Modifying mechanical properties of sheet metal materials by work hardening mechanisms induced by selective embossing

HEINZELMANN Pascal[1,a *], BRIESENICK David[1,b] and LIEWALD Mathias[1,c]

[1]Institute for Metal Forming Technology, University of Stuttgart, Holzgartenstraße 17, 70174 Stuttgart, Germany

[a]pascal.heinzelmann@ifu.uni-stuttgart.de, [b]david.briesenick@ifu.uni-stuttgart.de, [c]mathias.liewald@ifu.uni-stuttgart.de

Keywords: Embossing, High Strength Steel, Dual-Phase Steel, Tensile Test

Abstract. The selective modification of mechanical properties of sheet metal materials poses a promising approach for realizing lightweight designs, especially when achieved without additional material input. One method for locally adapting the mechanical properties of sheet metal components is to specifically induce work hardening into the sheet metal material by near-surface embossing. Previous studies have already shown this effect for the sheet metal materials DP500 and DP600. The present paper verifies these findings for embossed high-strength steel DP800 considering different blank thicknesses and embossing depths. During experimental investigations, tensile and bending specimens of different sheet thicknesses were manufactured with definite embossing patterns and subsequently tested with regard to their mechanical properties. To verify the true embossing depth, the specimens were measured optically. As a result of this contribution, it was found that the material properties of high-strength sheet metal materials can be modified for lightweight construction and crash properties by selective embossing. Parameter constellations for increasing the yield strength were found for the materials investigated.

Introduction

Today, automotive traffic accounts for a large amount of global greenhouse gas emissions, which is why both the EU and the United States of America are imposing increasingly stringent restrictions regarding the CO_2 output from motor vehicles [1]. Automotive manufacturers must take this into account during the vehicle development phase, not only concerning driving concepts but also the final vehicle weight. But weight optimization of vehicles is not only a crucial development issue in terms of reducing greenhouse gases but also concerns the availability of metallic raw materials [2]. This is exacerbated in the current situation by Russia's invasion of Ukraine and the tense markets associated with it [3], and the increased costs in the energy sector [4]. Against this background, novel approaches to manufacturing lightweight vehicle structures can significantly contribute to overcoming these challenges.

Lightweight constructions of car bodies are in most cases based on weight-optimized designs or the alloy-specific adaptation of the sheet metal materials used. In addition, such metallic lightweight structures can also be realized by modifying the component properties via selective work hardening during their forming [5]. In this context, Namoco et al. carried out experiments with aluminium alloys (A6061-T4 and A5052-H34) [6], which focussed on the targeted introduction of work hardening into the sheet metal material using both embossing and reforming

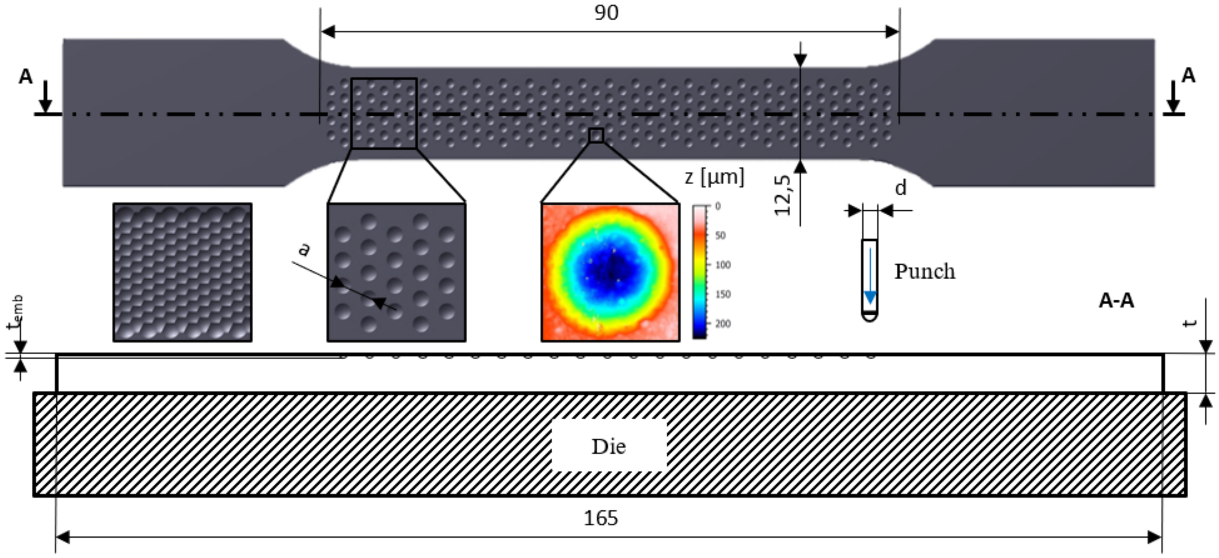

Fig. 1. Schematic of the embossing process with exemplary embossing arrangements.

processes. The results were evaluated based on the obtained values of yield strength, tensile strength and total elongation. Abe et al. examined the formability of embossed deep-drawn components and stated beneficial properties changes due to the embossing process carried out [7]. Walzer et al. investigated DP600 blanks and found that the incorporation of near-surface embossing increased the tensile strength of the sheet metal material [8]. Briesenick et al. carried out bending tests with DP500 blanks embossed in different ways and this way the maximum bending force required was increased by 75 % [9].

Based on these results, the investigations presented in this paper were intended to determine an optimum embossing geometry with regard to the highest possible strength increase of sheet metal structures. The embossing geometry here included the embossing pattern and the embossing depth. Furthermore, the property modifications attainable were evaluated using the example of the two sheet metal materials DP600 and DP800 having different initial yield strengths.

Experimental Method

Previous research work in the field of property modification of sheet materials by means of targeted application of work hardening has predominantly selected DP600 as test material. Materials with higher strengths, however, have not been investigated so far. Due to the existing results with DP600, which serve as a reference, the sheet metal materials DP600 and DP800 were selected for the investigation objectives presented in this paper. In these investigations, the influence of embossing geometries on changes in the mechanical properties yield strength R_p, and elongation at break A was evaluated. In Table *1* the material properties of the unembossed sheet materials are shown.

Table 1. Material properties of the steel blanks used in the tests carried out.

Material	Yield Strength R_p [MPa]	Elongation at Break A [%]
DP600	345.7	26.5
DP800	561.4	18.2

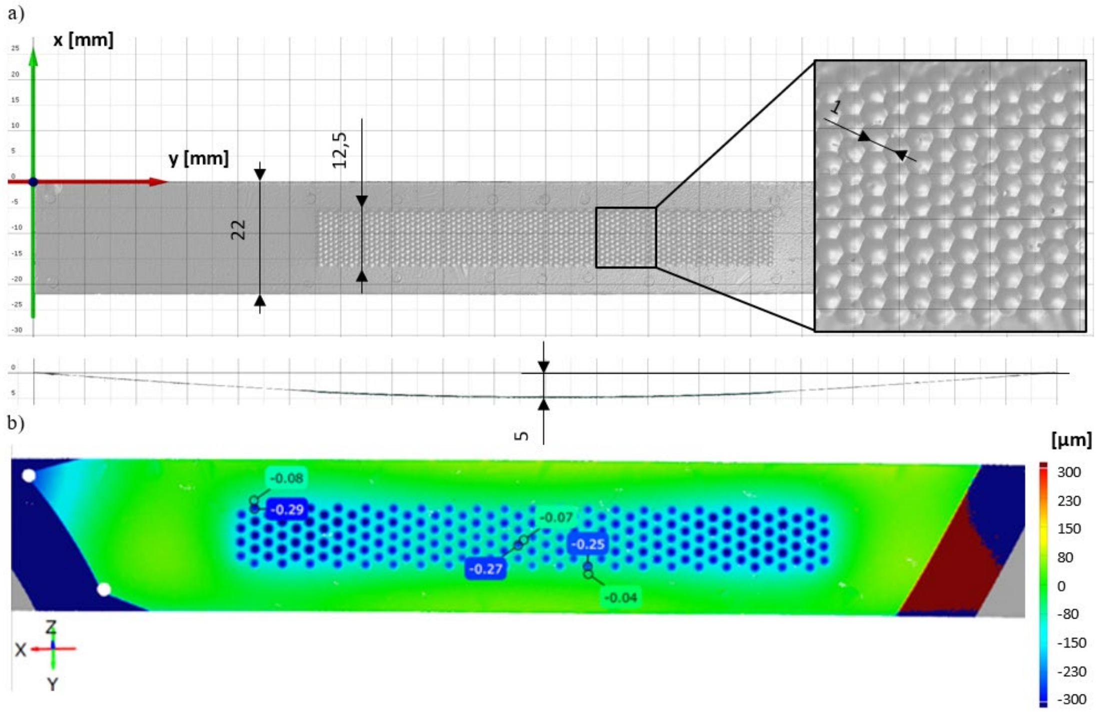

Fig. 2. Measurement of the embossed flat tensile specimens with different embossing geometries.

To evaluate the possible influence of different thicknesses of specimens on the property improvements achievable by means of embossing. The material DP600 was tested with sheet thicknesses *t* of 1.5 mm and 1.77 mm and DP800 was tested with sheet thicknesses of 1.5 mm and 1.85 mm. The different thicknesses were selected due to the availability of the materials used. To examine the mechanical properties changes, tensile tests were performed with embossed and unembossed specimens. The specimen geometry was determined according to DIN EN ISO 6892-1 [12] with form H and a measuring area of 12.5 mm × 50 mm. The embossing patterns to be investigated were applied beyond the measuring area on a surface of 12,5 mm × 90 mm for all specimens, thus ensuring that failure occurred in the measuring area. A hexagonal arrangement was chosen for the embossing patterns, varying the distance *a* between neighbouring embossings by 1 mm, 1,5 mm, and 2 mm as well as the embossing depth t_{emb} by 100 µm and 200 µm. In this respect, Fig. 1 shows an embossed flat tensile specimen with the minimal values *a* of 1 mm and an embossing depth t_{emb} of 100 µm.

A TRUPunch 5000R CNC punching machine was used to emboss the tensile specimen surfaces. This machine can perform up to 1,400 strokes per minute, thus allowing the embossings to be sequentially introduced within relatively short processing times. A modified round punch was used as embossing punch, with the face surface turned into a hemisphere with a diameter *d* of 4 mm. Due to the springback of the sheet metal material, the punch thereby had to penetrate deeper into the material´s surface than the targeted embossing depth. Various test embossing operations were carried out to determine the penetration depth required for this purpose. Furthermore, the embossings were always introduced into the sheet metal material´s surface before cutting out the pre-milled specimen geometry. Subsequently, the embossed sheet metal areas were cut out rectangularly (220 mm × 22 mm) and finally milled into the defined specimen shape to compensate for work-hardening caused by the cut-out. Table *2* lists the manufactured specimen variants in detail. Each variant was manufactured in quadruplicate for the reproducibility of the tensile tests.

Table 2. Specimen designation with details of the material, sheet thickness, embossing distance, and embossing depth.

Specimen Designation	Sheet Metal Material	Sheet Thickness t [mm]	Embossing Distance a [mm]	Embossing Depth t_{emb} [µm]
DP600_T1500_a1000_t100	DP600	1.5	1	100
DP600_T1500_a1500_t100	DP600	1.5	1.5	100
DP600_T1500_a2000_t100	DP600	1.5	2	100
DP600_T1500_a1000_t200	DP600	1.5	1	200
DP600_T1500_a1500_t200	DP600	1.5	1.5	200
DP600_T1500_a2000_t200	DP600	1.5	2	200
DP600_T1770_a1000_t100	DP600	1.77	1	100
DP600_T1770_a1500_t100	DP600	1.77	1.5	100
DP600_T1770_a2000_t100	DP600	1.77	2	100
DP600_T1770_a1000_t200	DP600	1.77	1	200
DP600_T1770_a1500_t200	DP600	1.77	1.5	200
DP600_T1770_a2000_t200	DP600	1.77	2	200
DP800_T1500_a1000_t100	DP800	1.5	1	100
DP800_T1500_a1500_t100	DP800	1.5	1.5	100
DP800_T1500_a2000_t100	DP800	1.5	2	100
DP800_T1500_a1000_t200	DP800	1.5	1	200
DP800_T1500_a1500_t200	DP800	1.5	1.5	200
DP800_T1500_a2000_t200	DP800	1.5	2	200
DP800_T1850_a1000_t100	DP800	1.85	1	100
DP800_T1850_a1500_t100	DP800	1.85	1.5	100
DP800_T1850_a2000_t100	DP800	1.85	2	100
DP800_T1850_a1000_t200	DP800	1.85	1	200
DP800_T1850_a1500_t200	DP800	1.85	1.5	200
DP800_T1850_a2000_t200	DP800	1.85	2	200

To monitor the dimensional accuracy of the produced specimens and their embossings, they were optically measured using a GOM ATOS Compact Scan System, as shown in Fig. 2. Furthermore, the diameters of the embossings on the surface were measured via a Keyence Microscope VHX. Ball segment equations were then used to determine the embossing depths. The Keyence Microscope VHX was used to get fast results to set the right embossing offset. To check all embossing depths over the embossing area the ATOS Compact Scan system was used. Finally, the tensile tests were carried out according to DIN EN ISO 6892-1 [10] using the universal testing machine Roell + Korthaus RKM100.

Results

For assessing the influence of different embossings on the mechanical properties of sheet metal materials, the two characteristic values yield strength R_p and elongation at break A were determined in each of the tensile tests described above. All characteristic values determined in this respect are summarized in Table *3*.

Table 3. Results of the tensile tests.

Experiment	Yield Strength R_p [MPa]	Elongation at Break A [%]
DP600_T1500_a1000_t100	507.35	21.82
DP600_T1500_a1500_t100	500.88	21.95
DP600_T1500_a2000_t100	443.06	22.68
DP600_T1500_a1000_t200	584.34	10.40
DP600_T1500_a1500_t200	545.65	14.48
DP600_T1500_a2000_t200	502.69	19.24
DP600_T1770_a1000_t100	539.41	17.53
DP600_T1770_a1500_t100	486.82	21.23
DP600_T1770_a2000_t100	432.26	24.40
DP600_T1770_a1000_t200	560.92	9.05
DP600_T1770_a1500_t200	528.68	12.67
DP600_T1770_a2000_t200	494.22	17.67
DP800_T1500_a1000_t100	680.81	13.53
DP800_T1500_a1500_t100	655.76	15.44
DP800_T1500_a2000_t100	592.40	16.66
DP800_T1500_a1000_t200	685.00	9.79
DP800_T1500_a1500_t200	661.47	11.81
DP800_T1500_a2000_t200	624.69	14.31
DP800_T1850_a1000_t100	672.87	14.26
DP800_T1850_a1500_t100	649.12	16.69
DP800_T1850_a2000_t100	597.22	17.03
DP800_T1850_a1000_t200	686.07	10.69
DP800_T1850_a1500_t200	673.37	10.88
DP800_T1850_a2000_t200	627.96	13.60

For evaluating these results, the characteristic values achieved must be considered in relation to the respective embossing geometry, i.e., the embossing depth and the embossing distance. Fig. 3 shows these relationships. First, Diagram a) illustrates the yield strengths of those tests performed with specimens having an embossing depth of 100 µm for all test materials and sheet thicknesses investigated. The different embossing distances and respective unembossed reference specimens are shown as coloured bars. Diagram c) shows the same evaluations for the embossing depth of 200 µm. In Fig. 3 b) and d) the evaluation is based on the elongation at break and follows the same scheme then done for the yield strength. The percentage values in the bars of the embossed tests refer to the change in the respective embossing geometry compared to the reference tests of the respective group. For the DP600 material, the increases in yield strength range from 26 % up to 66 %. The range of the DP800 material varies between 5 % and 22 %. When considering the change in elongation at break, a reduction can be observed for all cases. For DP600, this reduction ranges between -66 % and -9 %. For DP800, the reduction occurs in the range of -42 % to -2 %.

An influence of the different plate thicknesses could not be observed for the yield strength. For the elongation at break, a minor influence could be observed.

Considering the influence of the embossing depth on the yield strength, it can be stated that an increase in the embossing depth is accompanied by an increase in the yield strength. This applies more to the lower-strength material DP600 (up to 66 %) than to DP800 (up to 22 %). Thus, some DP600 tests with an embossing depth of 200 µm show similar and partly higher yield strength values than the reference measurements for DP800. An opposite effect can be recognised when considering the influence of the embossing depth on the elongation at break. With an increase in embossing depth, the elongation at break decreases compared to the lower embossing depth. DP600 by up to -66 % and DP800 by up to -45 %. Also, the embossing distance influences the yield strength and the elongation at break. Here, a reduction of the embossing distance leads to an increase in yield strength. This effect is not as high as the effect of the embossing depth, but still considerable. If the yield strength increases due to the reduction of the embossing distance, the elongation at break decreases to a similar extent.

Due to the different patterns, the results of the DP600 material can only be compared with the results of this paper to a limited extent. Qualitatively, it can be said that the results show a similar trend.

Summary

In this paper, the effects of near-surface embossing on yield strength and bearing at fracture were investigated. The dual-phase materials DP600 and DP800 with different plate thicknesses were considered. In general, an increase in the yield strength of the considered DP steel sheets was observed for all tested embossing geometries. In contrast, a reduction was found for the elongation at break for all embossed specimens. The results for the higher-strength material DP800 show property changes due to the introduction of embossing. These changes are overalls smaller in the DP800 material compared to the DP600 material.

When using embossed components, it is therefore important to consider which properties are relevant for the respective application and to what extent the properties should be changed. For this purpose, further research work will be conducted on tests with other materials and embossing geometries. Here, the focus should be when, or in what range, embossing no longer has any influence on higher and highest-strength materials. Moreover, low-strength materials will be considered as well. For a better understanding of the process, additional simulations are needed for providing a more detailed view of the process than just the experimental measurements. Simulations that include the history of the embossing process should also be considered, so the influence of the embossing is also taken into account for further simulative stress analyses. To simulate the whole embossing process, a high computational effort must be made. For faster simulations of embossed parts, the simulation of the processes must be more efficient Possibilities should also be found to transfer the result of the embossing process to simulations of embossed components with little calculation effort.

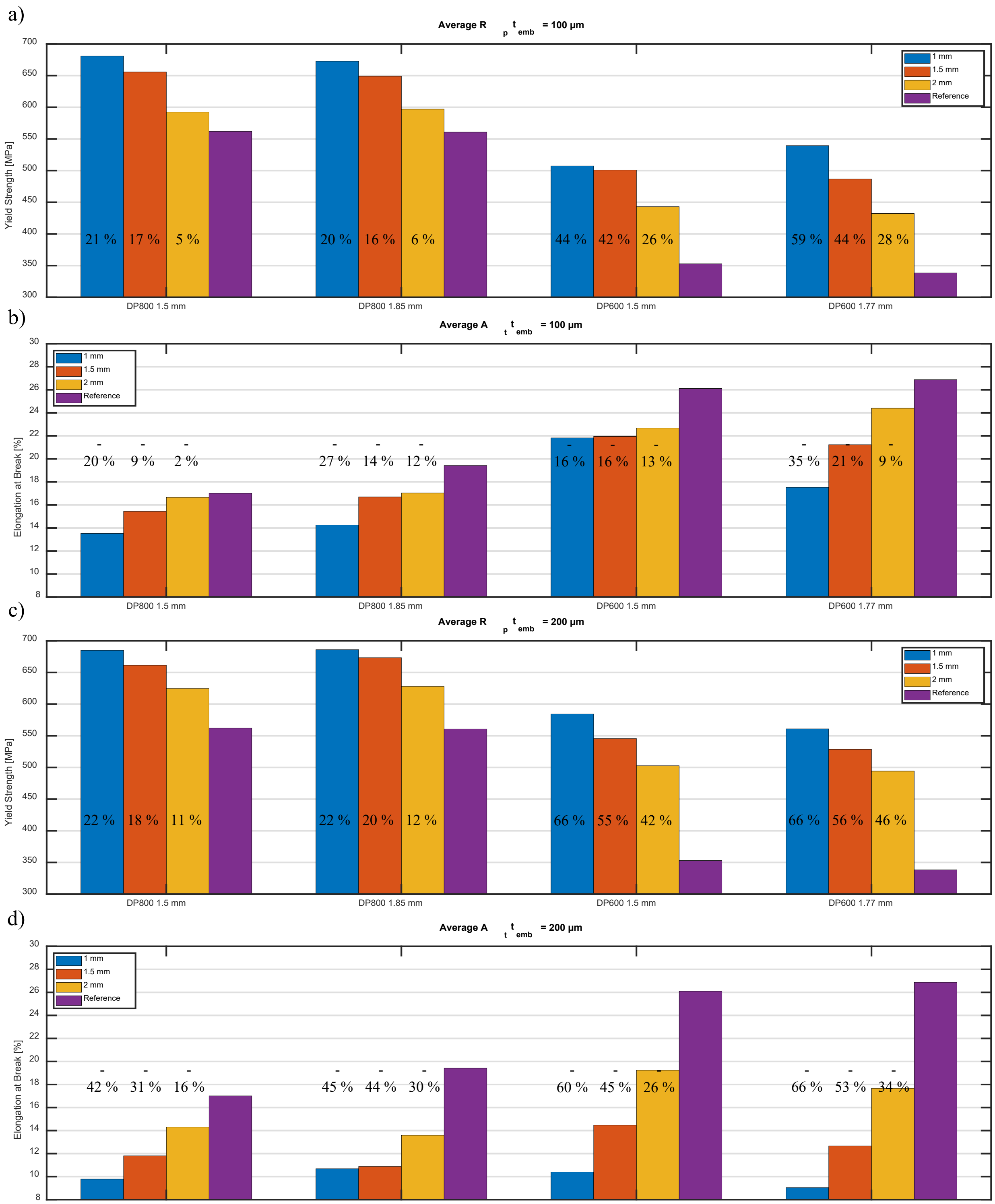

Fig. 3. Evaluation of tensile tests with respect to yield strength for a) t_{emb} = 100 µm, c) t_{emb} = 200 µm and elongation at break for a) t_{emb} = 100 µm, c) t_{emb} = 200 µm.

References

[1] K. Shanmugam, V. Gadhamshetty, P. Yadav, D. Athanassiadis, M. Tysklind, V.K. Upadhyayula, Advanced High-Strength Steel and Carbon Fiber Reinforced Polymer Composite Body in White for Passenger Cars: Environmental Performance and Sustainable Return on Investment under Different Propulsion Modes, ACS Sustainable Chem. Eng. 7 (2019) 4951-4963. https://doi.org/10.1021/acssuschemeng.8b05588

[2] R. Döhrn, Die Lage am Stahlmarkt: Produktion steigt wieder, Probleme bleiben, RWI Konjunkturberichte 72 (2021) 49-58

[3] C. Birkholz, M. Kraus, Die Energiekrise im Standortvergleich: Preiseffekte und Importrisiken. Sonderstudie zum Länderindex Familienunternehmen, München: Stiftung Familienunternehmen, Rep. 978-3-948850-15-9, 2022

[4] O. Holtemöller, S. Kooths, T. Schmidt, T. Wollmershäuser, Gemeinschaftsdiagnose: Energiekrise, Inflation, Rezession und Wohlstandsverlust, Wirtschaftsdienst 102 (2022) 761-765. https://doi.org/10.1007/s10273-022-3291-4

[5] C.S. Namoco, T. Iizuka, R.C. Sagrado, N. Takakura, K. Yamaguchi, Experimental and numerical investigation of restoration behavior of sheet metals subjected to bulging deformation, J. Mater. Process. Technol. 177 (2006) 368–372. https://doi.org/10.1016/j.jmatprotec.2006.03.208

[6] C.S. Namoco, T. Iizuka, K. Narita, N. Takakura, K. Yamaguchi, Effects of embossing and restoration process on the deep drawability of aluminum alloy sheets, J. Mater. Process. Technol. 187-188 (2007) 202–206. https://doi.org/10.1016/j.jmatprotec.2006.11.182

[7] Y. Abe, K. Mori, T. Maeno, S. Ishihara, Y. Kato, Improvement of sheet metal formability by local work-hardening with punch indentation, Prod. Eng. Res. Devel. 13 (2019) 589-597. https://doi.org/10.1007/s11740-019-00910-6

[8] S. Walzer, M. Liewald, Studies on the influence of embossing on the mechanical properties of high-strength sheet metal, AIP Conference Proceedings 2113 (2019) 160006. https://doi.org/10.1063/1.5112703

[9] D. Briesenick, S. Walzer, M. Liewald, Study on the Effect of Embossing on the Bending Properties of High-Strength Sheet Metals, in: Forming the Future: Proceedings of the 13th International Conference on the Technology of Plasticity (Springer eBook Collection), G. Daehn, J. Cao, B. Kinsey, E. Tekkaya, A. Vivek, and Y. Yoshida (Eds.), 1st ed. Cham: Springer International Publishing, Imprint Springer, 2021, pp. 2585-2595.

[10] C. Lesch, N. Kwiaton, F.B. Klose, Advanced High Strength Steels (AHSS) for Automotive Applications − Tailored Properties by Smart Microstructural Adjustments, Steel Res. Int. 88 (2017) 1700210. https://doi.org/10.1002/srin.201700210

[11] F. Ebrahimi, N. Saeidi, M. Raeissi, Microstructural Modifications of Dual-Phase Steels: An Overview of Recent Progress and Challenges, Steel Res. Int. 91 (2020) 2000178. https://doi.org/10.1002/srin.202000178

[12] DIN EN ISO 6892-1:2020-06, Metallische Werkstoffe_- Zugversuch_- Teil_1: Prüfverfahren bei Raumtemperatur (ISO_6892-1:2019); Deutsche Fassung EN_ISO_6892-1:2019, Berlin.