Investigation of the formability of aluminium alloys at elevated temperatures

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Abstract. Aluminium alloys are more and more widely applied in car body manufacturing. Increasing the formability of aluminium alloys are one of the most relevant tasks in today’s research topics. In this paper, the focus will be on the investigation of the formability of aluminium alloys concerning those material grades that are more widely applied in the automotive industry including the 5xxx and 6xxx aluminium alloy series. Recently, besides the cold forming of aluminium sheets the forming of aluminium alloys at elevated temperatures became a hot research topic, too. In our experimental investigations, we mostly examined the EN AW 5754 and EN AW 6082 aluminium alloys at elevated temperatures. We analysed the effect of various material and process parameters (e.g. temperature, sheet thickness) on the formability of aluminium alloys with particular emphasis on the Forming Limit Diagrams at elevated temperatures in order to find the optimum forming conditions for these alloys.

1. Introduction
In the past few decades, many investigations were performed on hot forming of aluminium alloys. S. Mahabunphachai and M. Koc investigated the 5082 and 6061 alloys in a hydraulic bulge test at elevated temperatures. They found that the formability continuously increased from room temperature to 300°C [1]. In 2003, D. Li and K. Ghosh published their investigations on 5754, 5182 and 6111 alloys. The investigations were completed at temperatures from 200 to 350°C. The formability of the 5182 alloy has increased significantly from 200°C to 250°C Above this temperature range, the increase of formability was lower than before. At the 6111 alloy a small further increase was experienced in the 200°C to 350°C temperature range [2]. The formability of 5754 alloy was continuously increased up to 300°C, and even above, but the increase was much smaller than in the lower temperature ranges. P.J. Bolt, N.A.P.M. Lamboo and P.J.C.M. Rozier investigated the 5754 and 6016 aluminium alloys at elevated temperatures. The tests were performed from 100 to 250°C. They deep-drawn box-shaped parts, and measured the maximum product height. The 5754 alloy produced larger formability above 200°C, while the 6016 produced a moderate increase until 200°C. Above 200°C, the formability went down. It reveals the presence of an optimum forming temperature [3]. In 2014, M. Kumar, N. Sotirov and C.M. Chimani published their investigations on warm forming of 7020 alloy sheet. They performed Cross-die tests at temperatures from 150°C to 250°C. They measured the depth of the specimen, and found that the depth increased highly from 150°C to 200°C, and above 200°C the gaining was much smaller than before [4].
As it can be seen, researchers have conducted their studies at laboratory environment for years, but no well-known technology has been developed for the industry. However, it is very important to transfer warm forming from laboratory to manufacturing plants.

2. Experimental investigations

2.1. Materials

The applied materials were the EN AW 5754 H22 and the EN AW 6082 T6. The EN AW 5754 (AlMg3) alloy is widely used in sports cars like Jaguar XK, Lotus Evora and Chevrolet Corvette. This alloy has medium strength among aluminium alloys. Its composition: 95.8% Al, 2.78% Mg, 0.29% Si, 0.36% Fe, 0.37% Mn. Temper: H22. Mechanical properties: Rp0.2=180 MPa; Rm=243 MPa; A=17% (Alcoa).

The EN AW 6082 is commonly used for structural elements in most of luxury cars like BMW 6, BMW Z8, Ferrari 548, Jaguar XJ, Jaguar XK, Range Rover and Rolls-Royce Phantom. Its composition: 0.7-1.30% Si, 0.50% Fe, 0.10% Cu, 0.40-1.0% Mn, 0.6-1.2% Mg, 0.25% Cr, 0.20% Zn, 0.10% Ti. Mechanical properties: Rp0.2=260 MPa, Rm=310 MPa, A50mm=8%.

2.2. Test specimens

During the experiments at different temperatures, the specimens had three different geometries with 1.0 mm thickness. The different geometries are determined in such a way to provide the desired FLC’s special strain paths both in the tension and the compression zone. These specimen geometries can be seen in Figure 1. For the investigation of the effect of sheet thickness, we used sheets with 1.0, 1.2 and 2.0 mm thickness.

2.3. Test equipment

In our tests, a computer controlled universal sheet formability-testing machine was used. This is able to perform various formability tests, e.g. Erichsen, Nakazima, Bulge, FLD, FLC tests. The equipment has electrohydraulic powertrain and it is suitable to test up to 3 mm maximum sheet thickness of steel, or 6 mm maximum thickness of aluminium. The forming tool geometry is a hemisphere with a diameter of 100 mm. The maximum load is Fmax=600 kN, the speed interval of the tool is between v=0 mm/s and v=5 mm/s.

The universal formability-testing machine is equipped with an optical strain measurement system, which records the distortion of the grid, which is painted on the sheet before the tests. The system has 4 CCD cameras to obtain the 3D point cloud from the mesh. The universal formability-testing machine with the optical strain measurement system can be seen in Figure 2. From the measurements, the Vialux-AutoGrid software determines the deformation and strain distribution along the curved surface. With these data, the FLC and FLD can be determined. In our investigations we followed mainly the ISO 12004-2 instructions, to obtain the Forming Limit Diagrams of tested aluminium sheets.

As a difference from the ISO 12004-2 instructions it should be noted that during the investigations no lubrication was used, thus during the experiments at elevated temperatures we could provide similar friction condition between the tool and the sheet. Without lubrication, we could eliminate the
influence of the different amount and quality of the lubricants, because always the same materials were in contact. But obviously, we have to keep in mind that the lack of lubrication could cause failures by the high friction, and forming results in some cases may completely be dominated by friction and less by the material’s behaviour itself. We planned to investigate the effect of dry friction also, with the aim to create a method for steel-based manufacturing to use their tools for aluminium stamping with additional thermo-cells and without lubrication. The lubrication always a hazardous material and using high temperatures like in our investigations, the lubrication oil or paste evaporates and smokes and we would like to avoid these hazardous effects. Next to the temperature the limit of the friction would also defines our process boundary.

Figure 2. Universal formability testing machine with the optical strain measurement system

3. Results

3.1. Experimental results with the EN AW 5754 aluminium alloy at different temperatures

During the experiments, the general conditions of industrial environment were considered. The tests were carried out besides room temperature at the following temperatures: 130°C, 200°C and 260°C. A laser thermometer measured the temperature of the sheets. The focus point was on the top of the dome. Due to the small thickness, the sheet reached the forming temperature within few seconds after closing the die. The speed of the forming tool was 0.5 mm/s in each measurement. No any lubricant was used, thus the lubrication condition was the same in each measurement.

From the experiments, the following main observations were made. The formability increased monotonically with the temperature until 200°C. Above this temperature, the decrease of the formability was observed, and at 260°C, it was even lower than at room temperature. The results show that the optimum forming temperature was closer to 200°C. It is worth mentioning that the formability at 200°C was twice as high as at room temperature. This is mainly due to the changes in the material properties and the microstructure evolution of the tested aluminium alloys.

This significant increase of dome height is well illustrated by the macroscopic figures of tested specimen (Figure 3.). The difference in the dome height of the specimens tested at room temperature and 200°C is very significant. In the tests where the specimens with the width of 80 mm were formed, the dome height was 21.75 mm at room temperature, and 55.82 mm at 200°C. The formability was the highest in this case. In the other cases, the dome height also increases until 200°C. Above this temperature, at 230°C small decrease observed, and above this temperature, the dome height was smaller than at room temperature in most cases. The specimen with the width of 200 mm was only the one which was a little bit higher than at room temperature. The dome height changes also indicates the formability, and in our cases when we did not use lubrication these are the most important characteristics, since the dome height means the maximal elongation of the sheet without lubrication.
Specimen tested at room temperature
Specimen tested at 200°C

**Figure 3.** Picture of specimens tested at various temperatures (Material: EN AW 5754)

Some results of dome test investigations are summarised in Figure 4, for the tested aluminium alloys at different temperatures. In the figure, the dome height changes are shown for three different specimen width, i.e. for b = 20, 80 and 200 mm. This diagram clearly demonstrates the changes of specimen dome height as an important formability characteristic at elevated temperatures.

**Figure 4.** Dome height changes of the specimens after forming at elevated temperatures

After testing all the specimens at the selected various temperatures (T = 20°C, 130°C, 200°C and 260°C) the Forming Limit Curves were determined at each temperature using the AutoGrid software. These results are shown in Figure 5, for the material grade EN AW 5754. In this figure, the significant increase of the formability up to 200°C can be well seen. We can also observe in this figure that there is a sharp decrease in the formability at 260°C. The Forming Limit Curve at 260°C falls even below of the FLC measured at room temperature.
In the microscopic pictures, (see Figure 6.) it can be also seen that the grain structure at 260°C at this temperature is significantly different from the grain structure obtained at 200°C, which contains more uniform, nearly equiaxed grains.

Figure 5. FLC curves for the EN AW 5754 aluminium alloy at different temperatures (sheet thickness t = 1.00 mm)

Figure 6. Microstructure at 200°C and above the optimal forming temperature (at 260°C)
3.2. Experimental results with the EN AW 6082 aluminium alloy at different temperatures

The EN AW 6082 aluminium alloy has higher strength than the EN AW 5754 one and as a consequence it has lower formability. That is the main reason why car manufacturers use this alloy for structural elements. We performed the tests on this alloy at the same temperatures as for the EN AW 5754 alloy, i.e. at room temperature, 130°C, 200°C and 260°C. The increase of the formability was smaller than for the EN AW 5754 alloy – as it was expected – however, the trend of changes was very similar. When we increased the temperature until 200°C, the forming limit curves are shifted up. At 260°C it has gone down to the level near to the values measured at room temperature. This difference is clearly revealed in the FLC curves determined for the various temperature values. The FLC curves for the EN AW 6082 aluminium alloy determined at room temperatures and at various elevated temperatures are shown in Figure 7.

![FLC curves for the EN AW 6082 aluminium alloy at different temperatures](image)

**Figure 7.** FLC curves for the EN AW 6082 aluminium alloy at different temperatures (sheet thickness t = 1.00 mm)

3.3. Experimental results of EN AW 5754 aluminium alloy with different sheet thicknesses

We also investigated the FLC curves for different sheet thicknesses. From these experiments, we can state that the formability of the EN AW 5754 alloy is continuously increased with the increasing sheet thickness. Concerning the formability we found that it was the best with 2.0 mm thickness and it has significantly lower values with 1.0 mm sheet thickness.

On the basis of these experimental results, we can state that the sheet thickness may significantly affect the formability of aluminium alloys, thus if we increase the thickness of a sheet, the formability will increase with it. These results are shown for the EN AW 5754 aluminium alloy grade in **Figure 8.** for three different sheet thickness. The results are similar in case of EN AW 5754 aluminium alloy with these thickness values.
4. Summary and conclusions

In this paper, the formability of two different aluminium alloys (EN AW 5754 and EN AW 6082) was investigated at elevated temperatures. Obviously, the formability of any materials is a quite complex phenomenon influenced by several parameters, besides the material grade like strain path, deformation history, strain-rate effects and failure mode, etc. It cannot be described just selecting one or two of these manifold formability indicators. However, within a limited volume of a paper we have to focus on some of these parameters.

In this paper, we mainly analysed the temperature dependence of aluminium alloys focusing first of all on the Formability Limit Diagram (FLD) and the changes of the Limit Dome Height (LDH) values. The selection of these two parameters may be reasoned by several facts. Using the FLD as a formability issue may be explained by the fact that all the numerical modelling programs that are more and more widely used not only in the academic research but in the everyday industrial practice as well, are based among others on the Formability Limit Diagrams. The selection of Limit Dome Height (LDH) as another formability indicator is also widely used in sheet metal forming mainly due to its simplicity of measurement techniques. These are the main reasons that in our investigations we applied these two formability indicators.

The formability investigations were performed by determining the Forming Limit Diagrams and the Limit Dome Heights for these alloys at various elevated temperatures. For the determination of Forming Limit Diagrams, we applied a universal formability-testing machine equipped with an optical strain measurement system. During the experiments we used the modified Nakajima specimens to be able to determine the whole range of the FLDs (both in the tension and compression side) with relatively small number of experiments.

The FLD tests were performed without lubrication to ensure the same lubrication and friction condition between the surfaces and furthermore to create a dry and more environment-friendly stamping process for the industry. It results in a slight difference concerning the relating ISO 12004-2 standard in the conditions of FLC investigations, but the results can be useful to define the boundaries in dry-hot stamping technology, too.

Figure 8. FLC curves belonging to different sheet thicknesses for EN AW 5754 material grade at room temperature
It is well known that by increasing the forming temperature the formability is usually increasing. Studying the effect of the temperature on the formability of aluminium alloys, we found that for the investigated aluminium alloys (EN AW 5754 and EN AW 6082) an optimum forming temperature exists where the formability has a maximum value. To find these optimum forming temperatures for the investigated aluminium alloys, we performed large scale formability investigations from room temperature up to the temperature range 130 to 260°C.

We could identify that at the optimum forming temperature, the FLC curves are shifted up significantly along the ε1 major strain axis (the maximum values of major strain components were about three times higher compared to the room temperature values).

Similar experimental evidences were found analysing the changes of the Limit Dome Height values. The difference in the dome height of the specimens tested at room temperature and 200°C is very significant. In the tests where the specimens with the width of 80 mm were formed, the dome height was more than twice high at 200°C for example for the alloy EN AW 5754 (21.75 mm at room temperature, and 55.82 mm at 200°C). The formability was the highest in this case. In the other cases, the dome height also increases until 200°C. Above this temperature, at 230°C small decrease observed, and above this temperature – e.g. at around 260°C, the dome height was even smaller than at room temperature in most cases.

It was experienced both in the FLD and LDH investigations that over the optimum forming temperature a significant decrease of the formability occurs. Therefore, to find and to hold the optimum forming temperature during the forming processes is of utmost importance. In our investigations, we found that the optimum forming temperature of both investigated alloys (both EN AW 5754 and EN AW 6082) is slightly above 200°C and a sharp deterioration occurs above this optimum value.

In these experiments, we also studied the effect of the material thickness. It was experienced that the formability was increased by the increase of sheet thickness.

References
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