

Characterization and Modelling of Sheet Material with Graded Strength for More Accurate Finite Element Analysis

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Abstract. Many sheet materials do not exhibit constant properties over the sheet thickness. On the one hand, this can be caused by a rolling process with a pass reduction of 1-2%, the so-called skin pass rolling. This is mainly used for deep drawing steel grades to eliminate the pronounced yield strength of the base material. Another possibility is abrasive blasting or shot peening of sheet metal. This causes plastic deformation of the sheet surface and material strengthening. The grading can be used to locally strengthen components or locally adapt the roughness. Since many production processes today are designed numerically, the mapping of such a grading is necessary but currently not implemented in FE code. The aim of this research is, to correlate the material hardness to a plastic pre-strain with a newly developed characterization method. For this purpose, graded material properties are generated by means of abrasive blasting as an example process. The resulting locally varying work hardening over the sheet thickness is further integrated in finite element analysis by the assignment of a starting condition of a 2d-shell element formulation. With this approach, it is possible to map the graded material properties easily in FE simulations with a very good accuracy.

Introduction

Modern processes require the use of innovative tools and technologies for the production of semi-finished products or tool inserts to meet the increasing requirements. A commonly used methodology for the adjustment of material and tool properties is the surface treatment. In this field, there are different methods. Chemical surface treatment can be a coating for example obtained by physical vapour deposition (PVD) or the carburization or exposing to nitrogen. Thermal surface treatment is conventionally done by using a laser beam. With this method, complex heat treatment patterns with varying energy density are possible. A third group of surface treatment methods are the mechanical processes.

Mechanical surface treatment is used for applying a defined texture or for work harden the material. In the following, the focus is on these surface treatment processes. Walzer and Liewald [1] used embossing patterns to influence the mechanical properties of high-strength steel DP600. With this method, an increase of the yield stress up to 40 % in comparison to the original material could be achieved. In contrast to this, the ultimate elongation decreased by over 50 %. Bennedetti et al. [2] used a shot peening process for improving the bending fatigue behavior of an AA6082 alloy. The shot peening resulted in a hardness increase of the boundary layer with a thickness of 0.8 mm. Zhuang and Halford [3] quantified the influence of a shot peening process with 40 % cold work on the surface of the treated material. Another possibility for surface hardening is the skin pass rolling. In this process a pass reduction under 2 % is applied [4]. The plastic deformation is thus mainly limited to the surfaces of the sheet metal [5]. It is commonly used for deep drawing steel grades to eliminate the pronounced yield point [6] of these alloys. The Lüders bands resulting from this pronounced yield point become visible through stretcher strain marks on the formed component and are therefore not desirable for outer body components [7]. There is also research for aluminum on how to reduce the pronounced yield point, which is present for Al5xxx alloys. Besides of grain size control, annealing and quenching strategies [8], slight deformation can reduce the pronounced yield point [9].

According to the state of the art, there are various processes to apply discontinuous material properties over the sheet thickness direction. Locally applied strength increase can produce improved

application behavior, especially for complicated components, by providing additional strength in relevant areas. Especially areas that are only stretched to a limited extent during the forming process can benefit from this. Such adaptations influence the numerical process design and therefore have to be considered for a high prediction quality. Thus, it is necessary to characterize this hardening increase and to map it in a mathematical model.

It is state of the art, to correlate the hardening increase with plastic deformation, when analyzing a forming process. Sundararajan and Tirupataiah [10] defined a correlation between hardness and flow stress by analyzing indentation tests with a round indentation geometry and heuristic formulations for the strain distribution. The identified graded material properties can be implemented in the simulation in many ways. One possibility is the mapping of the texture properties [11] or the microstructure [12]. A common disadvantage of all models is their complexity of these models in the parameter identification and the integration in FE code. Thus, the aim of this research is to develop a functional and robust relationship between hardness increase and plastic deformation based on experimental tests. Within the framework of this paper's experiments, the grading is realized in laboratory scale by using abrasive blasting. Further, the graded material is characterized with respect to the hardness distribution over the sheet thickness. This information is then implemented in FE code for a numerical modelling of a graded material. A validation of the methodology is done by comparing the numerical results with experimental data.

Methodology and Procedure

The investigations can be categorized into three parts. The development of a functional relationship between hardness increase and plastic deformation depicted in Fig. 1, the adjusting of graded material properties shown in Fig. 2 and the mapping of the graded material properties, which are followed by a final validation step of the proposed methodology presented in Fig. 3. The used material is the aluminum AA5182 with 2.0 mm sheet thickness. For the development of a functional relationship that allows an assignment of the resulting hardness increase to a plastic strain value, upsetting specimens are cut out of the sheet material by micro electrical discharge machine SARIX SX-200-HPM (Sarix SA, Sant'Antonino, Switzerland). The specimen geometry is 1.5 mm in diameter and a height of 2.0 mm. These specimens are further compressed to four target heights. These tests are carried out on a universal testing machine Z10 (Zwick GmbH Co. KG, Ulm, Germany) according to DIN 50106. For a reduction of the friction influence, the extrusion oil Dionol ST V 1725-1 is used as lubricant. The testing velocity is set to 1 mm/min. After upsetting, the specimens are cut in half perpendicular to the rotational axis and polished for micro hardness measurements with a Fischerscope HM2000 (Helmut Fischer GmbH, Sindelfingen, Germany) and a testing force of 50.0 mN. An array of 8 to 8 measurement points is applied over the cross section. With the identified Vickers hardness of the upsetting specimen and the initial hardness of the material, a functional relationship between hardness increase and plastic strain is identified, see Fig. 1.

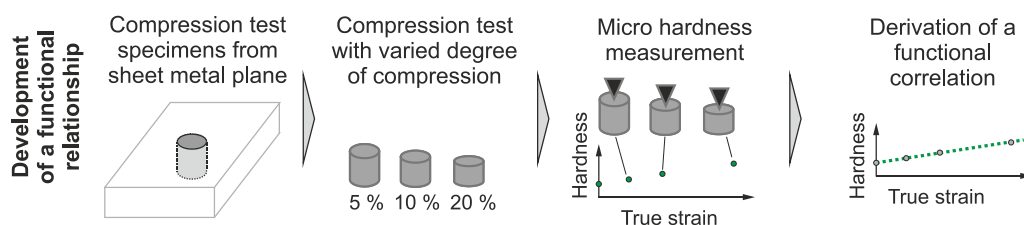


Figure 1. Methodology for the identification of the functional correlation between hardness and true strain

For adjusting the graded material properties over the sheet thickness as a sample process for this investigation, the original sheet material is abrasive blasted for a surface strengthening with a PEENMATIC 770S (iepcos AG, Leuggern, Switzerland). The parameters for the abrasive blasting are 2 bar preacceleration, 4 bar blasting pressure, and 30 mm distance between the sheet material and the nozzle. The used abrasive medium is MS4090A. The treated material is then prepared for micro

hardness measurement with the above-mentioned device. The measurement lines are oriented in sheet thickness direction with 50 measurement points per line. The resulting hardness profile can be translated to a plastic strain profile over the sheet thickness direction with the identified functional relation as depicted in Fig. 2.

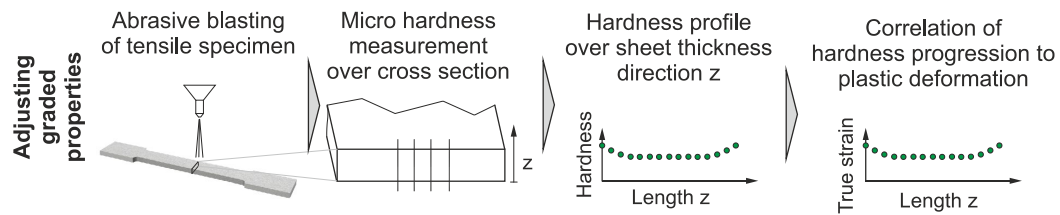


Figure 2. Methodology for adjusting and characterization of graded material properties

For an implementation of the characterized graded material properties in FE code, a conventional 2d-shell formulation and the material model Yld2000-2d [13] is used. The material parameters are characterized by tensile tests and hydraulic bulge tests in the initial state of the sheet, and not in the abrasive blasted condition. For statistical purpose three tests are carried out in each condition ($n = 3$). Therefore, uniaxial tensile tests in the three directions, 0° , 45° and 90° are carried out according to DIN EN ISO 6892-1. Additionally hydraulic bulge tests According to DIN EN ISO 16808 are performed. The tensile tests are performed with an universal testing machine Z100 (Zwick GmbH Co. KG, Ulm, Germany) at a straining velocity of 0.667 %/s. Strain measurement is applied by a 3D-DIC system ARAMIS (GOM GmbH, Braunschweig, Germany). For the numerical simulations, the previously identified pre-strain on the sheet surface is implemented by defining initial conditions for the integration points of the shell formulation. For a higher resolution accuracy, 21 integration points are used instead of the commonly used five integration points. The validation of the adjusted model in LS Dyna (Livermore Software technology, Livermore, USA) is done by analyzing an one-element test with tensile loading. The resulting numerical flow curves are compared to the flow curves out of experimental tensile tests with abrasive blasted material as well as in the untreated condition with isotropic properties over the sheet thickness direction. Further, the resulting differences between the experimental and the numerical flow curves are discussed. These tensile tests with the abrasive blasted material are only necessary for the validation but not used for the material modelling.

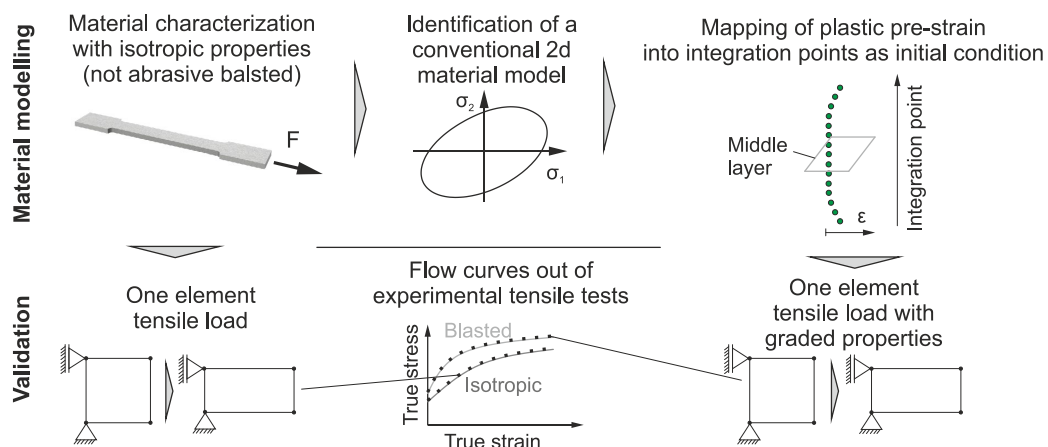


Figure 3. Methodology for the implementation and validation of graded material properties in FE simulation

Functional Relationship Between Plastic Strain and Increase in Hardness

In order to achieve the goal of a functional relationship between Vickers hardness increase and plastic strain, compression tests with a miniaturized specimen geometry are performed. The specimens are cut out of the 2.0 mm AA5182 sheet material and compressed to different heights. The resulting hardness of the upsetting specimens is then characterized by micro hardness measurements.

A comparison with the hardness of the initial sheet material allows inferences about the increase in hardness. This rise in hardness can be directly assigned to the resulting plastic deformation of the upsetting specimens, respectively. The result is an analytic function between hardness increase and plastic strain. The parameters of the upsetting specimens after testing with the resulting specimen heights, the original height and the resulting true strain in compression direction after unloading can be seen in Table 1. Additional, the hardness measurements of the cross section of the upsetting specimens are given with the corresponding standard deviation (SD). The initial hardness of the material is 88.2 HV0.005 with a standard deviation of 4.8 HV0.005. It is visible, that the hardness increase is not linear but comparable to the work hardening of metals as seen in the measurement points in Fig. 4.

Table 1. Resulting specimen height and corresponding true strain and Vickers hardness after upsetting

Height before upsetting	Height after deformation	True strain	Micro hardness
1.99 mm	-	0	88.2 ± 4.8 HV0.005
1.99 mm	1.92 mm	0.033	106.6 ± 4.9 HV0.005
1.99 mm	1.80 mm	0.088	124.8 ± 4.9 HV0.005
1.99 mm	1.73 mm	0.118	128.6 ± 5.0 HV0.005
1.99 mm	1.57 mm	0.188	138.4 ± 6.1 HV0.005

With this information, a functional correlation between hardness increase and true plastic strain can be derived. The resulting hardness value HV is calculated by a power law according to the approximation of Ludwik [14]:

$$HV = A + (B \cdot \epsilon)^C \quad (1)$$

With this formulation, all experimental measured hardness points can be approximated with good accuracy, see Fig. 4. The root mean squared error of the approximation is 9.5 MPa. The resulting parameters for Equation (1) are $A = 88.2$, $B = 9460.673$ and $C = 0.526$. Due to the occurrence of inhomogeneous strain in the cross section of the upsetting specimen as discussed in [15], a higher compression level would lead to barreling of the specimen. Inhomogeneities in the strain and thus also in the resulting hardness distribution are the consequence. This can be seen in the rising standard deviation of the micro hardness measurements from 0 to 0.188 true strain with 4.8 HV0.005 to 6.1 HV0.005.

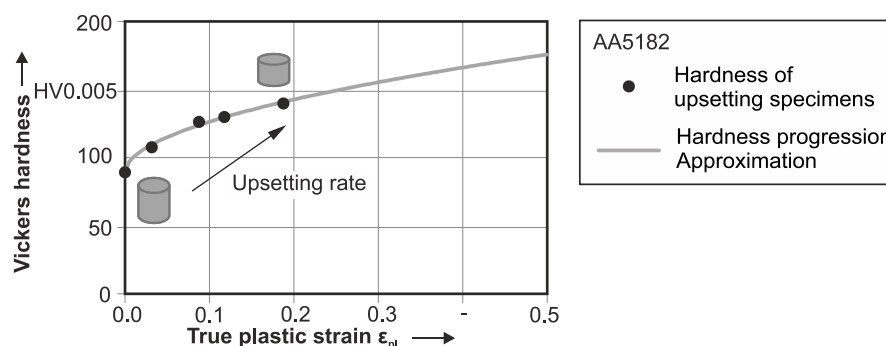


Figure 4. Correlation between Vickers hardness increase and true plastic strain for AA5182

The presented methodology can be adapted to every metallic material. However, upsetting specimen with a height to diameter ratio above one have to be fabricated. Thus, the methodology is limited to a certain sheet thickness that allows the fabrication. Additional, the friction has to be controlled in the upsetting process and barreling has to be prevented. Having this in mind, the

functional relationship can improve the analysis of formed parts especially for a quantification of the remaining formability in incremental or multi-stage forming processes.

Influence of Abrasive Blasting on Material Properties

For the adjustment of graded material properties, the AA5182 sheet material is abrasive blasted for surface strengthening of the material on both sides equally. Afterwards, tensile test specimens are cut out of the sheet material. The tactile measured sheet thickness of the blasted material is with 2.03 mm on a higher level than in the initial state (1.99 mm). Thus, it has to be proven, that there is no adhesion of the blasting material. The weight of the material is measured before and after the abrasive blasting. It turns out that a weight loss of 0.02 g results from the blasting process. Due to the identified mass and thus volume constancy, a higher sheet thickness can solely be caused by an increase in the surface roughness. This would lead to a higher distance between the peaks on both sides and thus to higher values in a tactile measurement. The resulting surface topography of the initial state and the abrasive blasted condition are shown in Fig. 5. For the abrasive blasted condition, a difference of up to 40 μm is visible. The measured roughness is further used for a cross section calculation of the abrasive blasted tensile specimen. Due to the volume constancy, the load bearing thickness can be given with 1.95 mm in the abrasive blasted condition.

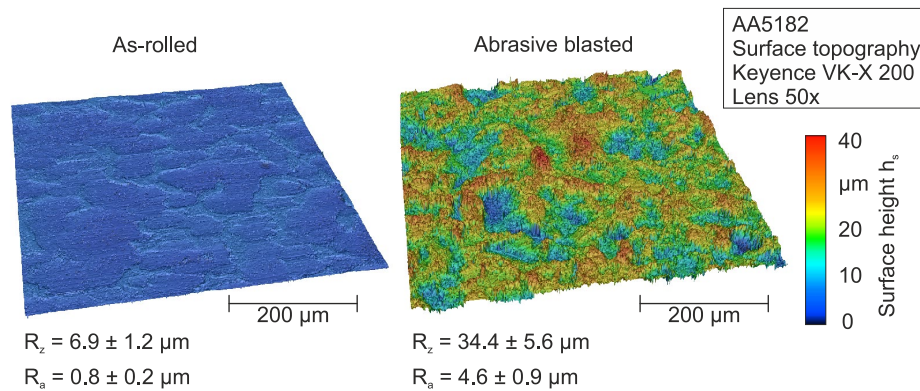


Figure 5. Surface topography of untreated and abrasive blasted aluminum AA5182

The resulting flow curves obtained from uniaxial tensile tests performed with abrasive blasted and as-rolled material are shown in Fig. 6. For the subsequent material modeling according to the proposed methodology in [13], tests are also carried out in 45° and 90° to the rolling direction in the untreated condition. Due to the surface hardening, three findings can be discussed:

- The yield strength is not measurably influenced by the abrasive blasting
- The Lüders strain is not present
- An hardening increase of about 20 MPa or 10 % is visible

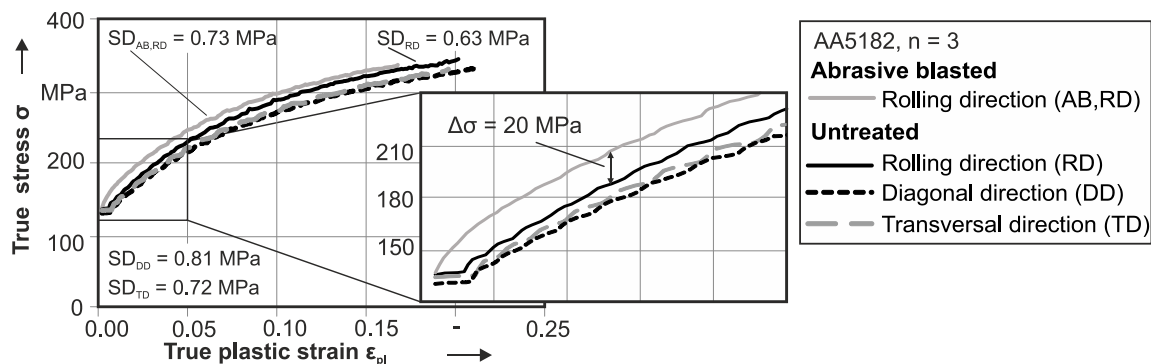


Figure 6. Respective average of three ($n = 3$) flow curves of untreated and abrasive blasted aluminum AA5182

For both conditions, the yield strength is on a comparable level. The yield strength of the abrasive blasted material is 133.8 MPa and for the as-rolled state, a yield strength of 135.5 MPa is characterized. As mentioned before, slight plastic deformation can reduce the Lüders strain for 5xxx aluminum [9]. In this case, the slight plastic deformation is applied by a surface treatment with an abrasive blasting process. Due to the absence of the Lüders strain, the material hardening starts with the onset of plastic deformation. This results in a translation of the flow curve in negative x direction and a more pronounced hardening behavior of the material.

In a following step, the hardness profile in sheet thickness direction is characterized by micro hardness measurements, see Fig. 7 on the left. Due to the symmetric hardness profile, the hardness is shown from the surface to the center of the material. On the surface the hardness is 169.3 HV0.005. Moving towards the middle layer, the hardness decreases significant until 0.3 mm below the surface. The abrasive blasting process does almost not affect the deeper layers. With Equation 1, the pre-strain level in the abrasive blasted sheet material can be calculated out of the measured hardness, see Fig. 7 on the right. As a result, the plastic pre-strain on the surface is given with a true strain of 0.45. Again, above a distance over 0.3 mm to the surface the pre-strain is almost zero and the influenced zone of the abrasive blasting process can be determined in the area of 0.0 mm to 0.3 mm below the surface.

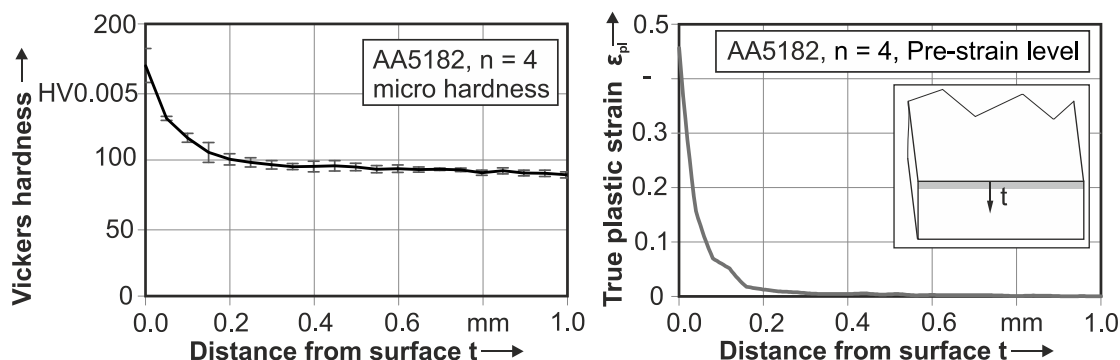


Figure 7. Hardness progression over the sheet thickness direction of abrasive blasted AA5182 (left) and corresponding pre-strain level in thickness direction (right)

It can be concluded that abrasive blasting is a good opportunity to achieve a higher flow stress, especially at low strain levels. Thus, this surface treatment could be used to locally increase the hardness in deep drawn parts especially in areas with a low plastic deformation. For the AA5182, the abrasive blasting additionally significantly reduces the Lüders strain. Moreover, the correlation of plastic pre-strain to the hardness offers the possibility to analyze the mechanical properties of formed components. For this purpose, it is necessary to characterize a cross-section of the component over its entire surface with micro hardness measurement points. Subsequently, a profile of the locally plastic strain can be derived from this hardness profile. Further, the pre-strain information can easily be transferred into a material model.

Modelling of Graded Material Properties

For an implementation of the characterized pre-strain in sheet thickness direction in FE code, a conventional 2d-shell formulation (fully integrated) is used. The material is modelled with the material model Yld2000-2d [13] and the hardening law Hockett-Sherby. The material parameters are characterized by tensile tests and hydraulic bulge tests in the untreated, and not in the abrasive blasted condition. This makes it a simple and applicable method for a wide range of forming simulations. The necessary testing effort is on a constant level and no further tests for the material model are needed. The resulting constitutive parameters of the yield locus are given in Table 2.

Table 2. Resulting constitutive parameters for the model Yld2000-2d

α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	m
0.9221	1.0804	1.1139	1.0664	1.0573	1.1650	1.0528	1.0528	8

The identified pre-strain in sheet thickness direction is implemented by defining initial conditions for the 21 integration points of the shell formulation. With the card “INITIAL_STRESS_SHELL” it is possible to define an initial value of the effective plastic strain for each integration point of a shell element. The validation of the adapted model is done by analyzing an one-element test with tensile loading. The resulting numerical flow curve is compared to the flow curve out of experimental tensile tests with abrasive blasted material, see Fig. 8. Further, the numerical flow curve of the untreated material state is depicted. Due to the absence of any failure criterion in the simulations, the numerically calculated flow curves reach higher strain levels than the experimental flow curve.

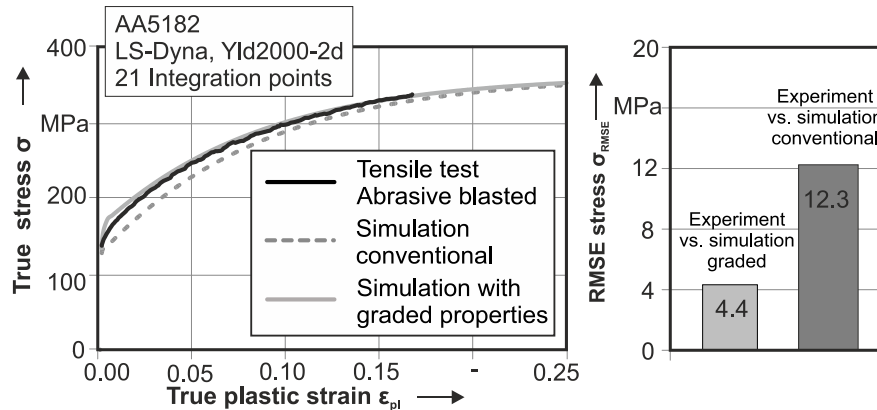


Figure 8. Numerical and experimental flow curves of graded material and numerical flow curve of the untreated state of AA5182

A different flow stress from the onset of yielding to a true strain of 0.03 between the model and the experimental curve is visible. This difference can be referred to the assumption of the correlation of the strain and the hardness with the model of Ludwik. The hardness of the sheet surface is significant higher than the measurement range of the upsetting specimens. Thus, inaccuracies of the extrapolation of the hardness progression could lead to an inaccurate pre-strain prognosis. In this context, further investigation with the scope of a better mapping accuracy of the functional correlation between hardness and true strain should be done. At a higher plastic strain, the accuracy of the model is on an acceptable level. In the as-rolled condition, a difference between the numerical calculated flow stress and the experimental progression of about 1.0 MPa is present due to the Portevin-Le Chatelier effect of the AA5182 material. This maximal difference of 1.0 MPa between experiment and simulation of the abrasive blasted condition is visible at 0.05 true strain onwards. Another aspect that has to be mentioned is the highly simplification of the graded material behavior with the integration point method. The potentially non-uniform material flow across the sheet thickness as a result of the grading is not taken into account in the starting condition of the integration points. Nevertheless, it is a simple and easy to apply method for the implementation of graded material properties in FE simulations.

Conclusions

The implementation of graded material properties in FE code is a forward-looking method for the improvement of the mapping accuracy in numerical simulations. Hence, an experimental approach for a correlation between hardness and plastic strain has been developed. This method can be used for the analysis of multi staged drawing operations, bulk metal forming processes for the identification of the remaining formability or processes with graded sheet materials. In this context, the process of abrasive blasting leads to an increase of the material hardness of more than 90 % for AA5182. With the functional relationship between hardness and plastic deformation, a pre-strain on the surface of 0.45 has been identified. The modelling of this graded material without time-consuming subroutines or sandwich sheets with challenging contact conditions was done with a 2d-shell element formulation. The material characterization is carried out exclusively with untreated material. The simplification with 2d-shell elements and an increased number of integration points leads to the

limitation of the material flow only in the loading direction. A possible inhomogeneous material flow over the sheet thickness direction is not considered. Nevertheless, the simplified integration method of graded material properties leads to a good mapping accuracy, without any consideration of the abrasive blasted material in the material model itself.

The key findings are:

- An experimental approach for a correlation between hardness and plastic strain is possible with upsetting specimen and hardness characterization
- Modelling of graded material properties without time-consuming subroutines or sandwich sheets with challenging contact conditions with 2d-shell elements.

Future work will focus on the implementation in a 3d material model with solid elements and on the material flow in sheet thickness direction of the graded material.

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