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Materials and simulation modelling of a crash-beam performance – a comparison study showing the potential for weight saving using warm-formed ultra-high strength aluminium alloys

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Abstract: Forming complex parts out of high and ultra-high strength aluminium alloys has proved to be more challenging in comparison to the currently used deep drawing steels. The novel “Warmforming-Process” offers the potential to produce light and highly integrated one-piece components out of such aluminium alloys at elevated temperatures. When considering aluminium alloys in the 7000 group, which can reach strength values (*UTS*) far above 600 MPa, crash components such as side impact bars would offer a suitable field of application.

It is important when taking into consideration the geometric design of structural components to utilise their load bearing characteristics in an efficient manner. This structural optimisation lends itself well to computational simulation techniques, which are essential in the evaluation of appropriate geometry and sizing of complex structures with challenging load scenarios.

Crash simulations using the nonlinear finite element method (FEM) of side impact protection beams have been used to demonstrate the weight saving potential of high and ultra-high strength aluminium alloys. A beam design formed from a *7000* series alloy was taken as a reference. Substituting various materials, inter alia press hardened steel (phs), and benchmarking against the original beam's crash performance, by changing the material thickness, equivalent beams were produced.

The thicknesses of the beam geometries have been evaluated by “sizing optimisation” and their possible mass reduction are compared against each other. The nonlinear FEM simulations show good agreement with a corresponding set of experimental results. It was seen that for a common crash performance the ultra-high strength aluminium alloys outperform press hardened steel components in terms of their weight. Thus, there is a significant weight saving potential to be realised if crash components are manufactured using 7000 series aluminium alloys. In this work, the weight saving potential was found to be in the region of 20 - 25%.

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1. Introduction

Current forecasts indicate that after the next 50 years the conventional resources of fossil fuel will be considered to be depleted and this will be set against an increased demand for energy as the global population and affluence rises [1, 2, 6]. Thus, the development of innovative and economical solutions to this demand, such as using lightweight aluminium alloy structures, is essential to curb this trend [3].

Yet, steel materials dominate the market within the automotive sector because of their adequate cost vs. performance ratio. Nevertheless, aluminium and its alloys play a major role for lightweight applications. In particular aluminium alloys in the 7000 series offer big advantages compared to press hardened steels if the specific strengths of corresponding materials are compared to each other (figure 1).

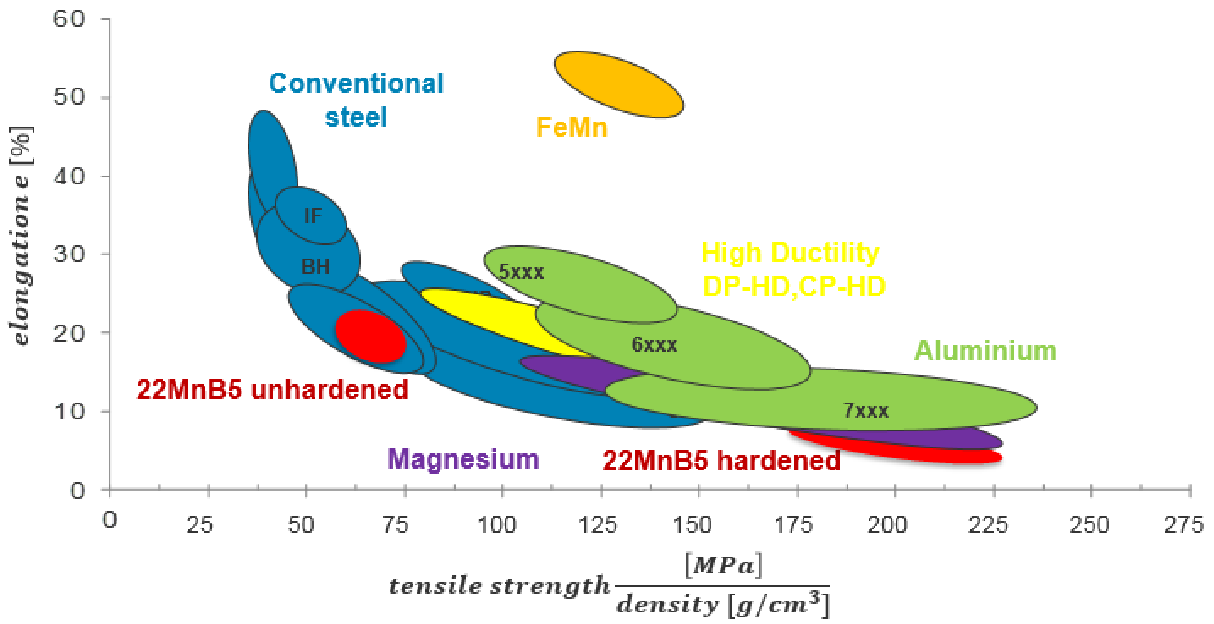

Figure 1. lightweight design potential of metallic materials

This positive property can be used to reduce energy consumption during the life of a vehicle [1]. An example of such development is the car body of the Ford F150 in which steel has been replaced by aluminium alloy to save weight [4], which results in a decreased fuel consumption and increased performance. The global car manufacturers need to reduce the weight of vehicles due to the exhaust emissions and their economic objectives. Therefore, car-makers use lightweight materials, in particular aluminium alloys, because the cost of other lightweight materials such as composites and magnesium alloys are predominantly used for racing cars, sport cars and luxury super-cars. In terms of the forming behaviour of high and ultra-high strength aluminium alloys the production process is still restricted. Without the invention of new production technologies it is a challenge to meet the requirements of the design trend (increasingly complexity of the geometries of sheet metal components).The range of aluminium applications can be extended by adapted thermal forming processes, such as, for example, the *warm-forming* process. Figure 2 demonstrates a typical process route of the *warm-forming* process for high-strength aluminium alloys.

Right before the actual forming process, the blank is heated up to 180 degree Celsius via contact heating to achieve a better formability of the aluminium alloys. After this, the blank is formed and cut in the forming unit, which is also heated above 180 degree Celsius. Due to the high strength after ageing of approximately 600MPa and a residual elongation of around 12% the 7000 aluminium alloy is applicable for crash components like *exempli gratia* side impact bars. On the basis of the wide range of applications for 7000 alloys and the warm-forming process described for low-cost mass production, it might be possible to replace steel crash components by high strength aluminium alloys in order to use the lightweight design potential and thus, to save weight.

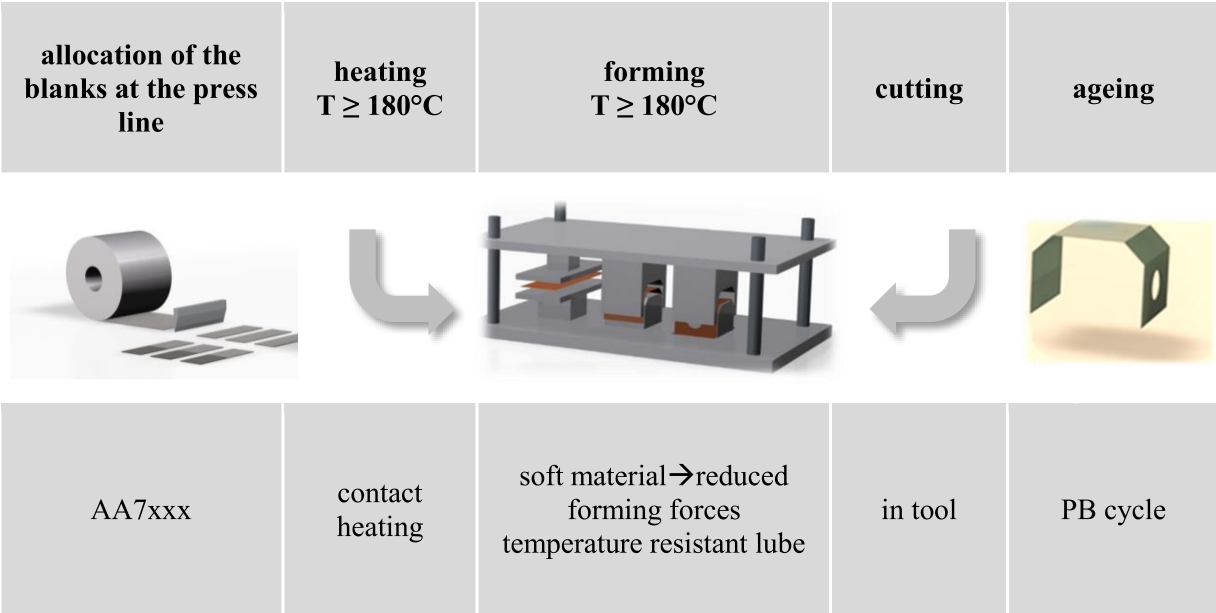

Figure 2. Warm-forming process route

2. Experimental

2.1. Materials

In this study aluminium alloys with the designation EN AW-6082, EN AW-7021 and EN AW-7075 were used and benchmarked against each other. In addition, a press hardening steel was taken for comparison and to demonstrate the lightweight design potential of each material. Table 1 illustrates the composition of tested materials.

Table 1. Chemical composition of used material

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
AA7075	0,05	0,12	1,53	0,01	2,65	0,18	0,01	5,86	0,05
AA7021	0,25	0,40	0,16	0,10	2,10	0,05	6,80	6,00	0,10
AA6082	1,30	0,50	0,25	1,00	1,20	0,25	-	0,20	0,10

	C	Si	Mn	P	S	Al	Cr	Ti+Nb	B
phs	0,35	0,50	2,00	0,02	0,005	0,10	0,50	0,10	0,005

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2.2. Mechanical behaviour

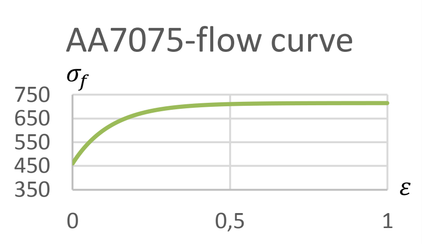
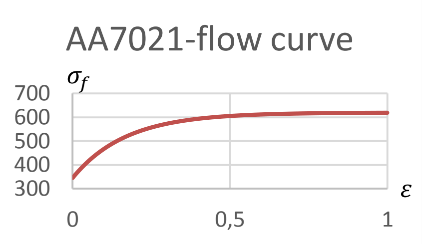
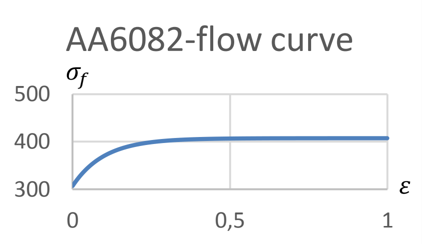
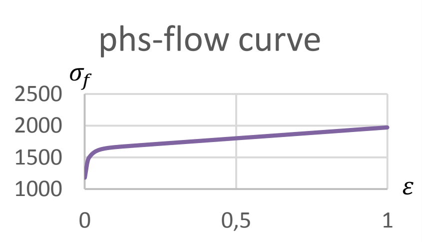
The tensile test is standardized according to DIN EN ISO 6892 [5] and is for the purpose of evaluating the mechanical behaviour of metallic materials subjected to a uniaxial tensile force. The tensile testing specimens were taken from a warm-formed crash beam (see figure 2 for the warm-forming process route) to consider any effects of material ageing. During testing the applied force versus length variation is measured with a specific sampling rate. For comparison table 2 shows the typical mechanical properties which are important for further investigations. The aluminium flow curves, which are used for the *FEM* simulation, are extrapolated to a forming limit of $\varepsilon = 1$ using Voce law [7] 'equation (1)'. The flow curve used for the press hardening steel (phs) material is extrapolated using the Hollomon law [8] 'equation (2)'.

$$k_f = b - (b - a) \times e^{-m \times \varepsilon} \tag{1}$$

$$k_f = C_0 \varepsilon^n \dot{\varepsilon}^m \tag{2}$$

$b = steady\ state\ stress$ $C_0 = material\ constant$
$a = variable\ for\ the\ onset\ of\ yielding$ $n = strain\ hardening\ coefficient$
$m = strain\ rate\ sensitivity\ parameter$

Table 2. Mechanical behaviour of the material used

	σ_f $[MPa]$	UTS $[MPa]$	e [%]	flow curve
AA7075	460	540	12	
AA7021	360	420	5	
AA6082	260	310	6	
phs	1200	1900	5	

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2.3. Laboratory

The experiment is performed by using a drop tower test (figure 3). In this test setup the side impact beam is welded on adapter plates and screwed to hinge joints. The distance between the hinge joints is $w = 1370mm$ and the distance of the beam to the ground is $l = 275mm$.

Drop tower test

Throughout the test a mass with 40,58kg is released from a height (h_0) of one metre in order to crash into the reference side impact beam made out of AA7075. The velocity of the mass (v_0) is calculated using the principle of conservation of energy as given in ‘equation (3)’.

$$v_0 = \sqrt{2gh_0} \tag{3}$$

During the crash a set of various parameters (e.g. reaction forces, deformations, deceleration time) are measured and analysed afterwards.

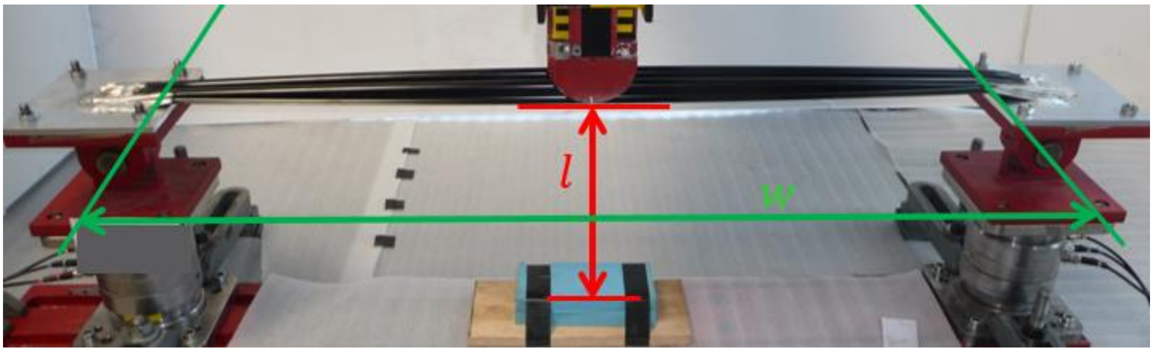

Figure 3. Test setup drop tower test (front view)

3. Simulation and optimisation of a crash-beam

3.1. Modelling and crash characteristics

Analogues to the experiment a model of the drop test is designed and implemented into the FEM simulation software. To minimise the computational time the complexity of the hinge joint is simplified (see figure 4). Thus, the hinge joint is modelled with a rigid body and one degree of freedom around the z-axis. The adapter plate, hinge joint and some elements of the side impact beam (uniform shell elements) are fixed together (analogous to figure 3). In addition, the initial velocity of the impactor (uniform shell elements), also defined as a rigid body, is set to $v_0 = \sim 4430 \frac{mm}{s}$.

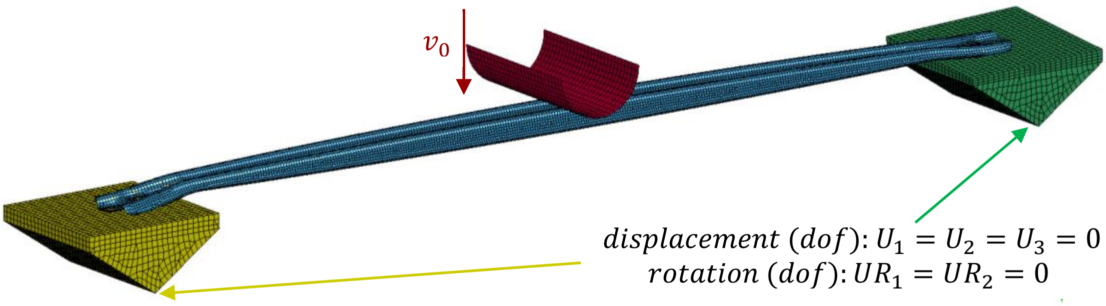

Figure 4. Simulation model of the drop tower test

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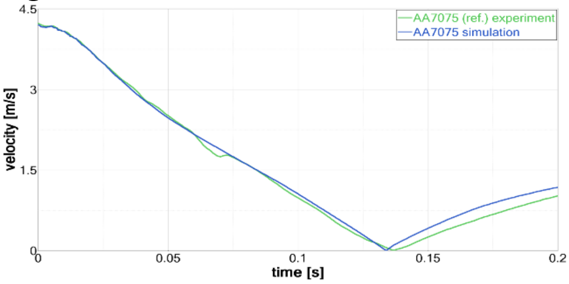
3.2. FE-Analysis (FEA) of the reference crash-beam made out of AA7075

After modelling the drop test the necessary material parameters (e.g. elastic-plastic material behaviour) and the thickness of the reference beam 1,6mm are implemented into the FE-Modell. Figure 5 illustrates a comparison of the predicted and the real deflection of the reference side impact protection beam. The results of the *FEM* simulation (Figure 6 and Figure 7) seem to be in good agreement with the experimental results.

Figure 5. Validation of the simulation model compared to the experiment (reference crash-beam)



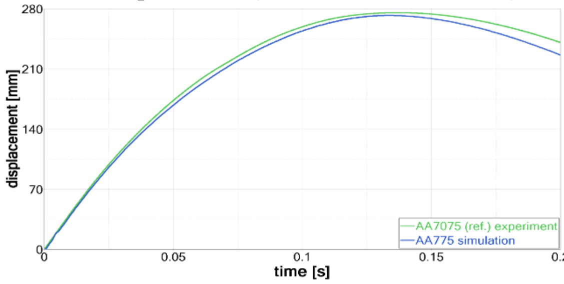


Figure 6. Predicted and real deflection of the side impact protection beam during deformation.

Figure 7. Predicted and real velocity of the side impact protection beam during deformation.

3.3. Sizing optimisation by thickness adjustment for various materials

After the validation of the FE-Model with the experiment of the reference side impact beam (figure 6 and figure 7) the material parameters, as described in table 2, are varied and the thicknesses are adjusted by sizing optimisation to reach the same performance indicated by the reference side impact beam. To avoid too many simulation loops a static equivalent load is adopted to carry out a sizing optimisation with a rough estimation of the thickness values. The aim of this numerical simulation is to adapt the thicknesses of the side impact beam to receive the same performance as indicated by the reference beam. To achieve the same deflection of each other an object function, like min/ max sheet thicknesses and a displacement constraint of 275mm, was configured.

According to the pre-defined thickness values of the optimisation results, the precision adjustment is made by explicit finite element analysis with an elastic-plastic material model using the flow curves given in table 2.

3.4. Simulation based comparison of various materials with same crash performance

The resulting deflections and velocities using different materials for the side impact protection beam are shown in figure 8 and figure 9. The maximum deflection of approximately 275mm is reached after 0.14seconds for all tested beams. It can be recognised that the side impact beam made out of AA7075 has a much smaller permanent plastic deformation than the other tested materials (figure 8). This is due to the relatively high residual fracture elongation which is approximately 12% (table 2).

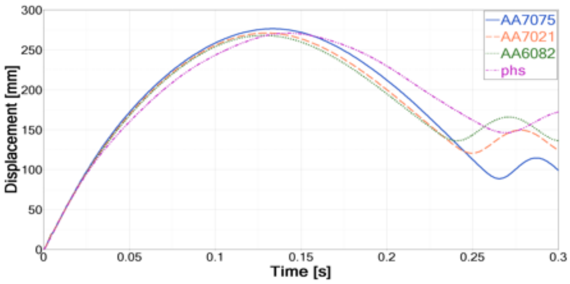


Figure 8. Deflection curves of side impact protection beams using different materials in the simulation.

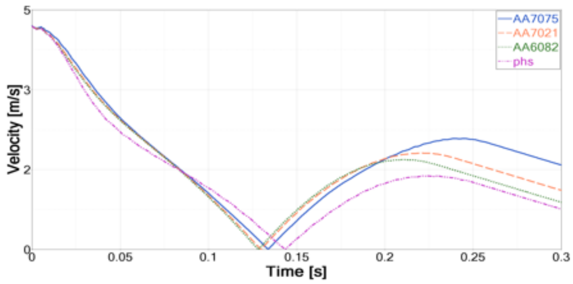


Figure 9. Velocity curves of side impact protection beams using different materials in the simulation.

3.5. Lightweight design potential of ultra-high strength aluminium alloys

After the adjustments of the thicknesses of the side impact protection beams (indicating an equivalent crash performance) using individual materials the weight of all beams are compared against the reference beam made out of AA7075. Figure 10 indicates the weight saving potential of high and ultra-high strength aluminium alloys. It can be recognised that the weight saving potential of a side impact beam made out of AA7075 is over 40%, if compared with a press hardening steel material. This corresponds to weight reduction of about 340g.

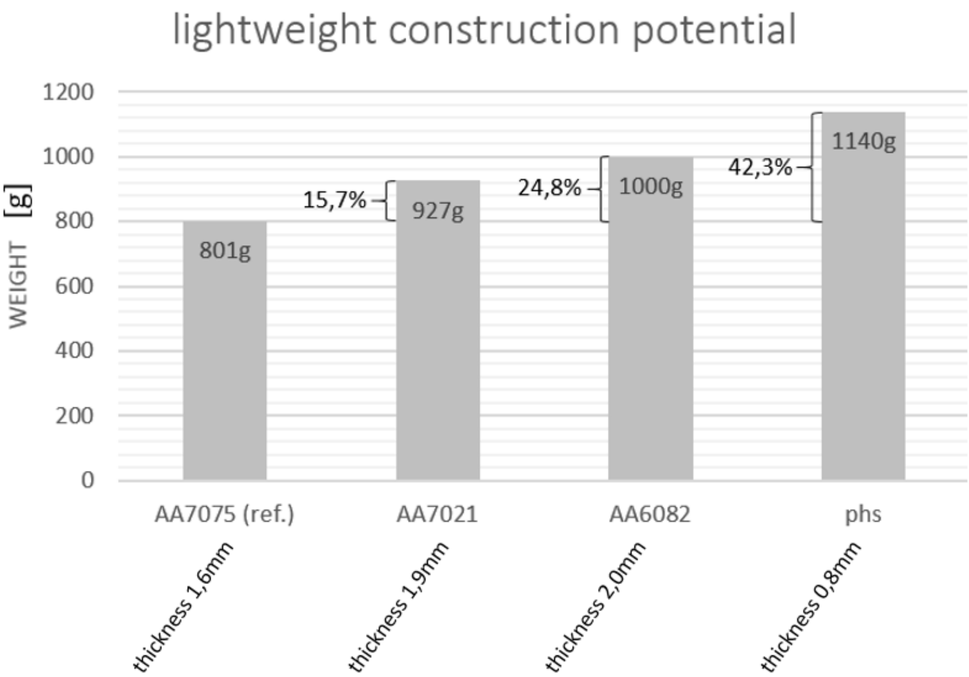


Figure 10. Lightweight design potential of crash beams using different materials

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4. Conclusion

The FEA simulation results of drop tests using side impact protection beam geometries are shown to be in good agreement with corresponding experimental results. The simulation model is validated and can be used for further investigations with various materials. By means of sizing optimisation the thicknesses of the different side impact beams, including various materials such as AA7021, AA6082 and a press hardening steel grade, can be adjusted to obtain equivalent crash performances. The precision adjustment (calibration) is made by explicit finite element analysis with an elastic-plastic material model with the various flow curves from table 2. The weight comparison shows that by using an ultra-high strength aluminium alloy, such as the AA7075 instead of a press hardening steel material, a weight saving of more than 40% can be achieved. Thus, to exploit the entire light weight potential of a crash relevant component it is essential to adjust any geometry dependent on the specific material behaviour.

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