductile fracture as described by e.g. Benzerga and Leblond (39). When Datsko and Yang (7) came up with the relationship between bendability and reduction in area after tensile testing, this was a purely empirical relationship, but a clear correlation between fracture strain and fraction of constituent particles is also found as shown by Westermann et al. (40).

The bendability of as-cast materials is poor (8, 41). From an industrial perspective formability of cast material is not of significant interest as cast components are directly cast into near final shape. But it is of interest with respect to understanding the fracture mechanisms. The constituent particles in as-cast materials are typically inhomogeneous distributed at the grain boundaries and dendrite boundaries. Marzouk et al. (41) have shown that the size and shape of the constituent particles in a cast alloy may influence the obtained bending angle significantly. Westermann et al. (8) showed that the combination of large grain size and distribution of particles along the grain boundaries were detrimental for the bending behavior of the cast and homogenized material, where the crack propagation was similar to the one shown in Fig. 9.

After deformation, either by extrusion or rolling, the constituent particles break up and become smaller and aligned along the deformation direction like beads on a string (42). The alignment of the particles remains unaltered by recrystallization, and such particle constellation is therefore found in both recrystallized and fibrous alloys. Several authors report that particles play a major role in strain localization and fracture propagation, e.g. (1, 9, 17, 43, 44), and in the work by Wilkinson et al. (10) a clear correlation between the predicted localization and the corresponding particle field is found. When considering the strong effect of the orientation of the bending axis, as presented in Fig. 6, Westermann et al. (8) concluded that the alignment of particles, like beads on strings throughout the material has a detrimental effect on the bendability. The bending angle was in general much lower when the bending axis was aligned along the extrusion direction and, hence, in the same direction as the stringers of particles, independent of grain morphology. The crack propagation was found to change from pure shear when the bending axis was aligned along the transverse direction (Fig. 10a), to a crack propagating in a zigzag pattern between the stringers of particles with the bending axis along the extrusion direction (Fig. 10b). Davidkov et al. (17) reported for a rolled and recrystallized sheet, that the formation of grain boundary precipitates, like β - and Q-phase, played an even stronger role than the constituent particles in the rolled material as they promote intergranular fracture.

The heat treatable alloys do not only contain constituent particles, but they gain their strength from precipitation of small hardening particles. These are much smaller than the constituent particles and form subsequent to hot deformation, either by natural aging or artificial aging at elevated temperatures. These precipitates affect both the yield strength and the work-hardening behavior of the alloy, see e.g. (45, 46). In the numerical study by Mattei et al. (32) it was concluded that large work-hardening parameters lead to lower local strains and decrease the dispersion due to material heterogeneity. The lowest work-hardening parameter is usually observed when the material is in the state of peak hardness (46). Nakanishi et al. (47) reported that the poorest bendability was found in the peak aged temper, while both the underaged and overaged tempers showed better bending behavior. This is in good agreement with the study by Mattei (32). Similarly, Westermann et al. (8) reported better bendability for the overaged materials compared to the underaged material for both as-cast, as-extruded, and recrystallized materials. Even though this observation was not directly correlated with the work-hardening parameter, a much larger plastic zone was observed in front of the crack tip in the overaged material and heterogeneity in the microstructure was found to be the reason for this behavior.

Texture

Texture is usually considered the main cause for anisotropic behavior in the wrought aluminum alloys. Texture is the distribution of crystallographic orientations of a polycrystalline sample, i.e. that some grain orientations are more pronounced after rolling or extrusion. Since many factors influence the mechanical behavior of a material, the effect of texture is more easily cultivated and studied applying crystal plasticity theory, either Taylor-based models (e.g. (11, 48)) or crystal plasticity finite element models (CP-FEM) (12). Dao and Li (49) concluded that surface roughening (orange peel appearance) work as initiation spots for the shear band formation. The effect of different texture components on shear band formation were systematically studied in the numerical work by Kuroda and Tvergaard (11), and a strong effect on shear band formation with strain localization was found especially for the texture components related to deformation texture, i.e. Brass, Copper, Goss and S. Interestingly, some of these components, i.e. Copper and Goss, seemed to be very dependent on the deformation orientation. The most commonly texture component associated with recrystallization, i.e. the Cube orientation, showed a very homogeneous strain field and was found to significantly enhance the resistance to shear localization independent of orientation. This is in agreement with the experimental work on single crystals performed by Ikawa et al. (50). This means that a material with a strong Cube texture will show better bendability than one with a weaker texture. In the work by Saai et al. (12) a material with a very weak deformation texture (close to random) was investigated and only a small effect of texture on the shear localization was observed in the simulations, similarly to the observations for random texture found by Kuroda and Tvergaard (11).

Conclusion

The behavior of the heat treatable aluminum alloys in three-point bending strongly depends on the microstructure and texture of the alloy. The texture that usually is associated with anisotropic mechanical behavior cannot solely explain the anisotropy observed in bending behavior. The texture, however, plays a major role when it comes to strain localization. In the fibrous alloys, the deformation texture is found to enhance the formation of shear localization leading to earlier failure in the sheet or plate, whereas the cube texture in the recrystallized alloys improves the bendability significantly. Not only texture leads to strain localization, also the grain size plays an important role, as a larger equi-axed grain size leads to earlier strain localization compared to a smaller grain size. The factor that has the largest effect on the bending behavior, which gives rise to an observed anisotropic difference in bendability, is nevertheless the non-homogeneous distribution of particles. Constituent particles aligned along stringers change the way the fracture propagates, and the presence of grain boundary precipitates may lead to intergranular fracture.

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Figures

Figure 1. Universal test machine equipped with tools for three-point plane strain bending.

Figure 2. Typical force-displacement curve in a three-point bending test. Failure is defined at the point with maximum force level.

Figure 3. Manual measuring of the bending angle after testing.

Figure 4. (a) Schematic illustration of the major stresses present in three-point bending and their direction relative to the bending axis (BA); compressive forces towards the tool and tensile forces at the outer side. (b) and (c): Typical strain distributions in bending cross sections along the bending axis. CA is the central axis of the sheet, NA is the neutral axis of the sheet and *t* is the sheet thickness. (b) linear distribution for small strains and (c) nonlinear distribution for large strains.

Figure 5. The compressive forces may cause intense shear band formation.

Figure 6. Bend specimens of the same alloy. To the left with the bending axis aligned along the extrusion direction and to the right perpendicular to extrusion direction (ED).

Figure 7. Typical microstructure for heat treatable aluminum alloys. (a) recrystallized microstructure and (b) fibrous microstructure with recrystallized surface layer.

Figure 8. Bending axis aligned along the seam weld in an AA6082.

Figure 9. Crack propagation in an as-cast AA7108. Large grains and constituent particles have a detrimental effect on the bending behavior.

Figure 10. The crack propagation dependent on the alignment of bending axis. (a) pure shear fracture when the bending axis is aligned along the transverse direction, and (b) shear fracture developing into a zigzag pattern when the bending axis is aligned along the extrusion direction.