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Robot-based guiding of extrusion profiles - Increase of guiding accuracy by considering the temperature-dependent effects

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Abstract

Three-dimensionally curved extrusion profiles are used to manufacture lightweight frame structures. These profiles have to be flexibly manufactured, especially for a small batch production. For this reason, a flexible process chain with an automated extrusion process was build up. In this paper an approach for offline calculation of path data for the guiding of unsteady extrusion profiles with industrial robots is presented. This approach includes a consideration of the profile deformation caused by cooling during production. The required correction values are determined by using a coupled kinematic and thermal FEM simulation.

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Keywords: path data, thermomechanical simulation, extruded profile, industrial robot

1. Introduction

The energy efficiency of machinery, vehicles and equipment can be increased by reducing the weight of the moving masses. Therefore, lightweight construction concepts will gain more and more importance in the future. One possibility of reducing weight is to optimize the supporting structure, for example, by using aluminum space frame structures. These aluminum space frames are already being used in the automobile and aviation industry [1, 2].

In addition, there is for example a trend in the automotive industry towards a greater variant diversity, which results in smaller quantities [3, 4]. For this reason, the quantity-flexible production of lightweight supporting structures becomes more and more the centre of attention. However, fully automated production lines are rarely used in low volume production of lightweight supporting structures due to the lack of flexibility.

Therefore, the groundworks for setting up a product-flexible process chain are investigated in the Collaborative Research Centre Transregio 10. As part of this research work, a flexible facility was built to manufacture three-dimensionally rounded aluminum profiles which form the basis for lightweight supporting structures (Figure 1).

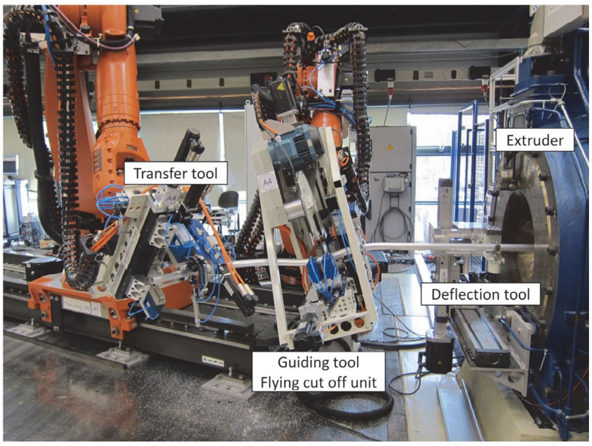

Fig. 1. Extruder and moving cut-off unit

The production of these profiles is carried out by using the method of "multi-axis rounding during extrusion". During this process, the three-dimensionally rounded aluminum profiles can be manufactured with

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the help of an extruder that has been modified accordingly. The pieces are shaped by a special deflection tool that is located at the outlet of the extruder. Synchronously with this process, the emerging profile is guided through the room by two tools, each of them mounted on industrial robots (Figure 1). This procedure prevents the influence of gravity caused by the already manufactured profile on the emerging limp profile. The desired length of the profile is produced by the flying cut-off unit [5] which is cutting off the continuously emerging profile with a circular saw mounted on the effector of the first industrial robot (Figure 1).

2. State of the art

2.1. The flying cut-off

The flying cut-off system displayed in Figure 1 and its control concept will be described in more detail below. The non-reactive guiding and cutting of the rounded profile is carried out by a combined device for guiding and circular sawing and a transfer tool that also allows guiding and clamping of the extruded profile. Both tools are operated by two six-axis industrial robots. The guiding units are mounted onto controllable additional axes [8].

The system is controlled by a numerical control that is supervising the individual controls of the industrial robots and guiding units. This way, the movements of all kinematics consisting of 23 axes are highly synchronous.

2.2. Path data compilation

The control data for the numerical control and the path data for both industrial robots and for the additional axes of the guiding units are created offline. The basis for the offline creation of the path data is a kinematic CAD model in the CAD program Catia V5. In this program, a CAD model of the profile to be manufactured manipulates the individual components of the model which are connected via kinematic constains. The model depicts the freedom of movement of the prototype installation. Coordinate systems are defined for every TCP of the robot in the model. The movement of the coordinate systems is registered relative to the initial positions of these coordinate systems. This path data can then be directly read by the robot control. The thermal expansion of the profile is already taken into consideration in this installation. For this purpose, the contour data which is available in the form of a CAD model of the profile is extended by a constant elongation factor. With a thermal expansion coefficient of 23 µm/K•m and at a production temperature of 400°C, for example, this means a change in length of approx. 8,7 mm/m [9].

3. Requirements

In order to ensure a high contour quality of the profile to be manufactured, the robot paths have to be exactly adjusted to the contour movement of the extruded profile. But during its production, the profile is subject to transient effects. The essential reason for this is the cooling of the profile that starts directly after its extrusion. As a consequence, a distortion of the profile occurs. This effect is reinforced even more by a variable cross section of the profile which is an extension of the installation presented at the beginning [6]. For the production of load-adjusted profiles, the wall thickness can be increased on one side over a defined length to twice its original thickness. In profiles with a one-sided thickening of the wall, a deflection occurs during cooling. This deflection of the profile is the result of the different temperature gradients when cooling profiles with locally thicker walls [7].

This problem cannot yet be taken into consideration in the current path creation. Therefore, this scientific paper presents an approach that takes a thermal distortion into account when creating the path data offline.

4. Approach for creating path data by taking thermal distortion into account

The approach of extending the path data creation includes the superimposing of correction values for the dynamic profile movement due to cooling onto the already existing path data. In order to consider the dynamic profile movement during the manufacturing process due to thermal distortion, correction values from a thermomechanical FEM simulation are added to the path data from the CAD simulation of the kinematics.

This is done by using a temporal and kinematic coupling. Figure 2 shows the connection.

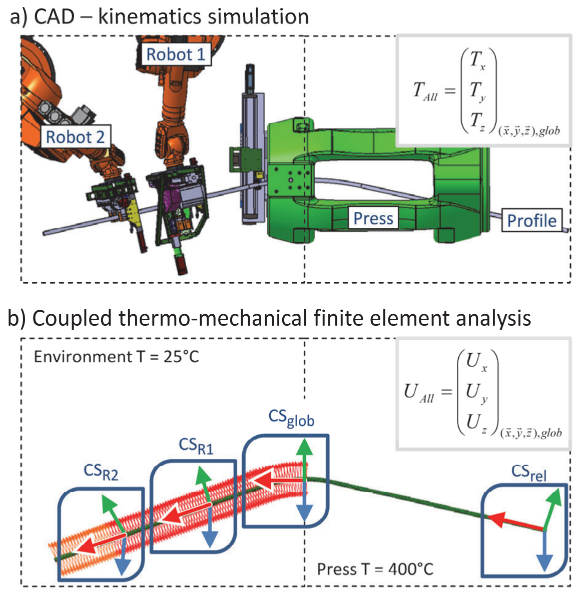

Fig. 2. Path data and calculation of the path data correction values

The path data of the robots consists of 250 space points per second and the respective orientations (T_{All}). The creation of the paths occurs in a CAD based kinematic offline simulation model. Correction values are superimposed onto this set of path points by a FEM simulation. The result is the following new trajectory.

$$T_{New} = \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix}_{(\vec{x},\vec{y},\vec{z}),glob} + \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix}_{(\vec{x},\vec{y},\vec{z}),glob} \quad (1)$$

4.1. Modeling of the kinematics simulation

A major challenge during modeling is the precise imaging of the profile movement and the coupling to the offline simulation model. In order to meet this challenge, a kinematic connection is created in the FEM simulation. In doing so, the continuous profile development is mapped by an equally growing heat transfer surface. Furthermore, the current position value of the guiding robots relative to the point of the profile generation must be possible to determine for an accurate assignment of the correction values of the FEM simulation.

Figure 2 a) shows the CAD kinematics simulation with the modeled plant. The guided profile in this example is already half produced. Figure 2 b) shows the thermo-mechanic FEM simulation. To map the kinematic connection of the CAD model, four coordinate systems are defined in the model. Figure 2 b) depicts the arrangement of the different coordinate systems. The CS_{rel} represents the point of origin of the simulation and the results of the simulation are available in this coordinate system. The CS_{glob} illustrates the transition point where the developing profile becomes the produced profile. This coordinate system is used for coupling the path data creation to the FEM simulation which means that the equality of the axial directions is ensured. The CS_{R1} and CS_{R2} are defining the reference points for the robots. These coordinate systems have a fixed distance to the CS_{glob}.

For kinematic control, the coordinate system CS_{glob} is moved along the neutral fiber of the profile. At the beginning of the correction value determination, the CS_{glob} can be found on the opposite side of the CS_{rel}. The coordinate system CS_{glob} moves at the real production speed of the profile towards the CS_{rel}. The movement of the coordinate systems along the neutral profile fibre is depicted in Figure 3.

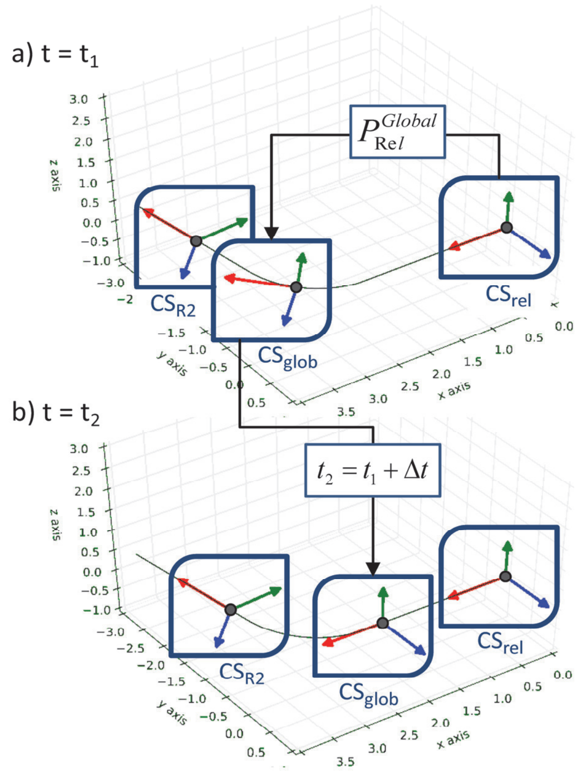

Fig. 3. time-related movement of the coordinate systems

In order to transfer the deformations determined with the help of the FE solver Abaqus (produced by Dassault Systemes) into correction values, they are adapted by a coordinate transformation. According to the time-related movement, the transformation matrix is also adapted. This means, it is calculated for every correction point. The corresponding conversion for the global correction values is:

$$U_{All} = \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix}_{(\vec{x},\vec{y},\vec{z}),glob} = \left(P_{rel}^{glob}\right)^{-1} \times \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix}_{(\vec{x},\vec{y},\vec{z}),rel} \quad (2)$$

The transformation matrix $P_{\mathrm{Re}l}^{Global}$ describes the conversion of the profile vector space (*rel.*) to the extrusion press vector space (*glob*). In order to be able to calculate the rotation of the coordinate system, supporting points for the transformation matrixes have to be defined. This has to be taken into consideration when modeling the extrusion profile. A conventional cross linking of the profile is not possible since the deformation at the profile points can not be systematically read out. The modeling is carried out via a shell. For a profile with a diameter of 40 mm, this shell consists of 32 elements which are distributed round the supporting point at the circumference. Each of these elements has 4 node elements which allow a definition of the orientation. At the beginning of every new set of layers, the counting mode is increased by 50. Figure 4 illustrates the structure.

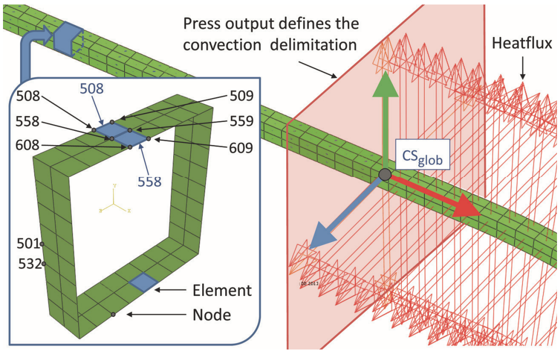

Fig. 4. Heat front and nodes as well as the numbering of elements

Therefore, every set of elements has a start node, an end node and a rotation center point that defines the neutral fibre of the profile. On the basis of these points, the supporting points and their local orientations along the neutral fibre are calculated with a kinematics routine. In order to be able to carry out the alignment of the coordinate systems at the profile curvatures in an accurate manner, the initial orientation is determined at the beginning (Figure 5a)). Afterwards, the polar orientation at that point is determined (Figure 5b)). After that, the CS is moved tangentially and then rotated around the appropriate orientation according to the initial orientation (Figure 5c), d)).

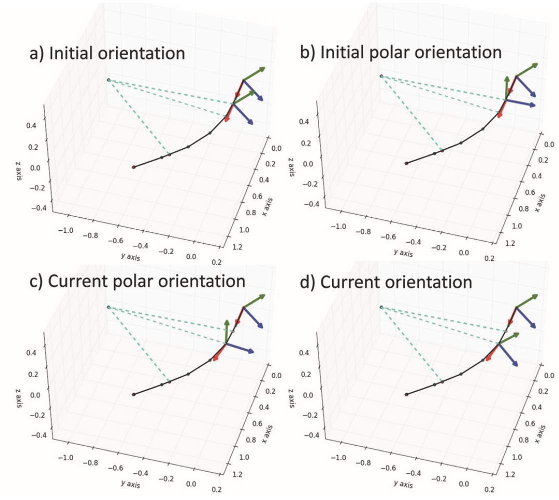

Fig. 5. Orientation of the supporting points

The description of the exactly defined node points also has the advantage that different heat transfers can be defined for the developing coordinate system of the profile (CS_{glob}). This permits the modeling and the thermomechanic simulation of a continuously developing profile.

4.2. Modeling of the thermosimulation

For simulating the heat dissipation, the elements are exposed to convection. During this procedure, only the elements which have already been extruded are exposed to convection. This is defined in different steps. For every step, an additional element convection is defined. The thermal parameters of the simulation model are determined according to [10] and [11]. The temperature-related expansion and the temperature-related elastic behavior should be considered. See Table 1.

Parameter	Value	
Conductivity [W/m K]	210	
Density [kg/ m³]	2700	
Young's Modulus [Gpa]	72.33	T = 0°C
	72.33	T = 200°C
	51.33	T = 300°C
	9.67	T = 400°C
Expansion [10^{-6}/K]	23.4	T = 60°C
	24.5	T = 150°C
	25.6	T = 250°C
Poisson's Ratio	0.35	
Specific Heat [J/K]	898	

Tab. 1. Parameters of the model

5. Results

The results of the simulation are displayed below. Figure 6a) depicts the deformation of a 2D rounded profile with a local increase in wall thickness in the curvature. Figure 6b) shows a 3D rounded profile whose wall thickness was also increased locally. The wall thickenings are highlighted in red.

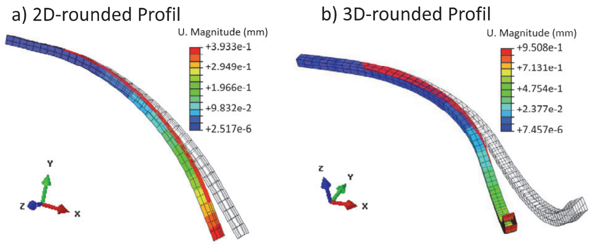

Fig. 6. Material displacement in the 2D and 3D profiles

The results for the correction values of the industrial robots that are guiding the profile through the room, were calculated by the means of a routine for certain distances of the robots from the exit of the press. The two industrial robots are located at a distance of 1.96 m for robot N. 1 or 1.22 m for robot N. 2 from the exit of the press. The routine has as input the node displacement calculated in the thermal simulation and determines according to the time the deformation of the profile at the robot position. This deformation can be compensated with correction values which are the opposite values of the node displacement of the thermal simulation.

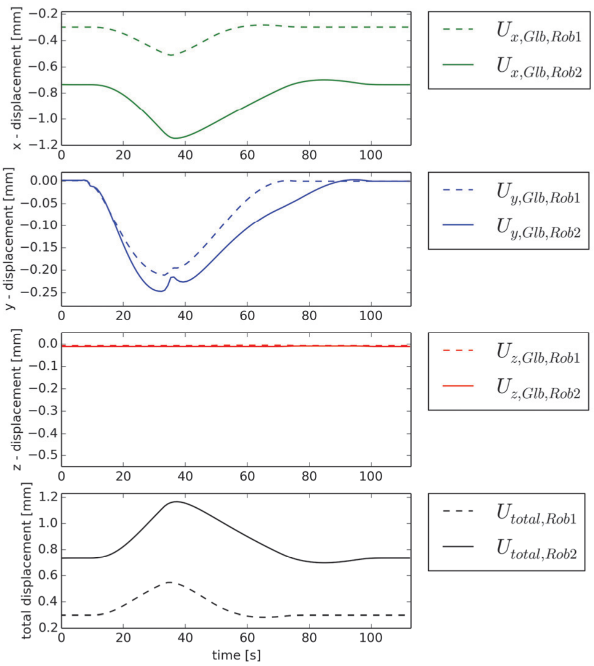

Fig. 7. Correction values for the production of a 2D rounded profile

2D profile	Robot 1		Robot 2	
	Min	Max	Min	Max
x-axis [mm]	-1.1	-0.7	-0.5	-0.3
y-axis [mm]	-0.2	0.0	-0.2	0.0
z-axis [mm]	0.0	0.0	0.0	0.0
Magnitude[mm]	0.7	01. Feb	0.3	0.5

Tab. 2. Extreme points of the correction values

Figure 7 and Table 2 as well as Figure 8 and Table 3 illustrate the results of the deformations of the 2D rounded profile or the 3D rounded profile.

At the time t=0 s only a pure deformation in x direction can be noticed. This deformation is caused by the displacement of the preceding profile. At the time t= 9.3 s, the production of the bent profile starts. This can be observed in both cases by the increase in correction values. The maximum correction values for the industrial robots are 1.2 mm in case of a 2D profile and up to 1.0 mm for a 3D profile.

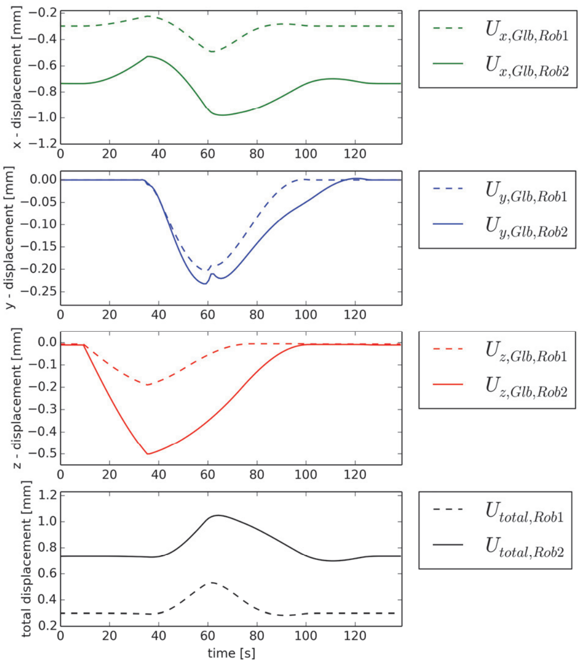

Fig. 8. Correction values for the production of a 3D rounded profile

3D profile	Robot 1		Robot 2	
	Min	Max	Min	Max
x axis [mm]	-1.0	-0.5	-0.5	-0.2
y axis [mm]	-0.2	0.0	-0.2	0.0
z axis [mm]	-0.5	0.0	-0.2	0.0
Magnitude[mm]	0.7	1.0	0.3	0.5

Tab.3. Extreme points of the correction values

6. Summary

In this publication, a new approach for offline calculation of path data for the guiding of unsteady extrusion profiles with industrial robots was presented. This approach includes a consideration of the profile deformation caused by cooling during production. The required correction values are determined by using a coupled kinematic and thermal FEM simulation. This way, a flexible offline path planning is available in the future that can take account of the profile movement due to cooling. Now, further investigations have to prove that also a high guiding quality can be reached by applying this approach. The improvement of the guiding quality will lead to an expected enhanced accuracy of the profile contour.

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