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Automated Driving by Standardizing and Scaling the Manufacturing Strategy

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Abstract

Driving, an incremental forming method, can be carried out on driving machines. In a past project, this traditionally manual manufacturing method was automated through performing manual manipulations and manufacturing identical parts by robot handling. An advancement of this automation scheme is to define a set of standard sheet metal parts and derive a manufacturing strategy by combining tracked strategies for these standard parts. In this paper, we present a method to derive manufacturing strategies for geometric variations of standard sheet metal parts. In addition, a model describing the relation between geometric and process parameters is built to improve transformed manufacturing strategies.

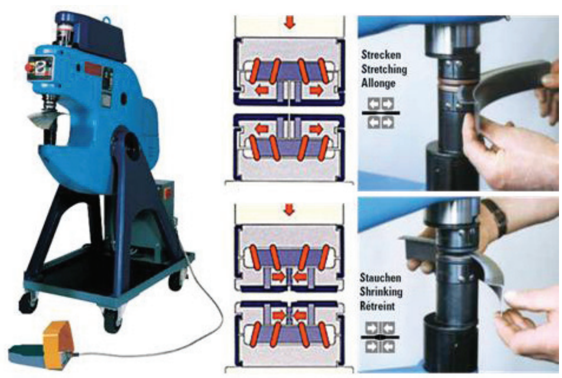
Keywords: Incremental Forming; Driving; Automation; Standardization; Transformation; Manufacturing Strategy

1. Introduction

In the field of sheet metal forming, there is a tendency towards reducing time cycles of production and at the same time achieving a high degree of customization as well as to an increasing number of prototypes. This requires a flexible and economic manufacturing method for individual part and small batch production.

One option to achieve these objectives arises from the so called Amino-Method. Since the early 1980s many investigations have been made to modify and optimize this process and to identify limits and constraints on it [1], [2]. Even though much effort has been spent in order to decrease these limitations, still there are strong bounds on the process [3], [4].

Within the framework of this paper we will focus on a more promising alternative to meet the requirements stated at the beginning: The driving process, an incremental forming method, which is carried out by a driving machine, the so called Kraftformer (Fig. 1 (a)). The machine employs universal tool sets that can be used to create almost any geometry for the sheet metal parts.



(a) (b)

Fig. 1. (a) Driving machine; (b) Driving tools for stretching and shrinking [5]

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The main tools used on the driving machine can perform stretching and shrinking in local forming areas of the metal part (Fig. 1 (b)). The final geometry is produced by this incremental forming method in a large number of steps. Even though this process is one of the oldest known incremental forming methods, systematic research investigations in this area have not started before 2001.

Research effort has been put into studying and analyzing the driving process and clarifying the scope and spectrum of applications [6], [7], [8], [9].

Driving is traditionally a manual manufacturing method. It needs to be automated to reduce the labour costs and to achieve cost-effective production. In [10], the automation scheme copied driving was introduced, in which an industrial robot was used to replace the manual manipulations. This automated driving process has two steps: The first step is to synchronously record the process parameters (stroke positions and forces) as a manufacturing strategy in the manual forming process by an optical tracking system; the second step is then to translate the manufacturing strategy for the interaction between the robot and the driving machine.

Because of the manual tracking step, the method developed above is suitable for a small batch size but not for individual parts. In order to further increase the automation level or rather to reduce the manual work in that automation process, it is proposed to derive the manufacturing strategy for a new metal part from a database of standard manufacturing strategies.

2. Problem Formulation

Driving is a very complex forming process, in which the material properties are changing by work hardening and the contact conditions are varying with every stroke. This makes it very difficult to directly model this driving process, thus a model-free idea will be presented here. It uses knowledge developed within the copied driving project, see [10]. The process is depicted in Fig. 2.

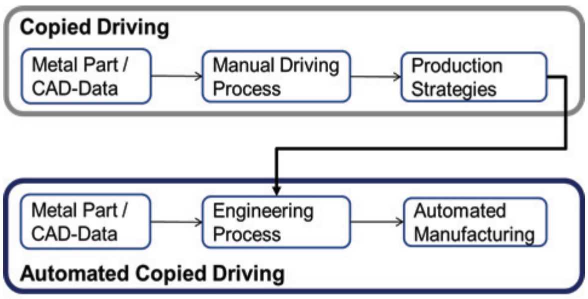


Fig. 2. Automation scheme: Automated copied driving

To further automate the manufacturing process, we now aim at completely replacing the manual driving step by deriving a manufacturing strategy for a new metal part from the strategies already recorded. The first step is to define a number of standard metal parts, from which, after a suitable fragmentation, the new metal part will be constructed. To keep the required number of standard metal parts as small as possible, it is essential to derive manufacturing strategies for transformed variants of these standard metal parts from the recorded manufacturing strategies. This transformation process will be the main focus of this paper.

3. Problem Formulation

With a manufacturing strategy, a metal sheet can be formed into some desired end geometry. On the one hand, while the number of manufacturable end geometries is infinite, the geometry features are mathematically describable by a limited number of geometric parameters. On the other hand, there is an infinite number of manufacturing strategies, even for a single corresponding geometry. Hence, it is essential to define a sheet metal part with a standard geometry and a corresponding manufacturing strategy.

3.1. Extraction of geometry features

Fig. 3 shows a motorbike tank that was produced by copied driving. It consists of a total of 10 metal parts welded together. These parts have different but similar geometries. The geometric features of one of them can be extracted and idealized into a combination of four simple geometrical components: one flat square surface, two quarter cylinders and one eighth of a sphere. Of course, the other combinations of the geometrical components could also be defined as required.

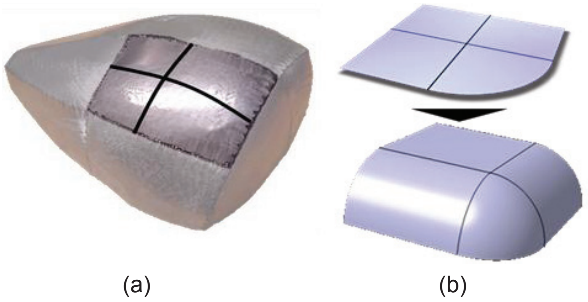
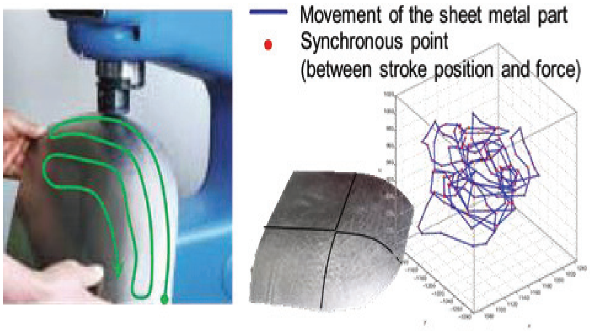


Fig. 3. (a) Motorbike tank, produced by the copied driving; (b) Exaction and idealization of the metal part

3.2. Standard manufacturing strategy

To obtain the geometry defined in the last section, the metal part must be formed with the driving machine using some manufacturing strategy. Such a strategy contains the forces of the strokes together with the sixdimensional positions of the tool center point (i.e., its position in the robot coordinate system and its Euler angles), which uniquely determines the stroke positions.



(a) (b)

Fig. 4. (a) Driving with a manufacturing strategy; (b) End geometry and the corresponding manufacturing strategy

The tool center point (TCP) is a uniquely defined point on the robot grasper. Hereby, the trajectory of the strokes has a somewhat helical form (Fig. 4 (a)) and the distance between one and the next stroke remains constant. After carrying out the tracking process of the manual driving, the standard manufacturing strategy of the defined sheet metal part is created (Fig. 4 (b)).

4. Transformations

The manufacturing strategy obtained by the tracking process is naturally only applicable for a part with specific dimensions. Of course, in practice one frequently needs to produce parts with the same geometric characteristics, but different dimension, e.g., scaled/sheared or otherwise transformed versions of the original part. Naturally it would be most reasonable to study different transformations of the final geometry of some part, i.e. to directly determine manufacturing strategies for some 3D-transformation of the part under consideration. This approach leads to numerous scientific and practical challenges that will be addressed elsewhere. Here we focus on a simpler idea of considering 2D-transformations of the initial geometry and hence study a transformation of the initial manufacturing strategy. The initial geometry of a sheet metal part is flat and roughly displays the contour of the end geometry. Within the scope of this paper we restrict ourselves to linear transformations. It is known that a manufacturing strategy depends on the initial and the end geometry of the sheet metal part. Thus it is assumed here that the standard manufacturing strategy can be linearly transformed, using the same transformation as for the sheet metal part, to a corresponding manufacturing strategy.

4.1. Linear Transformation

A two-dimensional linear transformation can be described by a 2x2 matrix. As every two-dimensional linear transformation is a combination of scaling, shearing and rotation, we can also write the linear transformation in a form more suitable for visual interpretation:

$$A = \begin{pmatrix} \frac{L_x}{I_x}\cos\beta & \frac{L_y}{I_y}\cdot\cos(\alpha-\beta) \\ -\frac{L_x}{I_x}\sin\beta & \frac{L_y}{I_y}\cdot\sin(\alpha-\beta) \end{pmatrix} \quad (1)$$

The meaning of the parameters is depicted in Fig. 5.

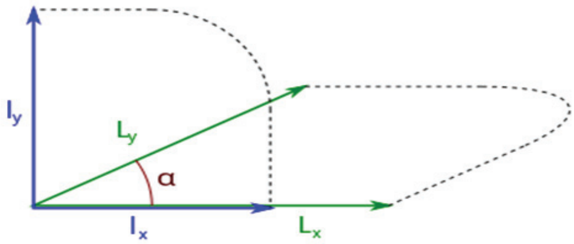


Fig. 5. Linear transformation

The matrix A performs a dilation (stretching or shrinking) in x-direction by a factor of L_x / I_x and by a factor of L_y / I_y in y-direction, a shearing by an angle α and a rotation by an angle β. In the application considered here, rotation is irrelevant with respect to the geometry. Hence we can assume β=0, simplifying the matrix to

$$A = \begin{pmatrix} \frac{L_x}{I_x} & \frac{L_y}{I_y}\cdot\cos\alpha \\ 0 & \frac{L_y}{I_y}\cdot\sin\alpha \end{pmatrix} \quad (2)$$

These parameters can be obtained from the original metal sheet and the desired transformed metal sheet, as seen in Fig. 5.

4.2. Transformed manufacturing strategy

The transformation matrix can now be used to devise a suitable manufacturing strategy. It consists of three-dimensional stopping positions for the robot grasper and corresponding stroke depths of the Kraftformer. The corresponding three-dimensional transformation can be obtained by combining the two-dimensional linear transformation described above with a coordinate system transformation mapping the robot coordinate system to the grasper coordinate system (Fig. 6).

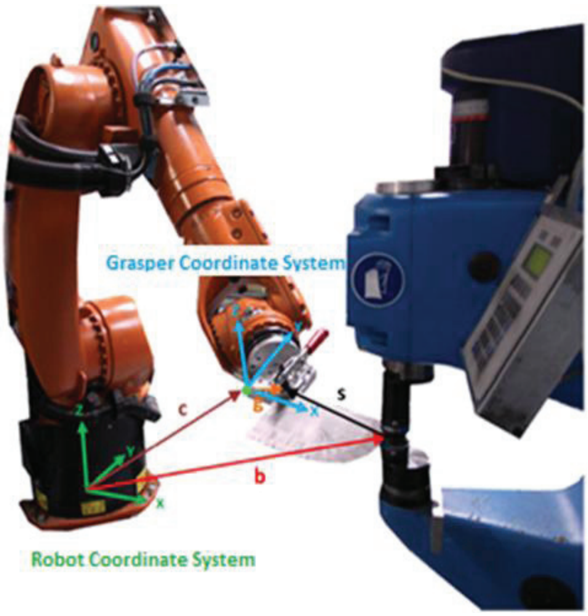


Fig. 6. Configurations of the robot, the grasper, the sheet metal part and the driving machine

A rectangular corner of the metal part is fixed on the grasper. The vector s from this corner to the center of the driving tool directly describes the geometry-dependent stroke positions. It is scaled with the transformation matrix A to reposition the corner of the metal part according to the new geometry of the sheet metal part. Moreover, the vector c from the origin of the robot coordinate system to the TCP (tool center point) can be calculated as follows:

$$c = b - As - g \tag{3}$$

The vector g from the TCP to the metal sheet corner is given in the robot coordinate system and the vector b remains unchanged as long as no relative displacement between the robot and the driving machine takes place.

5. Geometry Deviations of Scaled Parts

Now it is necessary to check the derived manufacturing strategy and determine whether the desired target geometry of the given sheet metal part can be created. The linear transformations scaling and shearing are analyzed separately.

The sheet metal parts were formed into the defined geometries (scaled or sheared) by use of the corresponding manufacturing strategy. Its real geometries are digitalized by a GOM ATOS [11] optical measurement system and then compared with the desired target geometries. The geometry deviations are subsequently analyzed.

5.1. Stretching and Shrinking

In the case of scaling in y-direction, the transformation matrix is

$$A = \begin{pmatrix} 1 & 0 \\ 0 & \dfrac{L_y}{l_y} \end{pmatrix} \tag{4}$$

In our experiments the standard metal sheet is scaled in y-direction with four different scale factors (Fig. 7). Note that, by symmetry, scaling in x-direction yields the same results. Fig. 7 also shows that the measured deviations increase with the deviation of the scaling factor. The reason for this is that the density of the strokes is changed after scaling. The different distances between the neighbour strokes affect the different material hardening in the local forming area. With a manufacturing strategy scaled by some large factor, the desired geometry cannot be reached any more within tolerable error bounds.

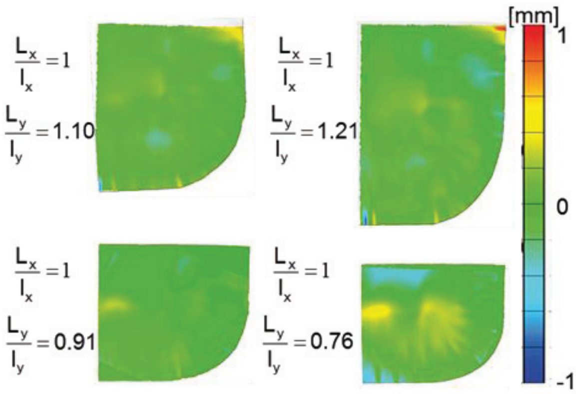


Fig. 7. Geometry deviations by the stretched manufacturing strategies

5.2. Shearing

In our experiments, the standard metal sheet is sheared around the rectangular corner with the four different shear angles α = 70°, 80°, 100° and 110°. The obvious geometry deviations are observed in the spherical area. They are greater than the corresponding values in the case of only stretching or shrinking. Again the deviations are caused by different densities of the strokes. If shearing is applied, the density is not just scaled as for dilations, so that the material hardening is more complex in the local forming area.

Naturally, the process described in section 4 will only be applicable for small enough scaling factors and shearing angles. For larger values of these parameters, a suitable transformation of the manufacturing strategy will have to include changing the number and density of strokes as well as the stroke curves on the metal sheets, e.g. by introducing new stroke curves for larger stretch factors. Several methods which take these aspects into account are currently under investigation. A first step in this direction will be studied detailed in the next section.

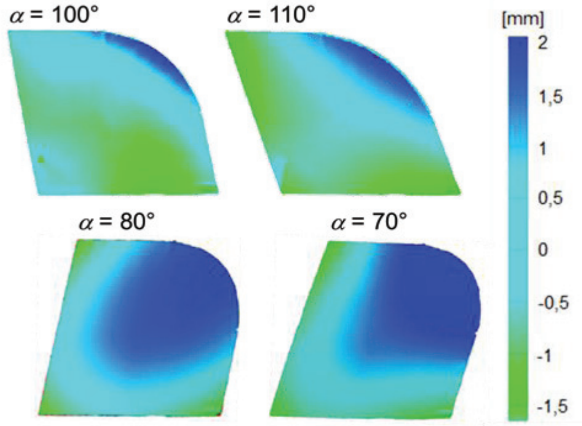


Fig. 8. Geometry deviations by the sheared manufacturing strategies

6. Curvature Model

As can be seen from the experiments presented in section 5, the curvature of the eighth sphere is the major geometric feature of the sheet metal part. It must be investigated more closely to decrease the geometry deviations between the standard and scaled sheet metal parts. As described in section 3.2, the end geometry is dependent on the sequence and the density of the strokes. Considering the helical structure of the stroke curve, the density of the strokes must be adapted differently between the longitudinal and lateral direction.

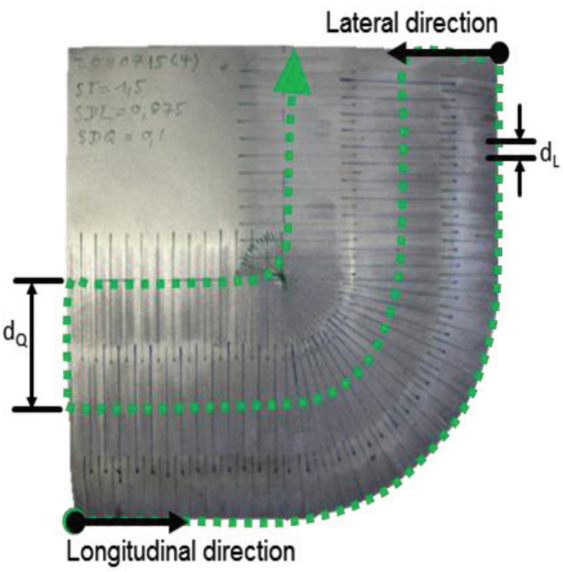


Fig. 9. Longitudinal and lateral density of the strokes as well as the stroke force determines the curvature of the sheet metal part

Denote the longitudinal and lateral densities by d_L and d_Q respectively and the stroke force by h_S. The curvature κ of the sheet metal part is regarded as a function of these parameters:

$$\kappa = \kappa(d_L, d_Q, h_S) \tag{5}$$

Hereby, the stroke force at the driving machine is digitalized into the parameter stroke depth h_S.

6.1. Regression model

To obtain a mathematical relation between the curvatures, the longitudinal density d_L, the lateral density d_Q and the stroke depth h_S, an experiment was designed full factorial in two series A and B. Since the variance of the density is limited within the tool surface, the density is defined on the diameter of the driving tool d_W:

A: d_L = {25%, 50%, 75%} d_W,
d_Q = {25%, 50%, 75%} d_W,
h_S = {1.2, 1.3, 1.4, 1.5, 1.6};

B: d_L = {87.5%, 100%} d_W,
d_Q = {87.5%, 100%} d_W,
h_S = {1.2, 1.3, 1.4, 1.5, 1.6};

Series B can be seen as additional design for series A. The total number of trials is (3×3×5) + (2×2×5) = 65.

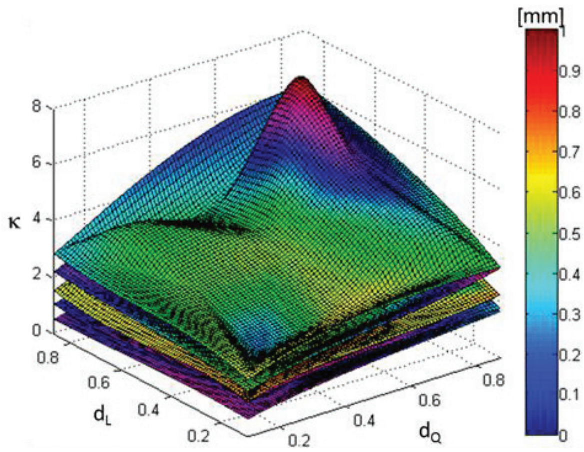


Fig. 10. Regression surface from experimental results

For every trial, a sheet metal part is formed and then digitized by the GOM ATOS optical measurement system. With the help of the GOM geometry processing software, the curvatures of the eighth sphere of the sheet metal part is calculated. From all the experimental results, a third-order regression model can be obtained as follows:

$$\kappa = -7.49d_L + 18.37d_L^2 - 9.26d_L^3 + 1.25d_Q + 6.58d_Q^2 - 7.22d_Q^3 - 3.69h_S + 0.68h_S^2 - 0.249h_S^3 + 4.94 \quad (6)$$

Fig. 10 shows the regression surfaces for each stroke depth in relation to d_L and d_Q and the color scale displays the regression errors of the model.

6.2. Validation

The model was validated by several sample trials. Tab. 1 shows the trials, their results and the deviations from the model results. It can be seen from the table that the maximal deviation between the model and reality amounts to 6% at most. Specifically, the densities or the stroke depth can be adapted according to the model in the transformed manufacturing strategy.

Table 1. Experiments for validating the curvature model

h_S [mm]	d_L [%]	d_Q [%]	κ model [m^{-1}]	κ experiment [m^{-1}]	deviation [m^{-1}]	deviation [%]
1,2	50	50	1,387	1,405	-0,018	-1.3
1,2	75	75	0,790	0,826	-0,036	-4.58
1,4	50	50	2,239	2,134	0,105	4.69
1,4	75	75	1,131	1,132	-0,001	-0.09
1,6	50	50	3,574	3,564	0,010	0.28
1,6	75	75	0,152	0,161	-0,009	-5.92

7. Summary

This paper describes an extension of the copied driving concept. In order to reduce the manual work in the copied driving process, it is proposed to use existing manufacturing strategies for producing a newly given sheet metal part. This was achieved by means of standardization and transformation of the manufacturing strategies. For the standardization, the geometry features of the sheet metal parts produced by copied driving were extracted to create the standard sheet metal part. The standard manufacturing strategy was then generated by the copied driving of the standard metal part. Furthermore, the transformation of the manufacturing strategy was carried out using a linear transformation. Because of the great curvature deviations between the transformed and desired metal part, a curvature model was built to obtain relations between the curvature, the longitudinal and lateral density as well as the stroke force. After validation, the model can be used to improve the transformed manufacturing strategies and to decrease the geometry deviations.

Acknowledgements

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