Sustainable tool technology: Wood-based forming tools

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Keywords: Sheet Metal Forming, Sustainability, Wooden Tools, Flexibility, Mass Customization

Abstract. Conventional, dies are manufactured subtractive for sheet metal forming. Beside the forming process, high tooling costs, material exertion and energy consumption, the die production offers chances for economic improvements. Especially, individualization and mass customization for small batch series require sustainable low-cost tooling approaches, where sustainable advances through biologicalization may offer new possibilities. In this work, sheet metal forming tools are manufactured by laminated black locust dies to reduce the overall ecological impact. The deformation and wearing behavior of the wooden tools is investigated during a drawing operation for low batch size of an automotive conventional sheet material.

Introduction

Following the Kyoto Protocol, the Paris Agreement declared and signed by 197 nations clearly postulate the goal to limit the global human made temperature rise by 1.5°C [1]. To ensure this, more sustainable approaches in all areas (e.g., production, infrastructure, food) are required to reduce the manmade ecological impact. On the other hand, a paradigm change from economy of scale to flexibility and customization in any production and consumer industry continuously increasing the demand for highly individualized mass customization of small batch sizes [2]. To enable flexibility in metal forming under the geo-political restrictions, new approaches are required to reconcile both goals in an increased globalization and price competition [3].

Even though flexibility is intrinsic for generic forming tools (e.g., freeform bending), it may be increased via agile or smart production systems [4]. On the other hand, shape-related tools in forming applications (e.g., rotary-draw-bending, deep drawing) require more resources when aiming for mass customization and individualization, since there is typically just one tooling form for each desired part geometry. Shape-related tooling approaches produced by additive manufacturing can reduce the base material consumption for customized forming tools but result in high energy consumption during the additive tooling process. Whereas sheet metal forming processes are often layout for high batch volume production, an individualized low batch size mass customization does need to fit the economic restrictions of the production process [5]. Biologicalization may offer an alternative approach for higher flexibility in metal forming, particularly when aiming for small batch size production. Biologicalization has been defined as "*The use and integration of biological and bio-inspired principles, materials, functions, structures and resources for intelligent and sustainable manufacturing technologies and systems with the aim of achieving their full potential."[2].* When Potting et. al postulated the circular economy in 2017, they defined 9R-strategies to layout a more sustainable production scheme from linear to circular economy [6]. Within the 9R-strategies there are several approaches to reduce natural resource consumption and environmental pressure. When combining the 9R-strategies with biologicalization this reveals a potential for sustainable manufacturing technologies and systems.

Since there is no suitable and economically approved technique to ensure individualized and flexible small batch size production in deep drawing [7], further investigations have to be proceeded. This study reveals a biobased approach following alternative tooling approaches by additive manufacturing [5,6]. The performance of composite structures from black locust (robinia pseudoacacia) tools for sheet metal forming is evaluated experimentally based on the rubber pad forming process.

Literature Review

In sheet metal forming, deep drawing is a common used forming process, where blanks are peripheral restrained by blankholder units and radially drawn into a forming die (cavity) by a punch [10]. Deep drawing is a forming operation where material flow is allowed under the blankholder, aiming for constant material thickness, whereas stretch forming results in a thickness change [11,12]. Since both production methods typically aiming for mass size production, grey cast tooling molds with post-mill shaping are the conventional way of manufacturing [13]. The performance of drawing tools is mainly determined by the tool wear behaviour on highly stressed areas (radii, cavity inlets). Depending on the lot size, sheet material (hardness, thickness and strength), desired part surface quality, surface treatments and lubricants must be considered during tool design [14]. Rubber Pad forming (RPF), a specific deep drawing process, is widely used for automotive and aerospace applications, where one of the form-shaping tools is replaced by a rubber pad (Fig. 1). Advantages, compared to a conventional deep drawing process which consist at least of two complementary tools, can be stated in one flexible pad alignment for different shape geometries, high part surface quality, elimination in misalignment of tools, low tooling costs, no additional lubrication, avoidance of galling on the sheet metal and friction defined specific geometries [15,16]. Despite the benefits, a limited lifetime of the flexible pads, higher production cycle times and higher necessary press capacities due to the energy loss are the drawbacks of this technique [17]. RPF reveals economic and technological advantages for small batch size production [18], which makes it suitable when aiming for higher forming flexibility and mass customization. In Addition to this, the substitution of metal-based tooling materials through biologicalization may improve the ecological value of the process, when renewable tooling materials could be used for in a suitable process window.

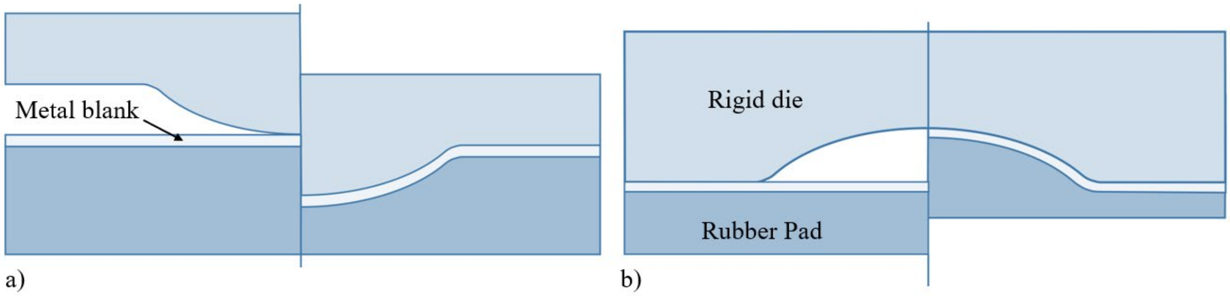

Fig. 1. Guerin process: Tool setup for (a) positive (male) and (b) negative (female) rubber pad forming.

Related Research

Higher product individualization, mass customization and changing consumer requirements regarding technical applications, lead to increasing derivatives in all production sectors. To ensure these demands without contravening geo-political restrictions, alternative approaches in manufacturing are inevitable. Biologicalization and alternative equivalents are auspicious odds to cover the demands of the present production era.

Additive manufacturing (AM) as one of the major innovations in individualized mass customization and production offers a wide range of applications to substitute conventional manufacturing systems [7,19]. AM offers the opportunity to adapt optimized structures and to manufacture them precise without surplus material [20]. In manufacturing, AM was successfully implemented as tooling material e.g., sheet metal forming [8,9,21,22].

Along AM, biologicalization is a suitable mechanism to adapt nature based optimization and material range to sustainable manufacturing systems [2]. [23] studied the performance of wooden based tooling material for a deep drawing process in a feasibility study. The manufactured wooden based forming tools glued together of 4 mm black locust (BL) sheets. The investigated a good performance on low batch size (<500 parts) for radii greater 5 mm. [24] examined the performance of polymer and wood based tools for sheet metal forming for a batch of 500 parts each. The revealed an overall feasibility for radii of 7 mm with slightly higher deformation on the densified wood-based compared to the polymer tools.

Methodology

Preceding investigations.

The aim of the present study is the investigation of a potential substitution of conventional tooling materials for sheet metal forming applications through biologicalization. For comparison, similar process boundaries were applied as in the preceding studies [8,9], where the mechanical stability of fused deposition modeling (FDM) printed dies from polylactic acid (PLA) with solid and reduced infill was investigated in forming DC03 (0.7 mm) sheet metal parts in a rubber pad forming process featuring a polyurethane pad (shore hardness 40). Based on the previous work, the load collective of the drawing process was adopted for composite layered tools of BL.

Mechanical characterization of black locust.

Black locust is a hardwood that can be grown and harvested in nutrient-poor and dry locations, offering good mechanical properties compared to alternative wood or biobased materials. According to [25,26] black locust offers the highest mechanical properties for all native wood species. The mechanical characterization (tensile, compression, bending, hardness) was performed on a Zwick Roell Z250 universal testing machine i.e., for the following geometries, according to relevant standards DIN EN ISO 527-1, *DIN 52192* and DIN 52186 respectively (see. Fig. 2):

Fig. 2. Black locust test specimen for mechanical characterization.

The results are summarized in Table 1, next to data from relevant literature [27-30].

Table 1. Mechanical properties for black locust.

Tensile properties		**Characterization**	**LOMANN** [27]	**KOLMANN** [28]	**VORREITER** [29]	**WAGENFÜHR** [30]
Tensile strength parallel to fiber	[N/mm^2]	153.14 (± 23.31)	88...136...184	98...145...181	145	88...136...184
Tensile strength perpendicular to fiber	[N/mm^2]	7.59 (± 1.36)	—	4	4	4
Tensile modulus parallel to fiber	[N/mm^2]	9325.95 (± 308.10)	—	—	—	—
Tensile modulus perpendicular to fiber	[N/mm^2]	1394.06 (± 409.82)	—	—	—	—
Compression properties						
Compressive strength longitudinal	[N/mm^2]	7.56 (± 2.01)	62...72...81	55...72...94	58	62...72...81
Compressive strength tangential	[N/mm^2]	20.86 (± 3.63)	—	—	13	—
Compressive strength radial	[N/mm^2]	28.02 (± 2.36)	—	19	13	—
Compressive modulus longitudinal	[N/mm^2]	8720.43 (± 622.56)	—	—	—	—
Compressive modulus tangential	[N/mm^2]	603.71 (± 28.03)	—	—	—	—
Compressive modulus radial	[N/mm^2]	750.24 (± 48.18)	—	—	—	—
Bending properties						
Flexural strength tangential	[N/mm^2]	141.54 (± 11.83)	103...136...169	147	118	103...136...169
Flexural strength radial	[N/mm^2]	145.95 (± 14.04)				
Flexural modulus tangential	[N/mm^2]	11107.98 (± 1327.36)	9000...11300...13500	8800...13300...16700	13300	9000...11300...13600
Flexural modulus radial	[N/mm^2]	11334.11 (± 1198.52)				
Hardness properties						
Brinell Hardness longitudinal	[N/mm^2]	79.15 (± 5.80)	—	73	78	67...78...88
Brinell hardness tangential	[N/mm^2]	41.94 (± 4.95)	—	47	39	28...34...47
Brinell hardness radial	[N/mm^2]	39.93 (± 3.38)	—			

Simulation of pristine and composite black locust specimen.

Following the mechanical characterization, the pristine longitudinal compression specimens were implemented in a simulation based on the Finite Element Method (FEM) in the Software LS Dyna. Based on the work of [31] two pre-defined material models were included for the simulation of BL specimen:

- MAT_143 (MAT_WOOD)
- MAT_058 (MAT_LAMINATED_COMPOSITE_FABRIC)

Implementing the base parameter gained from the mechanical testing both models were superimposed over the test curves of the BL samples (see Fig. 3). To estimate the performance of wooden based composite drawing tools from black locust, further numerical investigations were carried out. Assuming a deformable body for the forming dies an element stress analysis was performed, according to [9]. Even though the recent studies imply a deformable polymer die made from PLA, the volumetric analysis should reveal the performance of a deformable wooden composite structure from black locust. Since the RPF process applies the process force on the active tool (die) nearly lossless through the rubber pad, the stress distribution on a deformable body was assumed to be similar. From the analysis, the contour plot revealed the 3D element stress distribution through the die and emphasized the high stressed area along and into the radius inlet of the die cavity. Whereas the quantitative information is based on the PLA die, the qualitative outcome was assumed to be similar for the wooden composite die (see Fig. 4).

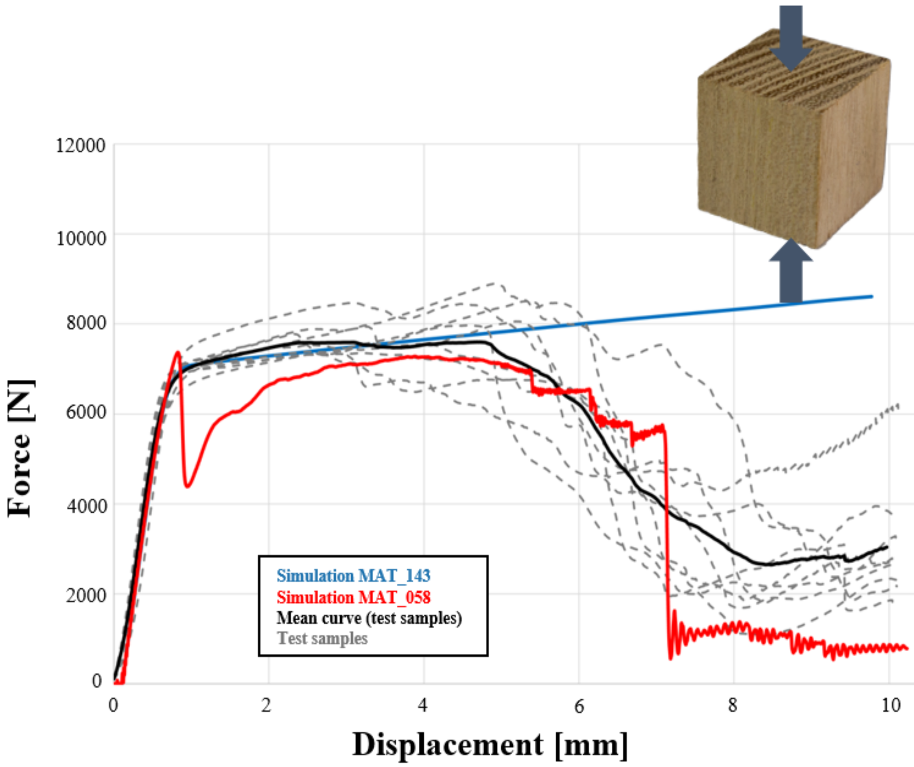

Fig. 4. Numerical validation with LS Dyna for longitudinal compression specimen for black locust.

From the stress contour plot gained from a linear static finite element simulation with ALTAIR Optistruct it is evident, that the drawing radius was heavily loaded while the cavity of the die faced minor contact forces except from the apex of the dome geometry. The load case, as maximum contact pressure over time, for the linear static finite element analysis was gathered from a forming simulation by PAM STAMP 2020.0. The hexahedron elements were discretized with a nominal

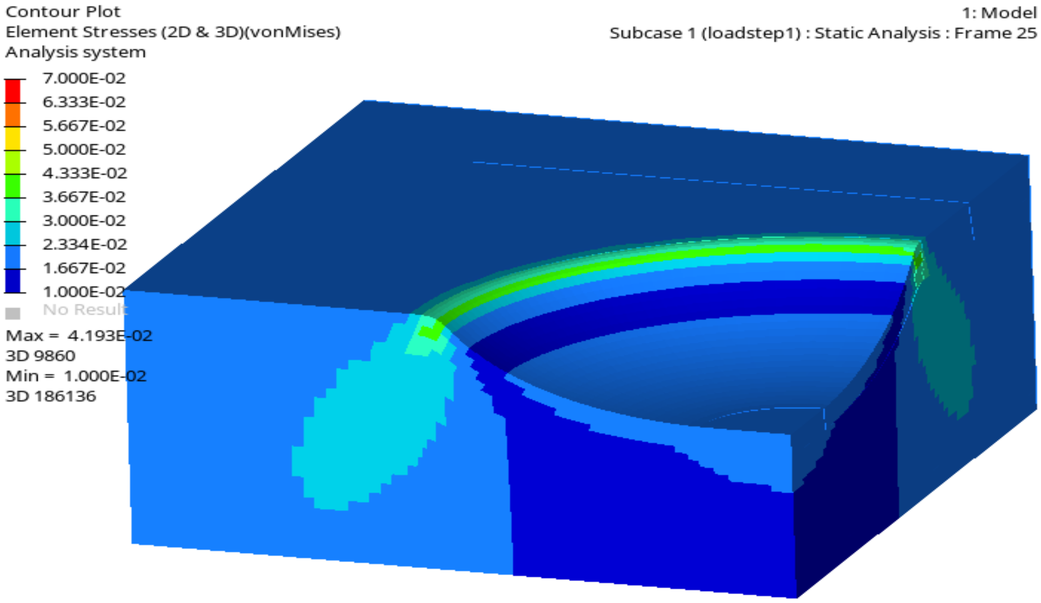

Fig. 3. Stress contour plot for deformable tool die.

size of 1.0 mm assuming an isotropic v. Mises material with young’s modulus of 1.7 GPa. According to [9] the boundary conditions were displacements of the bottom surface of the die are constrained in surface normal direction.

Drawing results for wood-based forming tools manufactured of black locust.

Based on previous characterization and numerical analysis as well previous investigations from [8,9], two composite structures were rectangular aligned out of 3mm black locust sheets glued together with polyurethane (see Fig. 5), according to [23].

Fig. 5. Black locust composite drawing tools: horizontal (left), perpendicular (middle) and hybrid structure with 2mm sheet metal (right).

Solid black locust planks were cut into thin veneer sheets and sanded with coarse mesh (P80) on a surface sander prior to composite bonding. The bonding performed using a hydraulic veneer press without affecting or damaging the mechanical performance of the wood layers. The drawing dies included two composite (horizontal and perpendicular stacked) and, due to high process forces on the radii inlets (radius of 2.5 mm), two composite-hybrid structures (horizontal and perpendicular stacked each topped with a 2 mm sheet of tool steel grade 1.2312). All dies were operated on a uniaxial testing machine along with a 40-shore hardness polyurethane pad. For each die version, a batch of 64 parts from 0.7 mm DC04 sheet metal was drawn with 175 kN on the universal testing machine.

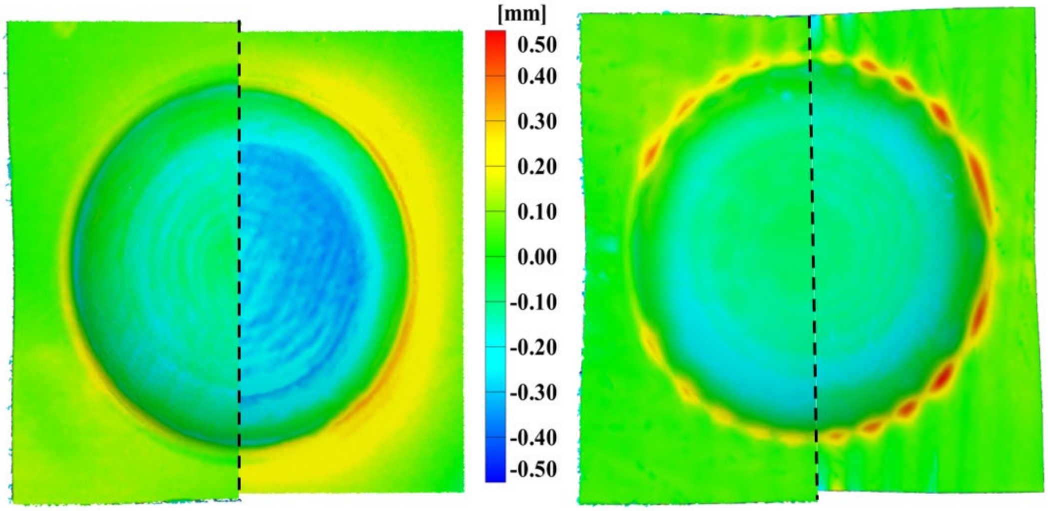

Fig. 5. Optical correlation for unused BL dies and the corresponding blank sheets of the first stroke (left half) and the 64th stroke (right half), for black locust horizontal (left application) and perpendicular (right application) composite die.

Due to permanent deformation of the wooden based forming tools, an optical analysis via optical surface scan was accomplished. Fig. 5 shows the spatial deviation for drawn sheet metal parts on wooden based forming tools (see. Fig., left and middle), where the left part shows the performance of the 1st and 64th part drawn on a black locust composite horizontal stacked and the right part shows the performance of the 1st and 64th part drawn on a black locust composite perpendicular stacked, respectively. The spatial deviation on the radii inlets correspond to the high stressed area in the contour plot (cf. Fig. 4).

Since Fig. 5 revealed qualitative differences of the forming behaviour between the first and 64th stroke for all drawn metal sheets, a comparison for the high stressed area along the radii inlet (cf. Fig. 4) was carried out to identify the drawing radius deviation of sheet metal parts on all BL dies (Fig. 6).

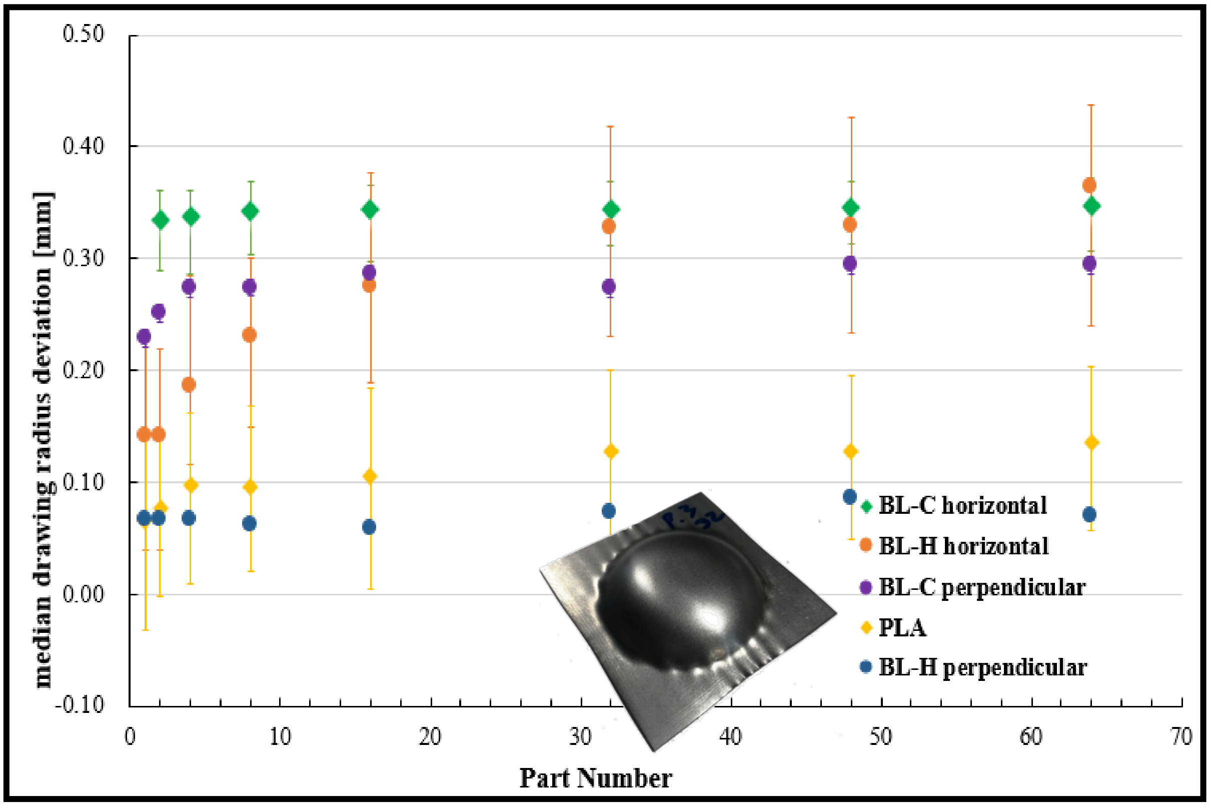

Fig. 6. Spatial deviation within the drawing radius for comparing the sheet metal parts produced by the BL-RPF process for different layouts. Statistical evaluation of a small batch series of metal parts indicates degressively increasing deviations from 0.09 mm (BL-H perpendicular) to 0.34 mm (BL-C horizontal).

Fig. 6 depicts the spatial drawing radii deviation up to 64 blank parts, drawn on BL dies with different stack layouts, showing the highest deviations on the BL-C horizontal die, whereas the hybrid BL-H perpendicular die reveals the lowest deviation. Along the batch size production, the deviation increased for all versions, which refers to the high contact stresses and the deformation behavior of the BL dies. Even though the metal parts drawn on the BL-H perpendicular die stabilize immediately after the first part, the remaining dies increased the radius deviation on the metal blanks roughly up to the 32nd part, which indicates a stabilizing character of BL dies in general, even without the hybrid components.

Summary

Biologicalization through wooden based forming tools offers chances to enhance flexibility and mass customization in sheet metal forming. While a solid and a topology optimized forming die manufactured by fused deposition modeling (FDM) successfully utilized for sheet metal forming in previous studies [8,9], in this study, the performance of the identical die geometry was investigated for different wooden based forming tools from black locust (robinia pseudoacacia). The wooden based tools are compared to a solid die from polylactic acid (PLA) regarding dimensional accuracy of formed sheet metal products. On each die variant, batches of 64 parts (steel grade DC04) are drawn in a rubber pad forming process and examined by optical correlation scans. The tests depict an overall comparable forming behavior of all die variants introduced to the process, while hybridization with tooling steel on the surface of the tooling dies lead to smaller drawing radius deviations on the cavity inlet. Slight permanent deformations are indicated along the drawing radii of all black locust forming tools caused by high contact stresses. Concluding, the wooden based forming tools revealed a suitable drawing performance for small batch size production. Future research should focus on high stressed areas of forming tools and appropriate replacement strategies via conventional metal inlays. In addition, further analysis of the deformation behaviour of wooden based tools could be conducted in numerical simulations as well as in forming tests to investigate the influence of local mechanical tool properties (e.g., local tool stiffness) on the product geometry.

Acknowledgements

The authors acknowledge the financial support by the Bundesministerium für Wirtschaft und Klimaschutz (BMWK) within the project ATLAS (grant number: 16TNW0003B). We acknowledge Jannik Stolz's contribution in providing the practical demonstrators.

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