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Influence of Chemical Composition and Process Parameters on Mechanical Properties and Formability of AlMgSi-Sheets for Automotive Application

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Abstract

The heat treatable AlMgSi-alloys of the 6xxx-series are widely used for automotive sheet applications due to their good combination of strength and formability. Magnesium and silicon are the main alloying elements in this group forming the age-hardening phase Mg_2Si. Moreover intentional addition of copper, manganese and also impurities (for example iron) can have a significant influence on the mechanical properties and on the forming behavior of automotive body sheets. Beside the chemical composition also thermo-mechanical process parameters can lead to changes in material properties. The purpose of this work is to investigate the influence of alloying elements and process parameters on (I) strength and (II) ductility in temper T4 and after the typical paint bake cycle at 185°C/20min. Furthermore (III) the formability of different AlMgSi-alloys is studied with bending tests, cross-die tests, hole expansion tests and FLC-analysis.

Introduction

The aluminum alloys have received considerable interest from the automotive industry, as they aim to design and manufacture light weight vehicles with the objective to improve fuel efficiency and reduce vehicle emissions. Aluminum sheets for automotive body-in-white application require high strength accompanied by good formability, corrosion resistance and weldability. Furthermore, for autobody applications the sheets should offer good surface appearance and high dent resistance. In this regard the heat treatable AlMgSi-alloys (6xxx series) are finding increased usage in the automotive industry in the last years. Heat treatable alloys have the advantage to combine both, good formability in temper T4 (solution-treated and naturally aged state) and high strength by way of age hardening created in the automotive paint bake cycle at ~ 185 °C. This paint bake cycle increases the strength of these alloys due to precipitation hardening and at the same time it enables the curing of the paint.

Silicon and magnesium are the main alloying elements of the AlMgSi-alloys. In the recent years several alloy modifications have been introduced to meet the requirements of the car manufacturers. The different types of 6xxx series alloys vary not only by the ratio between silicon and magnesium, they also have different additions of transition elements (e.g. Cu, Mn, Fe, V). Varying element contents in combination with specific processing modifications result in a wide range of mechanical properties in the final product. To utilize the potential of different 6xxx series alloys in view of processing and application more completely, the knowledge of interactions between chemical composition, thermo-mechanical process parameters and mechanical properties plays an important role. For this reason the present work compares four prominent AlMgSi-alloys (AA6016, AA6005A, AA6063, and AA6013) to illustrate these correlations. Beside the mechanical properties, also the forming performance will be compared by bending tests, hole-expansion tests, cross-die tests and by the forming limit curves (FLC).

Experimental

Within this study four different alloys, AA6016, AA6005A, AA6063 and AA6013 were investigated. The chemical composition of the investigated material is shown in Table I. These alloys were produced at AMAG rolling in form of 1.0 mm thick sheets. The thermo-mechanical treatment was similar for all variants. The alloys were DC-cast as large ingots and then scalped on their rolling surface. For the hot rolling the alloys were preheated. This kind of homogenization heat treatment reduces the segregation arising from non-equilibrium solidification during casting, equalize the distribution of the constituents and dissolves soluble phases. After this heat treatment the hot ingots were transferred to the rolling line. Then the hot band was coiled and allowed to cool before it was cold rolled to the final gauge. To adjust the right property profile (strength and formability), the material was then solution treated in a continuous heat-treatment line. During the solution heat treatment the material was rapidly heated up, followed by subsequent water quenching to achieve temper T4 after RT storage. Hereby recovery and recrystallization of the as-deformed microstructure takes place and the hardening phases dissolve which are afterwards necessary to receive a high strength after the paint bake cycle. To improve the age hardening response a further pre-ageing was carried out directly after solution annealing [1, 2]. Within this investigation the hereby produced temper is named T4*. The standard temper after solution treatment and natural aging (T4) and the pre-aged temper T4* are typical states which are delivered to the automotive industry. These tempers generally allow a good forming performance through all forming operations which are applied by the car manufacturers. The final strength of the manufactured parts will be achieved after the forming operations through cold work hardening and by age hardening during the final automotive paint bake cycle at typical 185 °C for 20 min. Within this investigation the hereby produced temper is named T6*.

Table I. Actual chemical composition of the investigated material

	Si [wt.%]	Fe [wt.%]	Cu [wt.%]	Mn [wt.%]	Mg [wt.%]	Cr [wt.%]	Zn [wt.%]	Si/Mg [-]
AA6016	1.03	0.17	0.08	0.08	0.32	0.01	0.01	3.2
AA6005A	0.81	0.19	0.04	0.17	0.50	0.01	0.01	1.6
AA6063	0.64	0.19	0.02	0.02	0.55	0.01	0.02	1.4
AA6013	0.75	0.27	0.75	0.50	0.98	0.01	0.02	0.8

The 6xxx series aluminum alloys are characterized in general through their main alloying elements Si and Mg and additions of Cu, Mn and Fe. As it can be seen in Table I, the alloys exhibit different Si/Mg-ratios. AA6016 has the highest Si/Mg-ratio which goes along with a high amount of Si in excess. From former investigations it is known, that a high Si/Mg-ratio results, on the one hand, in an increased strengthening coefficient, which improves the formability of the alloy [3]. On the other hand, industrial produced AlMgSi-alloys are always contaminated with traces of iron and together with the alloying element Si they form intermetallic particles (Al-Fe-Si) which influence the formability negatively. In AlMgSi-alloys, intermetallic particles are mainly β-AlFeSi and α-AlFeSi. These particles are formed during solidification and homogenization of as-cast ingots and do not dissolve when the alloy is further heat treated. The α-particles have a more globular morphology than the plate-like β-particles, which are known to promote the formation of voids during deformation [4, 5, 6, 7]. The formability can therefore be improved by promoting the formation of α-AlFeSi due to an optimized homogenization heat treatment or by adding α-stabilizer elements such as Mn [5, 7, 8]. Hirth et al. reported, that a higher Si-content does not have a significant influence on the aging kinetics, but primarily affects the initial strength level due to the increased solution and cluster hardening provided by the higher Si level [9]. Copper additions generally increase the artificial aging kinetics [10] but have a negative impact on bendability [11].

Characterization of the mechanical properties

To investigate the mechanical properties in temper T4/T4* and temper T6/T6* (after 2% prestrain, by 185°C/20min), tensile tests in LT direction according to DIN EN 10002 (Lo = 80 mm) were carried out. The results of tensile tests are also of particular value for sheet metal forming operations. The tensile strain hardening exponent n was measured according to ISO 10275 and the vertical anisotropy r according to ISO 10113. To evaluate the plane anisotropy Δr regarding to equation (1), the r-values were also measured in testing direction L and 45°:

$$\Delta r = \frac{r_{90°} + r_{0°}}{2} - r_{45°} \qquad (1)$$

Characterization of the formability

Forming Limit Curve (FLC). In order to describe fundamental formability characteristics of the investigated sheet materials a forming limit curve was determined and therefore the Nakazima test method was employed (acc. to EN ISO 12004).

Bending test. To characterize the bending performance a plane strain bending test according to VDA 238-100 was carried out. The test was performed on sheet metal strips with a length of 250 mm and a width of 70 mm, each taken from the later bending direction (within this study only bending in L-direction was carried out). The metal strips were pre-strained for 10% and afterwards the strips were machined to bending test samples of 60 x 60 mm².

Hole expansion test. Hole expansion tests were conducted on an Erichsen 142/40, 400kN hydraulic sheet metal tester. Specimens for hole expansion testing were prepared and tested according to ISO/TS 16630. The material sheets were cut along the rolling direction into square specimens of 100 x 100 mm². A conical punch with a top angle of 60° was used for hole-expansion purpose and the initial hole was made by punching using a die diameter of 10 mm (d_o). The motion of the punch into the hole was stopped when a crack at the edge of the expanding hole was observed. The limiting hole expansion ratio λ was then calculated according to:

$$\lambda = \frac{d_h - d_0}{d_0} \times 100 \qquad (2)$$

In equation (2) d_h [mm] is the average hole diameter after testing and d_o [mm] is the initial diameter of the hole. In Figure 1 the used die tool for the hole-expansion test, as well as a final expanded part, are shown.

(a) (b)

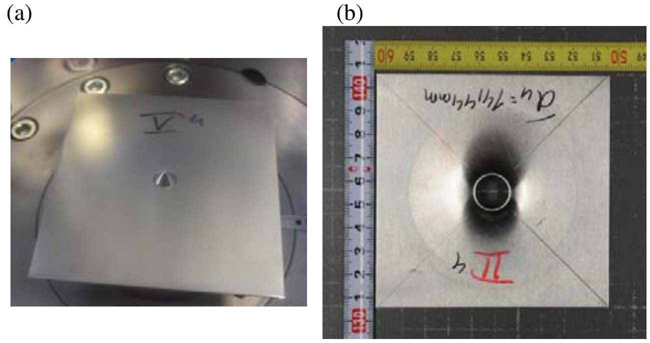

Figure 1. (a) The die tool used for the hole-expansion test and (b) the final deformed part

Cross-die test. This test has been used as a simulative test by the automotive industry to evaluate the forming characteristics of sheet metals. The drawing height (specimen height), as well as the maximum strain which can be sustained by the specimens before the onset of tearing, are the results of the cross-die test. The experimental setup and the produced specimen are shown in Figure 2.

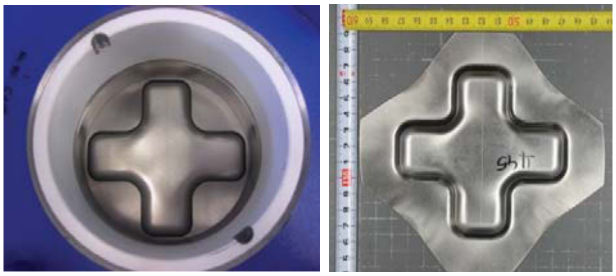

Figure 2. Die tool used for the cross-die test (left) and final deformed part (right)

Results and Discussion

<u>Mechanical properties</u>

In Figure 3 the mechanical properties of the investigated material are shown in temper T4* and after the simulated paint bake cycle treatment of 2 % prestrain + 185°C/20min (T6*). AA6013 exhibits highest strength level compared to the other alloys, which can be related to its chemical composition. Additions of copper to AlMgSi-alloys refine the precipitate structure, induce the formation of the strengthening phase Q' (Cu-containing phase) and increase therefore the strength level [12]. Furthermore, the relatively high Mn-content in AA6013 increases the initial strength, presumably due to solid solution hardening [13]. In contrast, AA6063 shows the lowest strength, both in temper T4* and in T6*. This alloy contains nearly no Cu and Mn and, also the Mg- and Si-content is comparably low. Alloy AA6005A shows a very high T6* strength, which can be related to the higher Mg-content in comparison to AA6016 (more Mg-Si precipitates (β``) can be formed).

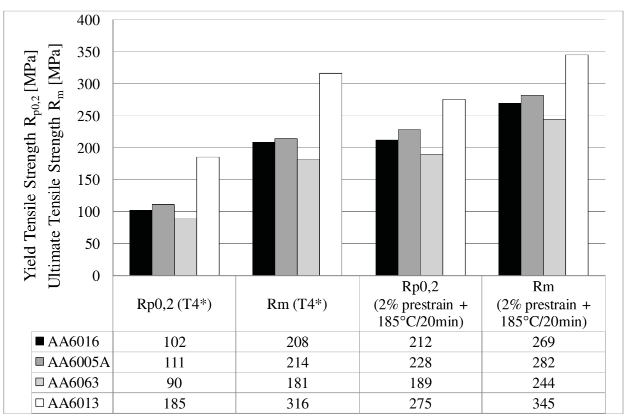

Figure 3. Yield tensile strength $R_{p0,2}$ and ultimate tensile strength R_m in temper T4* and in temper T6*

In order to explain the influence of the thermo-mechanical processing on mechanical properties, Figure 4 illustrates a comparison between standard temper T4 and the pre-aged temper T4* for AA6016. As it can be seen, temper T4* reacts to the applied simulated paint-bake cycle with a more pronounced increase in strength. It is assumed that the Mg-Si clusters formed during the pre-aging with subsequent natural aging exceed a critical size which makes them more stable than those in the naturally aged T4 state [14]. The stable clusters can act as nuclei for the β`` precipitation during subsequent artificial aging and enhance therefore the artificial aging kinetics.

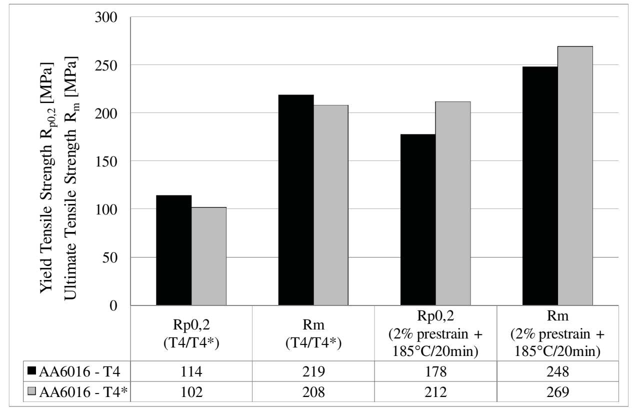

Figure 4. Yield tensile strength $R_{p0,2}$ and ultimate tensile strength R_m in temper T4 and T4* for AA6016

The elongation A_{80} and the uniform elongation A_g of the investigated material is illustrated in Figure 5. In this comparison AA6016 reaches the highest elongation values, whereas AA6013 drops behind. This result is generally understandable in relation to its high strength in temper T4*. Due to the lower elongation for AA6005A and AA6063, in comparison to AA6016, the assumption could be made, that a lower Si/Mg-ratio leads to lower elongation values.

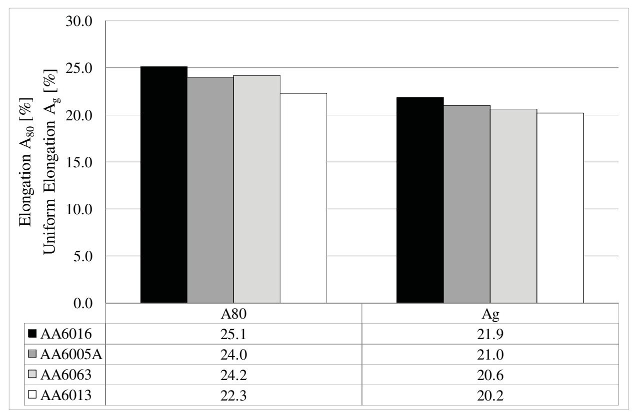

Figure 5. Elongation A_{80} and uniform elongation A_g in temper T4*

Figure 6 shows the vertical anisotropy r, the plane anisotropy Δr, the strain hardening exponent n and the yield ratio $R_{p0,2}/R_m$. These values give a first indication about the formability of the tested alloys. The anisotropy plays an important role during forming processes, especially during deep drawing. Materials with a high vertical anisotropy value possess a high resistance to plastic flow in the direction of the sheet thickness. The strain-hardening exponent can be considered to be an indicator for the maximum attainable deformation during cold forming. The higher the n-value and, consequently, the higher the uniform strain, the lower is the tendency of the material to neck locally. AA6005A and AA6063 reach a high r-value in 90° but the plane anisotropy of these alloys is comparably high. This means, that the forming behavior is not uniform in all rolling directions (0°, 45° and 90°). This could lead to earing during deep drawing. AA6016 has a comparably low Δr-value and shows the highest n-value. AA6013 shows the most uniform r-value in all rolling directions, with a plane anisotropy of 0. Normally the r-value in 45° direction is much lower, than the values for 0° and 90° (this applies for

AlMgSi-alloys). Due to the fact that r-values correlate with the rolling-texture it can be assumed that the high Cu-content in AA6013 influence the rolling texture positively in terms of anisotropy. Further texture-measurements would be necessary to explain these results more properly.
The yield ratio is also an indication for the alloys' formability and should be as low as possible. The investigated alloys show nearly identical results, with the exeption of AA6013. The high yield ratio of AA6013 is obviously related to its high strength in temper T4*.

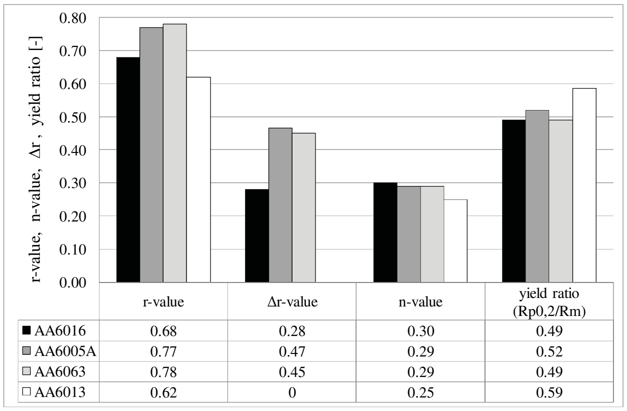

Figure 6. Vertical anisotropy r, strain-hardening exponent n, plane anisotropy Δr and $R_{p0,2}/R_m$ ratio in temper T4*

Forming Limit Curve (FLC)

With the forming limit curves, which are illustrated for the investigated material in Figure 7, it is possible to determine process limitations in sheet metal forming in a case of a linear strain path (e.g. necking and tearing). It can be seen, that AA6063 allows the highest deformation rate until first failures occur. This is related to the lower strength level in comparison to the other alloys. Although AA6013 shows the highest strength during tensile testing, the FLC is comparable to AA6005A. This result cannot be explained in detail within the scope of this paper, but we assume a correlation with the very low plane anisotropy Δr of AA6013 (due to a high r-value in 45°).

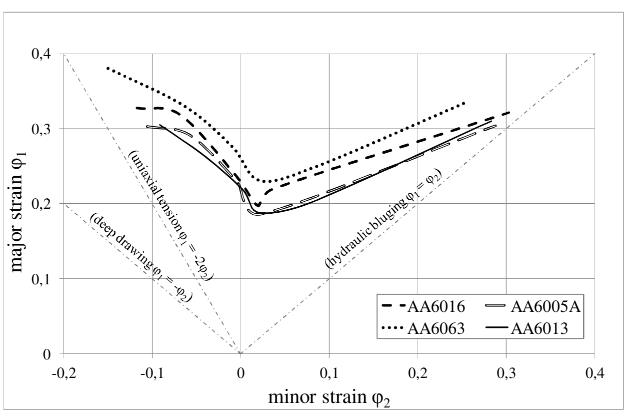

Figure 7. FLC (Nakazima) of AA6016, AA6005A, AA6063 and AA6013 in temper T4* for sheet thickness 1.0 mm

Bending Performance

Hemming is a typical assembly method used in the automotive industry to join the outer sheet to the inner part of the hang-on body panels. The requirements to an alloy which is subjected to hemming are very tough, because the material has to withstand a 180° bending over a radius equal to the half of the sheet thickness. Failure during bending of AlMgSi-alloys can occur through intergranular fracture due to the presence of grain boundary particles [15]. Furthermore, strain localization and intense shearing in relation to micro-voids formation around large phase particles can lead to fracture during bending [16]. Table II depicts the bending results of the investigated material. AA6016 and AA6063 show the best bending performance compared to AA6005A and AA6013. The poor bending performance of AA6013 can be related to its Cu-content due to the fact that copper tends to form grain boundary precipitates by improper solution heat treatment or cooling. Large intermetallic particles can also influence the bendability negatively [17]. AA6013 and AA6005A contain more Fe and Mn, which form intermetallic Al-Fe-Si or Al-Fe-Si-Mn particles. Davidkov et al. [15] reported that bendability depends on the value of the strain hardening exponent n, which can be also seen here.

Table II. Bending angle in [°]

	AA6016	**AA6005A**	**AA6063**	**AA6013**
Bending angle	156	134	159	84

Hole-expansion test

The design requirements of automotive parts often demand the presence of holes on the surface. Since hole expansion tests measure the elongation of the material near the holes, the calculation of the hole expansion ratio is of high interest to get information about material's susceptibility to edge cracking or edge stretching. The following Figure 8 demonstrates the hole expanded samples. The stress field in the formed edge where the cracks appear is similar to the stress field in the sheared edge during flanging operations. The edge condition before flanging, sheet-deformation during hole preparation, punch shape and microstructure (volume fraction and morphology of different phases) might affect the ability of the hole flange to stretch [18].

(a) (b)

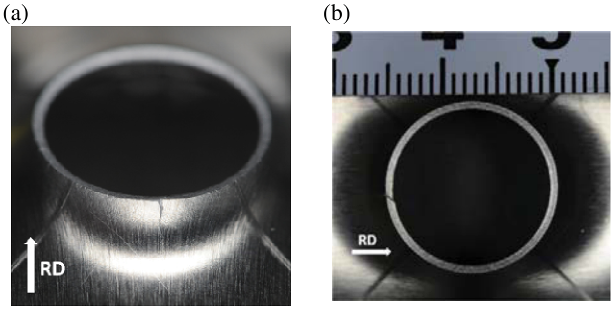

Figure 8. Appearance of a crack on the rim of an expanded hole (a) side view and (b) top view

The limiting hole expansion ratio λ of the investigated materials is listed in Table III. The alloys AA6016, AA6005A and AA6063 show nearly the same results with a ratio > 50 %. The alloy AA6013 reaches the lowest hole expansion ratio with 41,6 %, which was expected due to the high strength level of this alloy in temper T4*. AA6013 contains a high amount of alloying elements which form different phases (e.g. Al-Fe-Si-Mn, Mg-Si, Al-Cu-Mg-Si) with a high volume fraction through the thermo-mechanical processing. These phases can cause grain boundary precipitations (mainly Cu-rich precipitates). The fracture during deformation can be then initiated in the grain boundary through void initiation [19].

Table III. Limiting hole expansion ratio in [%]

	AA6016	AA6005A	AA6063	AA6013
Limiting hole expansion ratio λ	53.0	56.7	52.3	41.6

Cross-die test

The forming test in a cross-die has been used extensively in the automotive industry to assess the formability of sheet material. The geometry of the cross-die displays typical stress states which predominate during manufacturing of real automotive parts. Before the experimental test was carried out a simulation was performed to predict where and at which forming height first cracks occur. The simulation result was in good agreement with the experiment. First cracks occur due to thinning in the corners of the formed cross, which is illustrated with the blue color in Figure 9 (b). In this area the material is mainly suspended to stretching under tension.

(a) (b)

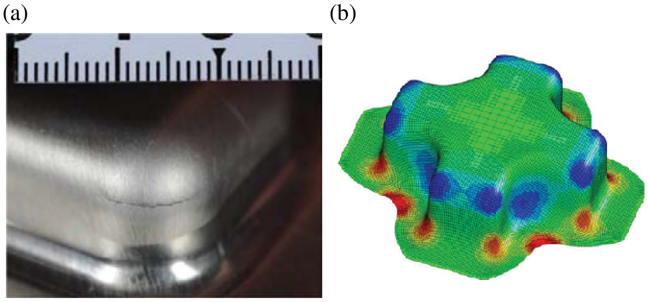

Figure 9. Appearance of a crack due to thinning on the corners of the cross-die sample (a) experiment and (b) simulation

The forming height of the investigated alloys is given in Table IV. It is found, that the alloys AA6005 and AA6016 reach the best results in this test, whereas AA6013 drops behind.

Table IV. Cross-die forming height in [mm]

	AA6016	AA6005A	AA6063	AA6013
Forming height	18.2	18.4	17.9	15.3

Conclusions

The automotive industry formulates various requirements on the materials' behavior. Alloys for structural parts or outer panels often require high strength to allow thickness reductions with no loss in dent resistance. Due to environmental and economical reasons, the automotive industry aims at temperature reduction of the paint bake cycle. Therefore there is an increasing demand for alloys showing higher age hardening response. However, for several parts the formability remains the major difficulty. The automotive OEMs want to have as much design freedom as possible, which challenges the sheet materials property profile.

Within this work four well-known 6xxx series alloys (AA6016, AA6005A, AA6063 and AA6013) were investigated in regard to mechanical properties and different forming operations. Beside the Nakazima tests (FLC), hole-expansion tests, bending tests and deep-drawing tests in a cross-die were conducted. The forming results were found to be strongly dependent on the chemical composition of the particular alloy. For example AA6013, which is widely used in the aerospace industry, showed poor forming performance during bending and hole-expansion, most probably because of its very high strength level in temper T4*. However, despite of its high strength AA6013 was almost competitive in the other forming tests. It is worth mentioning that forming limit curves are widely used in the sheet metal forming industry to characterize the forming behavior. However, this inspection feature is strictly valid only when the strain path is linear during the deformation process. But the strain path in real forming processes is linear only in rare cases. Such test procedure limitation makes it necessary to carry out more than one forming test to characterize the formability of a sheet metal. Bending operations, such as hemming or hole-expansion, are sensitive to the microstructure. Especially intermetallic particles, grain boundary precipitates and the overall distribution of constituent phases have a significant influence on bendability. In general, the microstructure of an alloy is determined by its chemical composition and its thermo-mechanical process parameters, which again affect the materials property profile. Therefore the knowledge of these interactions is of considerable interest for the materials selection. Especially the tolerance windows of alloying elements have to be considered.Figure 10 shows exemplarily the broad tolerance windows of Si, Mg and Cu of the investigated alloys. The black points in this chart show the actual chemical composition of the tested material within this work. As it can be seen, the used AA6016 was on the lower limit, both for Si and Mg. An increase of Si and Mg within the tolerance window would lead in completely different mechanical properties and of course, also the formability might not be the same.

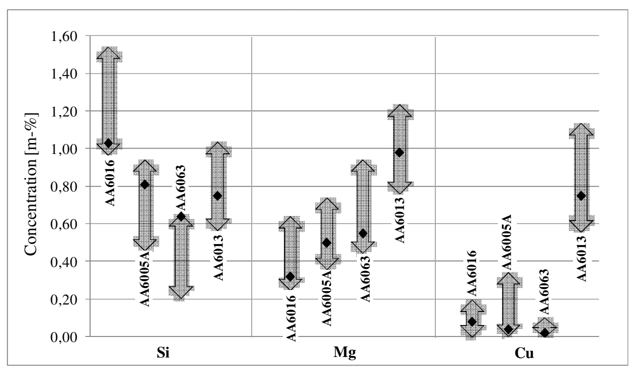

Figure 10. Tolerance window of the main alloying elements of AA6016, AA6005A, AA6063 and AA6013

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