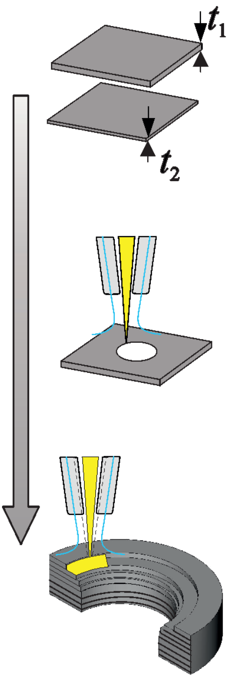
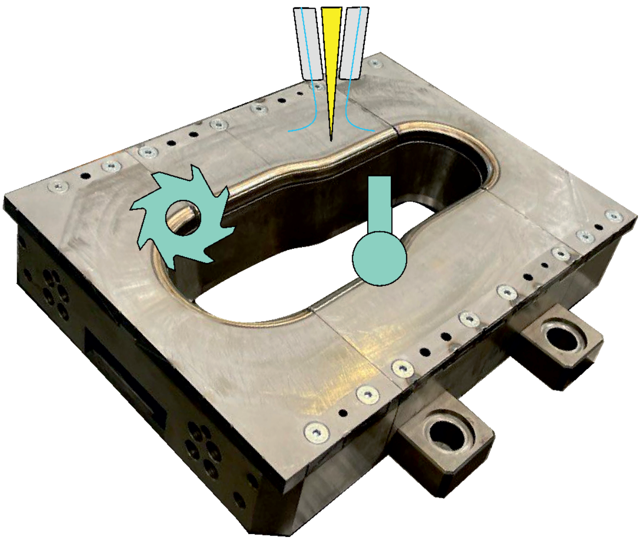
Institut für
Umformtechnik
und Leichtbau

Hamed Dardaei Joghan

Hybrid additive manufacturing of metal laminated forming tools





Reihe
Dortmunder Umformtechnik

Nr. 123

Hybrid additive manufacturing of metal laminated forming tools

Zur Erlangung des akademischen Grades eines

Dr.-Ing.

der Fakultät Maschinenbau
der Technischen Universität Dortmund

Dissertation

vorgelegt von

Hamed Dardaei Joghan, M. Sc.

aus

Tabriz

Dortmund, 2024

Vorsitzender der Prüfungskommission:	PD Dr. habil. Tobias Kaiser
Berichter:	Prof. Dr.-Ing. A. Erman Tekkaya
Mitberichter:	Prof. Dr.-Ing. Jan T. Sehrt
	Prof. PD Dr.-Ing. Andreas Zabel
Tag der mündlichen Prüfung:	27. 02.2024

Dortmunder Umformtechnik

Band 123

Hamed Dardaei Joghan

Hybrid additive manufacturing of metal laminated forming tools

D 290 (Diss. Technische Universität Dortmund)

Shaker Verlag
Düren 2024

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Dortmund, Technische Univ., Diss., 2024

Printed in Germany.

ISBN 978-3-8440-9481-7
ISSN 1619-6317

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgments

A main part of this dissertation is the project's outcome with the title"Reducing the stair step effect for dies manufactured by layer-laminated manufacturing by additive and formative post-processing," with project number 426515407 funded by the (German Research Foundation (DFG) at the Institute of Forming Technology and Lightweight Components (IUL) at the Technical University of Dortmund. Therefore, I would like to take this opportunity to thank DFG for supporting their fund. Getting through my dissertation required more than academic support, and I have to thank many people.

I would like to express my deepest gratuities to Prof. A. Erman Tekkaya for his trust and allowance to write my doctoral thesis under his supervision. During my work at IUL, I have received constant encouragement, constructive discussions, and guidance to develop scientific and personal views from him. I would also like to thank the head of the Institute for Hybrid Additive Manufacturing (HAM) at the University of Bochum, Prof. Dr.-Ing. Jahn Sehrt, for his co-supervision of my dissertation. I would also like to show gratitude to my examination committee, including Prof. PD Dr.-Ing. Andreas Zabel and PD Dr. habil. Tobias Kaiser.
I would also like to thank all my colleagues at the IUL for the pleasant working atmosphere, helpfulness, and friendly relationship. Dr. Marlon Hahn is incredibly grateful for his support and encouragement and our numerous scientific discussions. I also thank Dr. Ramona Hölker-Jäger and Prof. Till Clausmyer for their scientific support. This journey would not have been possible without the support of the technical staff, particularly Dirk Hoffmann, Werner Feuer, and Sven Lukis, who significantly contributed to preparing the parts, and Jeanette Brand and Nina Hänisch for their support at the IUL office. I would also like to thank all the students who wrote student works under my supervision and students' assistants for their excellent cooperation.

I appreciate my family's support while I was working on my dissertation.

Finally, I must express my profound gratitude to my parents, whose encouragement was the primary motivation to overcome the difficulties throughout my academic journey. I also want to thank my brothers for the unconditional support of our parents over the years, which assisted me in concentrating on my research and work abroad.

Dormund, Febraury 2024

To my parents

Abstract

This thesis introduces and investigates a new resource-efficient manufacturing method for rapid tooling. The presented hybrid method combines two additive manufacturing processes: sheet metal lamination and direct energy deposition (DED). In this combination, the core of the forming tool is fabricated by sheet lamination in a short time and at a low cost. The resulting step areas are compensated by laser metal deposition (LMD), which is a subset of the DED process. Three post-processing methods, milling, ball burnishing and laser polishing, are applied and compared to improve the surface roughness of the deposited areas.

The results show the essence of the two-step filling strategy, in which a bonding step should bond together the tool sheets, and in the next step, the remaining stair-step areas should be filled by LMD. The tensile strength of the fillet bonding for different process parameters and tool sheet combinations shows that the higher laser power and feed rate result in higher strength; however, the sheet thickness also needs to be considered to avoid the melt-through of the thin sheets. In the filling step, filling in the radius direction shows better surface roughness, but the nozzle life is shorter. The preheating of the die sheet to reduce the residual tensile stress shows only a 25 % reduction, which causes waviness of the deposited surface. Therefore, it can be neglected.

A semi-analytical model to analyze the stress distribution showed the possibility of using the low-strength tool sheets in a major part of the laminated tool. Deep drawing experiments are successful for two types of blanks. The wear test study shows low wear of the dies manufactured by the hybrid method in comparison with the conventional method. The feasibility of manufacturing complex geometries is demonstrated by a manufactured demonstrator.

The economic and technological advantages of the hybrid method are compared with conventional and fully manufactured tools by LMD, and the number of possible sheet combinations for tool lamination is reduced by considering cost and energy criteria.

Zusammenfassung

In dieser Arbeit erfolgt die Entwicklung und Untersuchung eines neuen ressourceneffizienten Fertigungsverfahrens für das Rapid Tooling. Das vorgestellte Verfahren Tooling kombiniert zwei additive Fertigungskategorien: Sheet lamination und Direct Energy Deposition (DED). In dieser Kombination wird der Kern des Umformwerkzeugs durch Blechlaminierung in kurzer Zeit und zu geringen Kosten hergestellt. Die entstehenden Treppenstufenbereiche werden durch Laserpulvarauftragschweißen (LPA), zugehörig zur DED-Kategorie, kompensiert. Drei Nachbearbeitungsmethoden, Fräsen, Glattwalzen und Laserpolieren, werden zur Verbesserung der Oberflächenrauheit der aufgebrachten Flächen eingesetzt und verglichen.

Die Ergebnisse zeigen, dass das Konzept einer zweistufigen Füllstrategie, bei der die Werkzeugbleche zunächst zusammengefügt wurden, und im nächsten Schritt die verbleibenden Treppenstufenbereiche durch LPA gefüllt werden, von Vorteil ist. Untersuchungen an Kehlnahtverbindungen bei verschiedenen Prozessparametern und Werkzeugblechkombinationen zeigen, dass eine höhere Laserleistung und Vorschubgeschwindigkeit zu einer höheren Festigkeit führen; allerdings sollte auch die Blechdicke berücksichtigt werden, um das Durchschmelzen der dünnen Bleche zu vermeiden. Beim Füllen zeigt sich, dass ein Auffüllen in radialer Richtung eine bessere Oberflächenrauheit als Auffüllung in der Kehlnahtrichtung aufweist. Die Vorwärmung des Werkzeugblechs zur Verringerung der Zugeigenspannungen führt nur zu einer Verringerung um 25 %, was zu einer Welligkeit der aufgebrachten Oberfläche führt. Daher kann sie vernachlässigt werden.

Ein semi-analytisches Modell zur Analyse der Spannungsverteilung zeigt die Möglichkeit der Verwendung von Werkzeugblechen mit niedriger Festigkeit in einem Großteil des laminierten Werkzeugs. Tiefziehversuche sind für zwei Arten von Blechen erfolgreich, für kaltgewalzten hochfesten Stahl (HC380LA) und für eine Spezieltiefziehgüte (DC06). Verschleißuntersuchungen zeigen, dass der Verschleiß der mit der Hybridmethode hergestellten Matrizen im Vergleich zur konventionellen Methode gering ist. Ein Demonstrator beweist die Herstellbarkeit auch komplexer Geometrien.

Die wirtschaftlichen und technologischen Vorteile des Hybridverfahrens werden mit konventionellen und vollständig mit LMD gefertigten Werkzeugen verglichen und die Anzahl der möglichen Blechkombinationen für die Werkzeugauslegung wird unter Berücksichtigung von Kosten- und Energiekriterien reduziert.

Index

Publication of contents

Dardaei Joghan, H., Hahn, M., Sehrt, J.T, Tekkaya, A.E., 2022a. Hybrid additive manufacturing of metal laminated forming tools. CIRP Annals, vol. 71, pp. 225-228.

Dardaei Joghan, H., Hahn, M., Tekkaya, A.E., 2022b. Effect of preheating during laser metal deposition on the properties of laminated bending dies. The International Journal of Advanced Manufacturing Technology, vol. 125, pp. 157-168.

Dardaei Joghan, H., Hahn, M., Aboola, O. E., Tekkaya, A. E. 2023a. Resources and manufacturing technology evaluation of hybrid additive metal laminated tooling for forming. Materials Research Proceedings, vol. 28, pp. 21-30.

Dardaei Joghan, H., Jölker-Jäger R., Komodromos A., Tekkaya A. E. 2023b. Hybrid additive manufacturing of forming tools. Special Issue on Automotive Lightweight, vol. 6, pp. 311-323.

List of supervised student theses

Bill Febrian Winoto, 2021. Development of a semi-analytical model for laminated forming tools under process forces. Master thesis.

Jakob Hamm, 2020. Untersuchung und Beurteilung der Strategien zur Verbindung lamellarer Stahlbauteile durch einzelne Schweißnähte mittels Laserpulverauftragschweißen. Bachelor thesis.

Mehmet-Kasim Ocakli, 2022, Hybride additive Fertigung einer laminierten Werkzeuggeometrie mit Freiformflächen. Bachelor thesis.

Niklass Resse and Neshanth Paskaran, 2021. Erstellung einer Berechnungsmethode für die produktionstechnische Bewertung von Fertigungskombinationen mit Schicht-Laminat-Verfahren und Laserpulverauftragschweißen. Project work.

Ololade Emmanuel Agboola, 2023. Effect of process parameters of laser metal deposition and laser polishing on flat surfaces. Project work.

Ololade Emmanuel Agboola, 2023. Realization of hot stamping dies using an optimized hybrid additive laminated tool. Master thesis.

Surav Tank, 2023. Investigation of laser polishing and ball burnishing effects on laser metal deposited surfaces. Project work.

Formula symbols and abbreviations

Nomenclature

Symbol	Unit	Description
A	mm^2	Area
A_c	mm^2	Material mixture area with substrate after deposition
A_D	mm^2	Deposited area
A_g	-	Fracture strain
A_P	mm^2	Part's area
A_s	mm^2	Scrap's area
a	mm	Free length of the tool sheet
a_b	mm	Length of stacked beam under support
a_e	mm	Radial depth of cut
a_p	mm	Axial depth of cut
b	mm	Width of the tool sheet
b_S	mm	Tool sheet offset
c_d	mm	Clearance between the die and the punch
C	-	Constant value
C_L	mm	Cutting length
c	-	Thickness-to-length ratio
D	N	Axial stiffness of stacked beam
D_B	mm	Blank initial diameter
D_{Die}	mm	Inner diameter of deep drawing die
D_P	mm	Punch diameter
d	mm	Cylindrical hole with diameter
d_L	mm	Laser spot diameter

Symbol	Unit	Description
$\dot{D}$	g/min	Deposition rate
E	MPa	E-Module
E_{B}	J	Energy for ball burnishing
E_{Bulk}	J	Energy for production of bulk material
E_{H}	J	Energy for hardening
E_{LC}	J	Energy for laser cutting
E_{LMD}	J	Energy for LMD
E_{LP}	J	Energy for laser polishing
E_{M}	J	Energy for milling
E_{Powder}	J	Energy for production of powder
E_{PP}	J	Energy for post-processing
E_{Sheet}	J	Energy for production of sheet
E_{rq}	J	Required energy consumption
F_{H}	N	Horizontal force
f	mm/min	Feed rate or scanning speed
f_{P}	mm/min	Feed rate of laser polishing
G	GPa	Shear modulus
H	mm	Height of elastic support
H_{B}	RC or Vickers	Hardness
H'_B	-	Change of hardness
h_{c}	mm	Depth or height of the cup
h_{d}	mm	Hatching distance
I	mm^4	Inertia of moment
j	-	Degree of polynomial

Symbol	Unit	Description
k	GPa	Elastic modulus of elastic bed
L	-	Constant value
M	N.mm	Bending moment
m	-	Slope of the inter-planer spacing to different tits
m_{P}	kg	Part’s mass
m_{s}	kg	Scrap’s mass
m_{Step}	kg	Sum of stair-step areas
$\dot{m}$	g/min	Powder feed rate or mass flow
n	-	Number of stacked tool sheets
P	W	Laser power
P_{BH}	MPa	Blank holder pressure
P_{N}	-	Number of possible sheet combinations
P_{P}	W	Laser power for laser polishing
P_{r}	MPa	Reaction pressure of elastic bed
q	N/mm	Distributed force
Q	N	Shear force in beam theory
Q	mm^3/h	Material removal rate
R	mm	Die corner radius
R'_{m}	mm	Bending radius after unloading
R'_a	-	Change of average surface roughness
R'_z	-	Change of maximum height of surface roughness
R_{a}	µm	Arithmetical mean deviation of the profile in 2D
R_{m}	MPa	Ultimate strength

Symbol	Unit	Description
R_m	mm	Bending radius before unloading
R_P	mm	Punch corner radius
$R_{p0,2}$	$N \cdot mm^{-2}$	Tensile strength
R_z	µm	Maximum height of the profile in 2D
r	-	Anisotropy coefficient
r_n	-	Normal anisotropy
Δr	-	Planer anisotropy
S	$N.mm^2$	Stiffness of stacked beam
S_a	µm	Arithmetical mean deviation of the profile in 3D
SEC	J/kg	Specific energy consumption
S_k	µm	Roughness depth of the core
S_{mr}	%	Areal material ratio
S_z	µm	Maximum height of the profile in 3D
s	mm	Thickness position
T	°C	Temperature
T_s	mm	Sum of the stacked beam thicknesses
T_H	s	Time for hardening
T_{LC}	s	Time for laser cutting
T_{LMD}	s	Time for LMD
T_{PP}	s	Time for post-processing
T_T	s	Total manufacturing time
t	mm	Tool sheet thickness
t_b	mm	Blank thickness
u	mm	Displacement of the stacked beam

Symbol	Unit	Description
u'	rad	1st order invariant of displacement (Bending angle)
u''	1/mm	2nd order invariant of displacement
u_2'''	1/mm	3th order invariant of displacement
V	mm^3	Volume
v_P	mm/min	Punch velocity
W_a	µm	Waviness arithmetical mean deviation of the profile in 3D
W_D	mm	Working distance between laser nozzle and deposited surface
X	-	Material yield
x^N	-	Normalized length in the x-direction
$z*$	mm	Distance of the neutral layer to the middle of the beam layer's cross-section
z^N	-	Normalized length in the thickness direction
β	-	Deep drawing ratio
Γ	-	Coefficient factor
γ	°	Angle
$\bar{\varepsilon}_{Plastic}$	-	Equivalent plastic strain
ε	-	Strain
θ	W/(kg/mm)	Track-specific power density
θ_z	°	Angle of rotation of normal to the mid-surface of the deflection in beam theory
Λ	-	Correction factor for maximum von Mises stress
λ	J/mm	Applied energy per unit length by laser polishing

Symbol	Unit	Description
μ	-	Friction factor
ρ	Kg/mm^3	Density
$\sigma_{v.M.}^{N}$	-	Normalized von Mises stress
σ_f	MPa	Flow stress
σ_n	MPa	Normal stress
σ_r	MPa	Radial stress
σ_t	MPa	Tangential stress
σ_w	MPa	Weld fracture strength
τ	MPa	Shear stress
ν	-	Poisson's ratio
$\varnothing$	-	Dilution ratio

Indices

Index	**Description**
0	Initial value
eff	Effective
eq	Equivalent
max	Maximum
min	Minimum

Abbreviations

Abbreviation	**Description**
2D	Two dimensional
3D	Three dimensional
AM	Additive manufacturing
AWJ	Abrasive water jet
BC	Boundary condition
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CIRP	International academy for production engineering
CNC	Computer numerical control
CVD	Chemical vapour deposition
DED	Direct energy deposition
EBSD	Electron backscatter diffraction
EDX	Energy-dispersive X-ray spectroscopy
FEM	Finite element method
FGM	Functionally graded material
FSW	Friction stir welding
GMAW	Gas metal arc welding

GTAW	Gas tungsten arc welding
HAM	Hybrid additive manufacturing
HAZ	Heat affected zone
LBMD	Laser-based metal deposition
LDMD	Laser direct metal deposition
LENS	Laser engineered net shape
LFF	Laser freeform fabrication
LLM	Layer laminated manufacturing
LMD	Laser metal deposition
LMDS	Laser metal deposition shaping
LOM	Laminated object manufacturing
LSA	Laser surface alloying
LST	Laminated steel tooling
N.A.	Neutral axis
PEL	Profiled edge laminae
RT	Room temperature
SEC	Specific energy consumption
SOM	Surface over-melt
SSM	Shallow surface melting
TIG	Tungsten inert gas