Low-cost tooling concept for customized tube bending by the use of additive manufacturing

TRONVOLL Sigmund A.[1,a*], TREFFEN Helena[1,b], MA Jun[1,c]
and WELO Torgeir[1,d]

[1]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, 7491, Norway

[a]sigmund.tronvoll@ntnu.no, [b]helenatr@stud.ntnu.no, [c]jun.ma@ntnu.no, [d]torgeir.welo@ntnu.no

Keywords: Low-Cost Tooling, Tube Bending, Flexibility, Additive Manufacturing

Abstract. Bending is commonly used in the manufacturing of finished and semi-finished, profile-based products. However, costly profile and bend geometry dependent tooling hampers its applicability for low volume production or prototyping. Additive manufacturing (AM) offers a potential for making tools in low-volume production, which is particularly attractive for customized manufacturing and prototyping with near production intent tooling. In this research, an industrial bending process for tubes and profiles, called rotary drawing bending (RDB), is used as a case. In the RDB process, the mandrel die installed inside the tube or profile blank is of crucial importance to secure the quality of the cross-section of bent shapes. Moreover, this die is normally difficult and expensive to produce. In addition, each mandrel is tailored to a single profile's inner geometry, hence posing an obstacle to acquiring a tooling setup for multiple cross-section dimensions. As a countermeasure, a novel mandrel tooling concept is designed by using a metal rod core with an AM-sleeve fitted to the rod outside, as an easy-to-replicate solution for significantly lowering the costs of offering the capability of forming processes with different cross-section dimensions. Fused filament fabrication (FFF)—a cost-effective AM process—is used for fabricating the mandrel die with various pre-designed and optimized shapes. Using both the AM mandrel in polylactide (PLA) and the conventional metal mandrel in a series of bending experiments of AA6082-T4 Al-alloy tubes, the dimensional and qualitative results of tubes bent with different mandrels is analyzed, discussed, and compared.

Introduction

To meet the increased customer demands for product variety, the manufacturing sector is transforming from mass production to mass customized production, with higher flexibility and on-demand manufacturing [1]. However, for the die-based manufacturing processes such as metal forming, they are increasingly challenged to meet the demands on flexibility [2]. In the metal forming area, the design and fabrication of tools are normally expensive and need a long lead time, which significantly limits the transformation of conventional forming towards the customized forming. This calls for new tooling concepts and methods that allow the time-efficient, cost-effective fabrication of tools for mass customized metal forming.

Additive manufacturing (AM) used for rapid prototyping offers a potential for making tools in low-volume, customized production, which is particularly interested by the industrial metal forming processes. In recent years, some attempts at AM-based tools used in metal forming have been carried out. A typical application of AM as a method for tooling making to realize the metallic dies with optimized cooling channels in hot metal working such as hot stamping [3]. For instance, Komodromos et al. [4] employed a Directed Energy Deposition (DED) to produce the hot stamping tools with integrated cooling channels. After the DED process, the tool surfaces are ball burnished to reduce the surface roughness for more effective heat transfer. Joghan et al. [5] utilized hybrid AM method to make metal laminated forming tools. In this method, laser metal deposition is used for bonding the sheets and smoothening the edges, and subsequently milling, roller burnishing, and laser treatment are applied as post-processing for improving the strength and surface finish. Similarly, a layer-laminated manufacturing method and a laser melting process were applied in the manufacturing of the dies with conformal cooling channels for extrusion processes [6]. Chantzis et al. [7] proposed a Design for AM (DfAM) method for hot stamping dies which exploits the benefit of lattice structures for reduced thermal conductivity. It shows that the proposed method can significantly improve the cooling performance of a hot stamping die with printing times reduced by at least 12% compared to traditionally manufactured AM dies. This shows that high end AM systems, as those capable of manufacturing metal parts, has a potential for improving process control and manufacturing rate.

For increased flexibility in low-volume manufacturing, more inexpensive AM-solutions would be preferred, as the associated cost and leadtime is the key parameter, rather than geometric complexity. In this case, fused filament fabrication (abbreviated FFF, also called filament-based extrusion AM) has attracted some scientific interest. Strano et al. [8] demonstrated the potential applicability and versatility of FFF as a rapid tool manufacturing technology for different applications in shearing, bending, deep drawing, and injection molding. Frohn-Sörensen et al. [9] utilized the FFF process to manufacture the tooling to draw a small series of sheet metal parts in combination with the rubber pad forming process. In addition, a variety of common polymer materials (PLA, PA, PETG, PC) were comprehensively compared in compressive and flexural tests to provide an guide for material selection in AM-based polymer tools for metal forming [10].

The body of research on AM-based tooling in metal forming is obviously more extensive than the above-summarized ones. However, most of them focus mainly on cold and hot forming of sheets, and in tooling that will be in compression, and are hence not that affected by FFFs tensile anisotropy [11]. The use of AM in making tools for complex tube bending processes has not been explored earlier, and the process that will be discussed in this paper is rotary draw bending (RDB), which is shown in Fig. *1*. This is one of the more popular bending processes, and normally operates with a tooling system including 5-6 complex-shaped tools, in which tooling is one of most important issues affecting the production cost. The tools are also dependent on either or both the bend radius, profile inner- and outer-geometry. Therefore, most workshops keep a limited inventory of tooling variants, which is a significant limitation to their capability in terms of geometric flexibility.

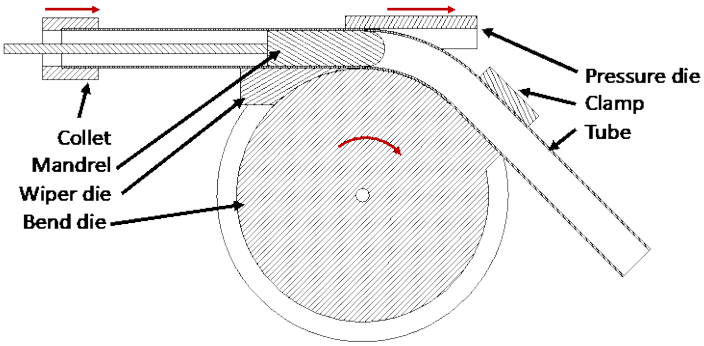


Fig. 1. Conceptual tooling layout of rotary draw bending (RDB).

The aim of this research is to develop a new cost-effective tooling concept for tube rotary draw bending processes by utilizing low-cost FFF manufacturing methods, and initially investigating its applicability to be used for mandrel bending. First, the newly proposed mandrel die concept is introduced. Secondly, using aluminium tubes with different wall thicknesses, a series of bending experiments with and without conventional mandrels and new AM-based mandrels is presented.

Finally, the dimensional accuracy and qualitative aspects of formed tubes is evaluated to verify the feasibility and capability of the new AM-based mandrel die concept for tube bending.

Low-Cost Tooling Concept for Customized Bending

For both product development and low production purposes using RDB, being able to quickly change the wall thickness of tubes or profiles would be beneficial, but requires change of the mandrel, which is a crucial tool for bending components with a high diameter to thickness ratio. Keeping a catalogue of mandrels suitable for all wall thicknesses could be costly, while acquisition on demand through buying or in-house machining might be preferrable. Conventional mandrel shapes, as shown in Fig. *2*, does however require multi-step CNC machining, which often comes with a considerable cost and lead time. It is in this domain we believe additive manufacturing could provide a significant benefit in bringing lead time and cost for changing mandrel to a minimum. As a first step in this effort, we are investigating the feasibility of using spherical end mandrels manufactured using standard FFF process equipment and standard PLA filament material.

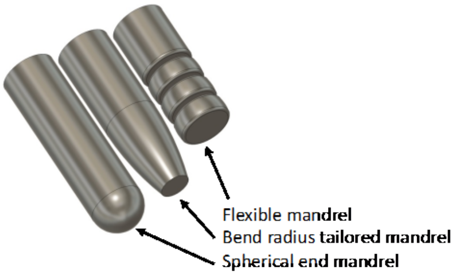


Fig. 2. Mandrel types in tube rotary draw bending.

To provide structural integrity and overcome the inter-layer bonding problems found in FFF parts, the PLA-mandrels used in this study were constructed with a steel core, while adding a bolt-on outer interchangeable PLA sleeve to provide the required geometry, as shown in Fig. *3*. As the suggested hybrid mandrel system is believed to be softer than its metal counterpart, we expect that for getting a comparable result, the mandrel extension (shown in Fig. *3*) would need to be increased.

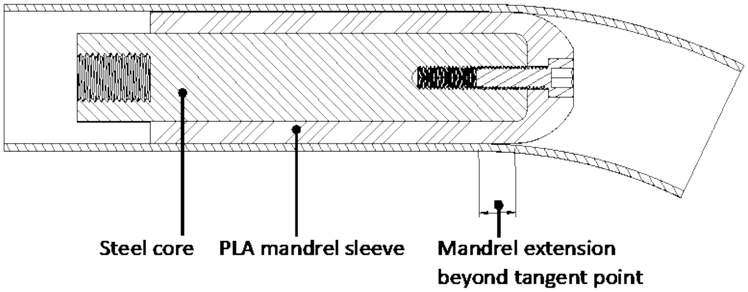


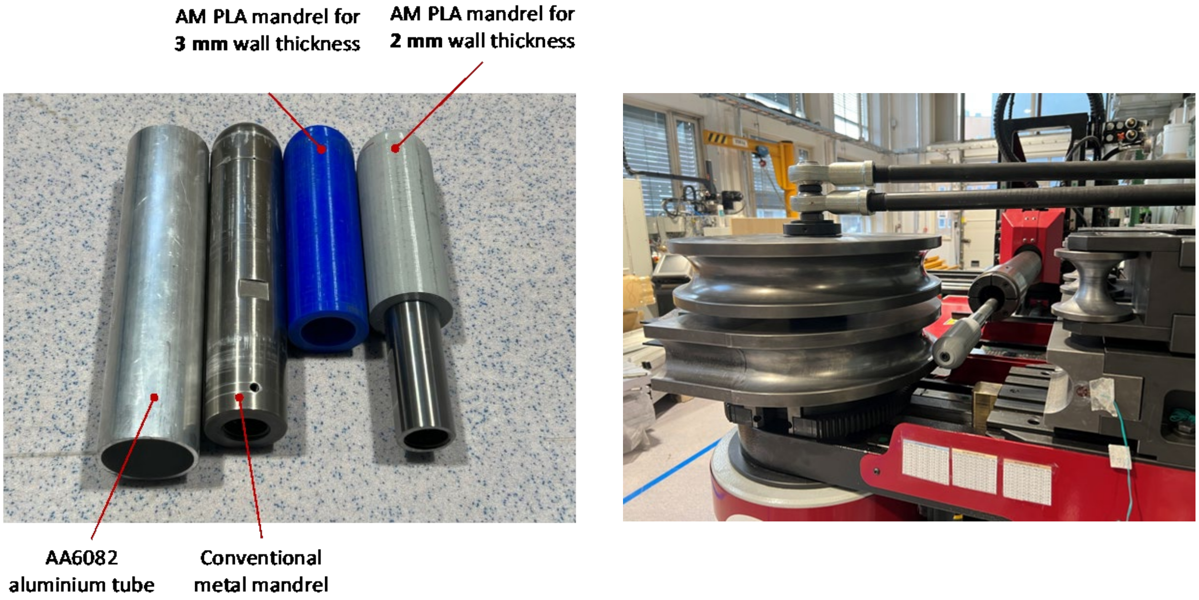
Fig. 3. Hybrid steel/PLA mandrel construction.

Experimental Setup

Using a *Star Technology 800 EVOBEND* tube bending machine, with tooling designed for Ø60 mm profiles and 222 mm bend radius, experiments with tube thicknesses of 3 and 2 mm, and mandrel extension lengths were conducted as shown in Table *1*. The manufactured bends were then evaluated based on the flattening of the cross section radially relative to the bend axis, measured using a caliper. For the bend radius and outer tube diameter, experience has shown that 3 mm thickness tubes do not exhibit wrinkling defect if manufactured without mandrel, while 2 mm ones do. The 2mm tube experiments are therefore also evaluated qualitatively on the basis of the mandrel's capability of mitigating the wrinkling defect on 2 mm tubes bent without a mandrel. The steel and AM mandrels, and how they are installed in the tool system is shown in Fig. *4*.

Table 1. Experimental matrix.

Experiment #	Mandrel type	Mandrel extension (e)	Tube thickness	Samples
1	No mandrel		3 mm	2
2	Steel	0 mm	3 mm	2
3	AM	0 mm	3 mm	2
4	AM	5 mm	3 mm	2
5	AM	10 mm	3 mm	2
6	No mandrel		2 mm	2
7	AM	5 mm	2 mm	2
8	AM	10 mm	2 mm	2



(a) (b)

Fig. 4. (a) AM PLA mandrels and conventional metal mandrel, and (b) assembled tooling in the RDB tooling system.

Results and Discussion

Qualitative and quantitative results for the 3 mm thickness samples are shown in Fig. *5* and in Fig. *6*, respectively. Qualitative assessment does not reveal any major difference between the different mandrels. Quantitatively, the AM mandrel provides a significant support to limit tube flattening and reduces the tube flattening with 50% compared to the samples bent without mandrel. Comparing with the steel mandrel, however, the PLA mandrel is seen to provide less support for 0 extension distance, with 1 mm larger cross section flattening (2-2.5 mm in total), suggesting that the PLA mandrel is significantly softer than the metal version. The flattening is reduced to values comparable to those for steel mandrel if the mandrel extension is increased to 10 mm for the PLA mandrel, which results in approximately 1 to 1.5 mm of flattening. Although increased mandrel extension will increase the contact pressure on the mandrel, there is no indications that the PLA mandrel is being degraded significantly, as it shows no cracks or scuffing marks.

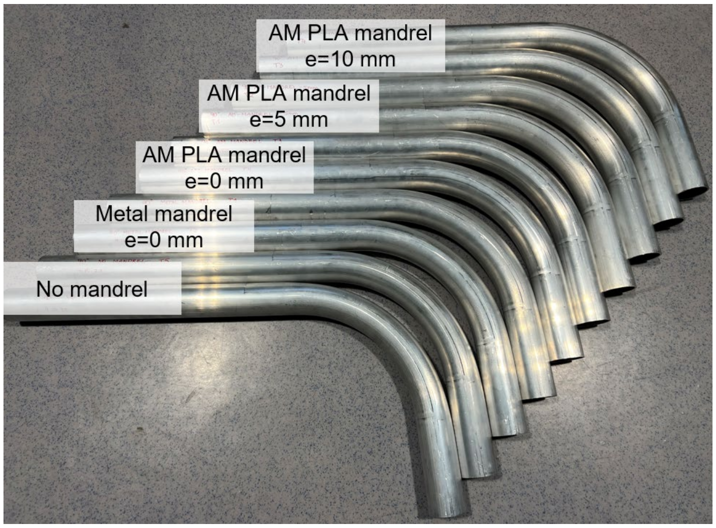


Fig. 5. Qualitative results from tube bending with 2mm wall thickness.

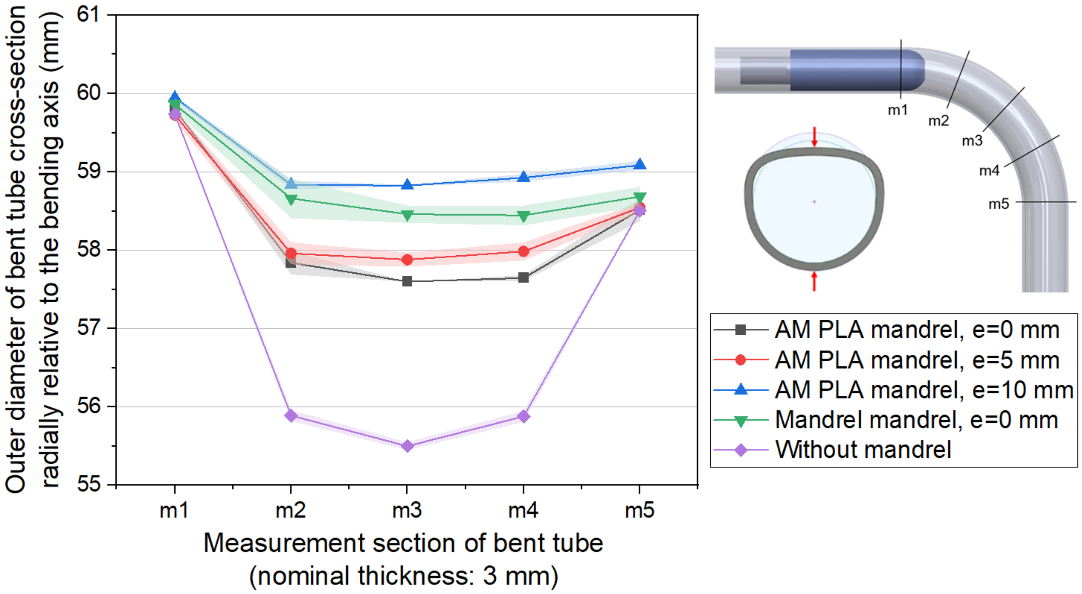


Fig. 6. Radial tube flattening from tube bending with 3 mm wall thickness.

Qualitative and quantitative results for the 2 mm thick samples are shown in Fig. 5 and in Fig. 6, respectively. As shown in Fig. 5, the lowered wall thickness results in pronounced intrados wrinkling when bending without a mandrel, which is effectively mitigated with the use of the AM mandrel. The samples from bending without a mandrel are left out of the quantitative results due to wrinkling. The 2 mm thickness tubes display a slightly higher flattening than for 3 mm thick tubes, with approximately 3 to 4 mm flattening using an extension distance of 5 mm, which is reduced to approximately 2.5 to 3 mm when increasing the extension distance to 10 mm. As in the case with the mandrel for 3 mm wall thickness tubes, there is in this case also no indications that the PLA mandrel is being degraded significantly, as it shows no cracks or scuffing marks as well.

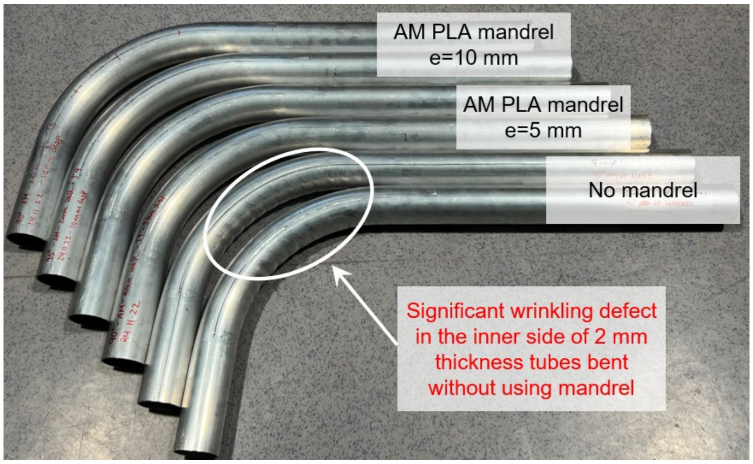


Fig. 7. Qualitative results from tube bending with 2mm wall thickness.

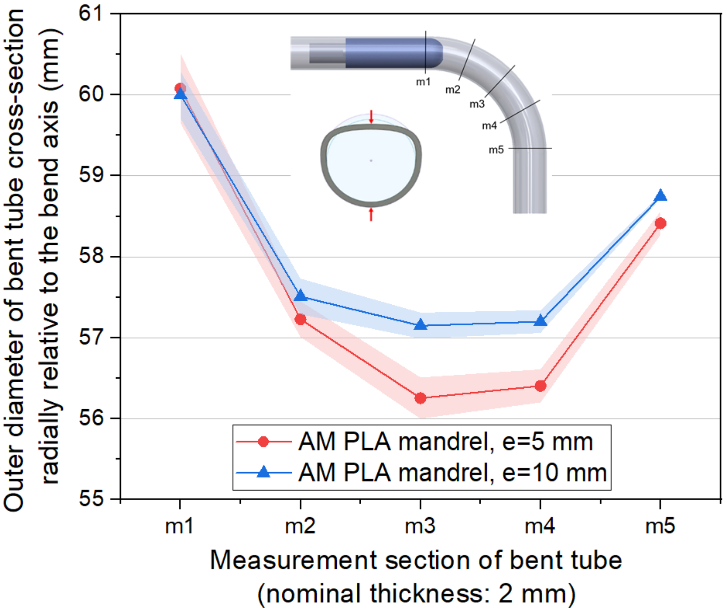


Fig. 8. Radial tube flattening from tube bending with 2 mm wall thickness.

Summary

The proposed tooling concept with a hybrid steel-PLA mandrel is found to provide sufficient support and structural integrity to significantly reduce both the cross section flattening and wrinkling for the investigated cases of tube bending using rotary draw bending of aluminum tubes. With the simplicity of the manufacturing using additive manufacturing, and the low cost associated with the material and manufacturing system for fused filament fabrication, using this type of mandrels provides a significant process improvement over bending without mandrel, and on par with steel mandrels if the mandrel extension length is increased.

As the concept explored in this paper seems promising, replacing other complex tools, as the wiper die could provide additional value. We would also suggest investigating the method's applicability on bending of tubes with higher material strength as steel or titanium. We also believe that further research should target investigating the durability of these AM mandrels, to investigate its applicability for manufacturing larger volumes.

Acknowledgements

The authors gratefully acknowledge the support from NTNU Aluminum Product Innovation Center (NAPIC), and through the *TaFF* project (*Digitally-Controlled, Toolless and Flexible Forming*) in collaboration with *Benteler Automotive Raufoss AS*, funded through *The Research Council of Norway* through grant number 317777.

References

[1] J. Cao, M. Banu, Opportunities and Challenges in Metal Forming for Lightweighting : Review and Future Work, J. Manuf. Sci. Eng. 142 (2020) 1–24. https://doi.org/10.1115/1.4047732

[2] D.Y. Yang, M. Bambach, J. Cao, J.R. Duflou, P. Groche, T. Kuboki, A. Sterzing, A.E. Tekkaya, C.W. Lee, Flexibility in metal forming, CIRP Ann. - Manuf. Technol. 67 (2018) 743-765. https://doi.org/10.1016/j.cirp.2018.05.004

[3] D. Chantzis, X. Liu, D.J. Politis, O. El Fakir, T.Y. Chua, Z. Shi, L. Wang, Review on additive manufacturing of tooling for hot stamping, Int. J. Adv. Manuf. Technol. 109 (2020) 87-107. https://doi.org/10.1007/s00170-020-05622-1

[4] A. Komodromos, F. Kolpak, A.E. Tekkaya, Manufacturing of Integrated Cooling Channels by Directed Energy Deposition for Hot Stamping Tools with Ball Burnished Surfaces, BHM Berg- Und Hüttenmännische Monatshefte. 167 (2022) 428-434. https://doi.org/10.1007/s00501-022-01264-w

[5] H. Dardaei Joghan, M. Hahn, J.T. Sehrt, A.E. Tekkaya, Hybrid additive manufacturing of metal laminated forming tools, CIRP Ann. 00 (2022) 1-4. https://doi.org/10.1016/j.cirp.2022.03.018

[6] R. Hölker, M. Haase, N. Ben Khalifa, A.E. Tekkaya, Hot Extrusion Dies with Conformal Cooling Channels Produced by Additive Manufacturing, Mater. Today Proc. 2 (2015) 4838–4846. https://doi.org/10.1016/J.MATPR.2015.10.028

[7] D. Chantzis, X. Liu, D.J. Politis, Z. Shi, L. Wang, Design for additive manufacturing (DfAM) of hot stamping dies with improved cooling performance under cyclic loading conditions, Addit. Manuf. 37 (2021) 101720. https://doi.org/10.1016/J.ADDMA.2020.101720

[8] M. Strano, K. Rane, M.A. Farid, V. Mussi, V. Zaragoza, M. Monno, Extrusion-based additive manufacturing of forming and molding tools, Int. J. Adv. Manuf. Technol. (2021). https://doi.org/10.1007/s00170-021-07162-8

[9] P. Frohn-sörensen, M. Geueke, T.B. Tuli, M. Manns, B. Engel, P. Manuskript, P. Frohn-sörensen, M. Geueke, T.B. Tuli, M. Manns, B. Engel, 3D printed prototyping tools for flexible sheet metal drawing, (2021) 1-26

[10] P. Frohn-Sörensen, M. Geueke, B. Engel, B. Löffler, P. Bickendorf, Compressive and flexural material properties of PC , PLA , PA and PETG for additive tooling in sheet metal forming, (2022). https://doi.org/10.31224/2239

[11] Q. Sun, G.M. Rizvi, C.T. Bellehumeur, P. Gu, Effect of processing conditions on the bonding quality of FDM polymer filaments, Rapid Prototyp. J. 14 (2008) 72-80. https://doi.org/10.1108/13552540810862028