Dimensional Accuracy of Aluminium Extrusions in Mechanical Calibration

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Abstract. Reducing dimensional variations in the extrusion process without increasing cost is challenging due to the nature of the process itself. An alternative approach—also from a cost perspective—is using extruded profiles with standard tolerances and utilize downstream processes, and thus calibrate the part within tolerance limits that are not achievable directly from the extrusion process. In this paper, two mechanical calibration strategies for the extruded product are investigated, utilizing the forming lines of the manufacturer. The first calibration strategy is based on global, longitudinal stretching in combination with local bending, while the second strategy utilizes the principle of transversal stretching and local bending of the cross-section. An extruded U-profile is used to make a comparison between the two methods using numerical analyses. To provide response surfaces with the FEA program, ABAQUS is used in combination with Design of Experiment (DOE). DOE is conducted with a two-level fractional factorial design to collect the appropriate data. The aim is to find the main factors affecting the dimension accuracy of the final part obtained by the two calibration methods. The results show that both calibration strategies have proven to reduce cross-sectional variations effectively form standard extrusion tolerances. It is concluded that mechanical calibration is a viable, low-cost alternative for aluminium parts that demand high dimensional accuracy, e.g. due to fit-up or welding requirements.

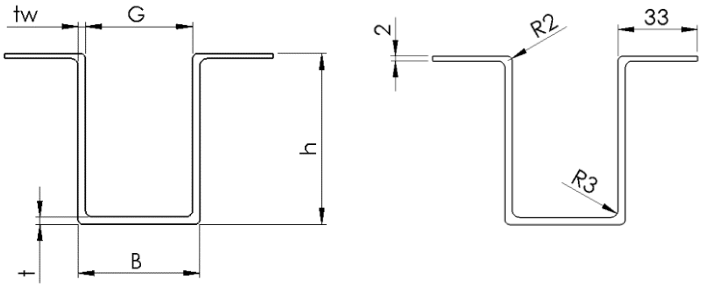
INTRODUCTION

The global trend of reducing energy consumption and CO_2 emission has caused a major increase in use of aluminium application in the automotive industry. Extruded products have unique geometrical design possibilities to create customized cross-sections. However, due to the nature of the extrusion process, variations in geometry limit the possibilities to meet strict tolerances of the final product, e.g. due to fit-up or welding requirements. Reducing dimensional variations in the extrusion process without increasing cost is challenging. Our hypothesis is that by using extruded profiles with standard tolerances and utilize other downstream processes, parts can potentially be calibrated within tolerance limits in a cost-efficient way [1,2].

In this paper, the capabilities of two mechanical calibration methods are analysed in the forming lines of the manufacturer. The first calibration strategy assessed is based on global, longitudinal stretching in combination with local bending, while the second strategy utilizes the principle of transversal stretching and local bending of the cross-section.

METHOD

Extruded U-profiles are used to conduct a comparison between the two calibration methods using numerical simulation. The profile shapes are illustrated in Fig 1. To provide response surfaces the commercial FEA program, ABAQUS, is used in combination with Design of Experiment (DOE). DOE is conducted with a two-level fractional factorial design to collect the appropriate data.



(a) (b)

FIGURE 1. Aluminium profile, geometrical factors for DOE. B and G is unequal for the Longitudinal Calibration and Transverse Calibration (a). Other dimension equal for both profile types (b).

FEA

The transverse calibration (TC) model consists of a die and an inner die block. The longitudinal calibration (LC) model consists of an inner die, lower die and the outer die block. Both calibration setups are shown in Fig 2. The total length of the profile is 500 mm. Taking advantage of symmetry of the U-profile, only one-fourth of the profile is modelled to reduce computational time. The U-profile is illustrated in Fig 1 and dimensions and relevant tolerances are tabulated in Tab 2. The CAD models are made in SOLIDWORKS and imported to ABAQUS CAE for further meshing and simulation. The dies and die blocks are modelled with discrete rigid elements, whereas the U-profile has linear brick elements type, C3D8R, with reduced integration and hourglass control. The profile is partitioned and mapped meshed to obtain best possible results. The dies are fixed whereas the die blocks are allowed translation along the *z*-axis. The general contact algorithm is invoked in the simulations. To ensure reliable contact conditions between the transverse profile, the rigid die block and the die, a gap of 0.3 mm is added in the TC setup. For the LC method, the inner die is fixed 4 mm above the lower die to allow the bottom wall to deform under calibration. The modelling parameters are summarized in Tab 1.

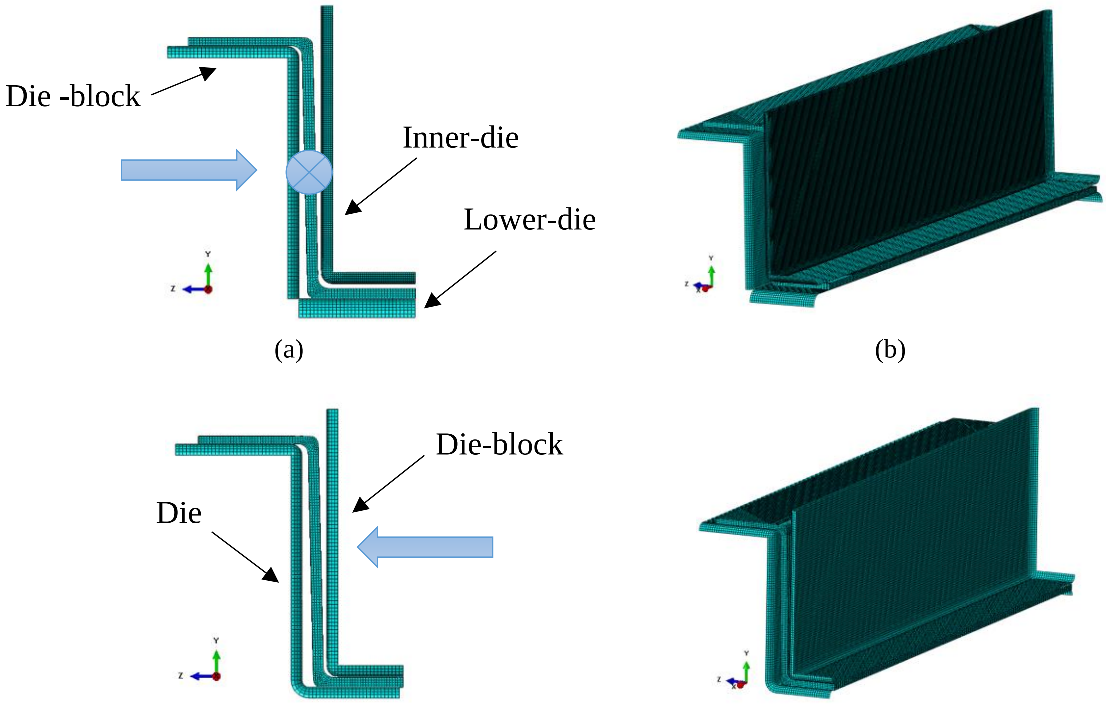
The material used is Aluminium 6082-T4, which means it is solution heat treated in the extrusion process and naturally aged. The U-profile have a Young's modulus of 70,000 MPa, Poisson's ratio of 0.33 and mass density equal to 7,200 kg/m^3. A Coulomb friction coefficient, $\mu = 0.2$ is used between the aluminium profile and steel tools. The stress-strain relation is expressed by a piecewise linear and isotropic hardening model with initial yield stress YS=150 MPa, ultimate tensile stress UTS=323 MPa at 0 and 16.2% plastic strain, respectively.

The preferred method for springback simulation is combining the explicit and implicit integration scheme to obtain accurate results. During the TC process, a forced displacement is applied on the block to stretch the profile in the transverse direction. It is necessary that the bottom wall of the profile is stretched to a minimum of 2% plastic strain. The LC profile is first pulled in the longitudinal direction with a forced displacement applied at the end surface. After the profile is stretched to an average of 2.5% plastic strain in the longitudinal direction, the outer block presses the profile to the desired width, imposed by a forced displacement. All forced displacements were defined by a smooth step to avoid disturbance and thereby attain a good quasi-static response. The springback simulation was performed in ABAQUS/Standard by removing the rigid tools with the symmetry boundary conditions still active.

TABLE 1. Modelling parameters

U-profile	
Element type:	C3D8R: An 8-node linear brick
Material models:	Piecewise linear hardening
Approximate Element size:	0.75
Nodal restraints:	XSYMM and ZSYMM
Die blocks and Dies	
Element type:	R3D4: A 4-node 3-D bilinear rigid quadrilateral.
Material models:	Discreet rigid
Element size:	1 mm
Nodal restraints:	*Dies:* fixed. *Die blocks*: free translation along z-axis

To ensure robust results the influence of different numerical parameters was investigated by convergence studies. Mesh size, step time and the damping factor for the implicit springback simulation were determined. The parameters utilized are summarized in Tab 2. A quasi-static response was insured by evaluating the physical representation of the kinetic energy of the model. The kinetic to internal energy ratio was also kept beneath the recommended value of 5% [3]. This energy evaluation is important because the accuracy of the springback stress solution is highly dependent on the accuracy of the stress state prior to unloading. The final simulations were conducted with a mesh size of 0.75mm, step time of 0.2s for all steps and with a single precision set. The mesh size is tabulated in Tab 1. For the implicit simulation, the "specify damping factor" (DF) scheme in ABAQUS was found most appropriate to use. This is also suggested in the paper on springback prediction on thick-walled high-strength titanium tubes, [4]. The DF value is set to 0.02 with an accuracy value of 0, following the guidelines suggested in the paper [4].



(a) (b)

(c) (d)

FIGURE 2. Run 1 of the calibration setup for the longitudinal (a) and (b) and the transverse method (c) and (d). The light blue arrows indicate the calibration mechanisms.

DOE

By using DOE with two-level fractional factorial design, the factors change simultaneously during the experiment. All factors have a chosen high (+) and low (-) level, as tabulated in Tab 2. The levels are set to typical dimensional tolerances for extruded U-profiles. Even though the resolution decreases with a fractional factorial design, it is used to minimize the number of experiments. By utilizing a resolution IV, the design avoids any ailing between the main factors and the dual interaction factors. The total number of runs needed is defined by 2^{k-p}, where k is the number of factors and p describes the fraction of the full experiment. Resolution IV gives, 2^{4-1}, which equals to 8 runs and are shown in Tab 3. The four geometrical factors investigated are believed to be the most influential ones concerning calibration of the profile gap opening, G. G is taken as the distance between the two vertical webs. The tolerance range for the gap opening is 0 to +3mm. This tolerance range ensures the necessary predictability to the calibration process, where the gap opening is never narrower than the nominal value of the gap. The four geometrical factors and the gap is illustrated in Fig 1. Due to the deterministic nature of FEA, the experiments are not repeated or conducted in a randomized order. The statistical computer program MINITAB is utilized to provide the design matrix and the corresponding statistical results for the evaluation of the two calibration methods. The main response is the U-profile's final gap opening, G. During the experiment the initial gap, G, was set to +3 mm the nominal gap opening. A confidence level of $\alpha = 0.05$ was used to evaluate if the chosen factors were statistically significant or not.

TABLE 2. Fraction factorial matrix with resolution IV. All values are given in [mm].

			Transverse Calibration Method			**Longitudinal Calibration Method**		
No.	**Dim**	**Source of variation**	**Min level (-)**	**Mid level (0)**	**Max level (+)**	**Min level (-)**	**Mid-level (0)**	**Max level (+)**
1	*B*	Width of profile	49.4	50	50.6	57.2	57.8	58.4
2	*h*	Height	69.5	70	70.5	69.5	70	70.5
3	t_w	Thickness of web	2.7	3	3.3	2.7	3	3.3
4	*t*	Thickness of bottom	2.7	3	3.3	2.7	3	3.3

RESULTS

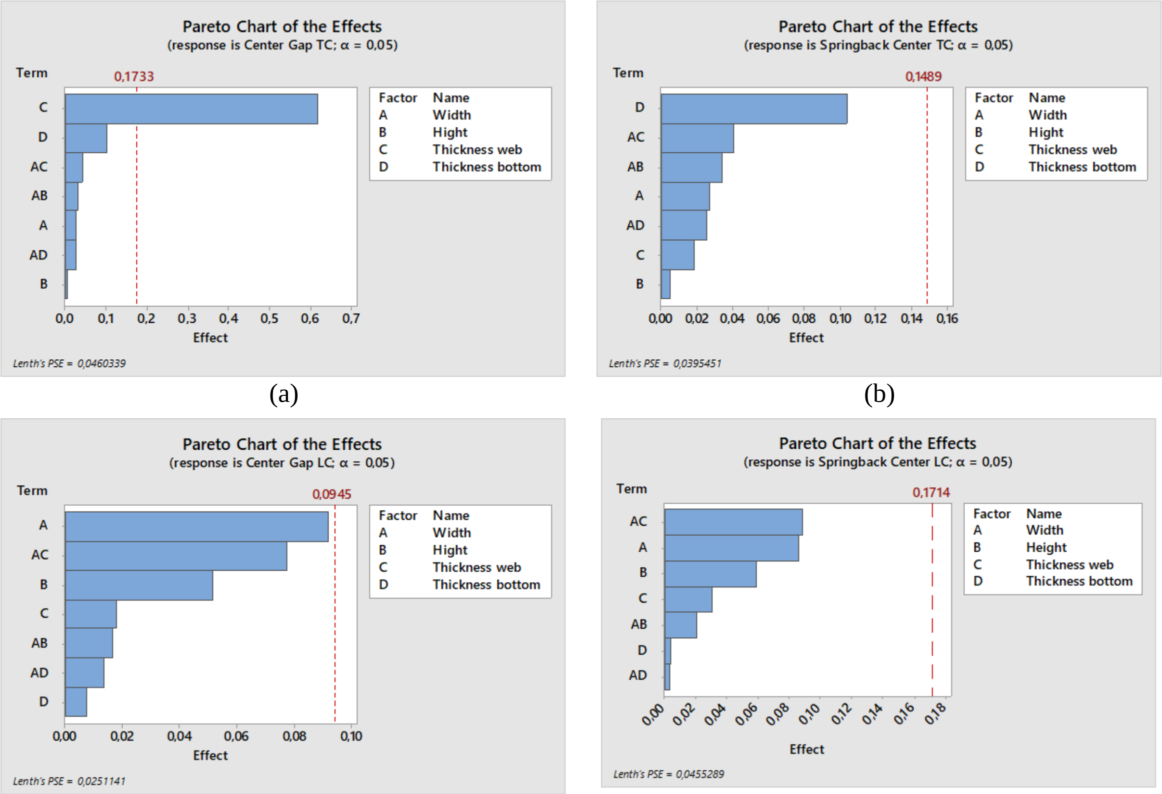
TABLE 3. Fraction factorial matrix with resolution IV. All values are given in [mm]. G_E and G_C is half the gap of the profile measured on the inside, at the end and centre of the profile, respectively. Δs_E and Δs_C is the springback measured as the deviation of the gap opening before and after the tools are removed.

Run no.	**B**	**h**	**t_w**	**t**	**Response TC**				**Response LC**			
					G_E	**G_C**	**Δs_E**	**Δs_C**	**G_E**	**G_C**	**Δs_E**	**Δs_C**
1	-	-	-	-	25,132	25,034	0,169	0,263	24,699	25,211	-0,337	0,17
2	+	-	-	+	25,087	24,966	0,214	0,333	24,537	25,186	-0,501	0,148
3	-	+	-	+	24,983	24,931	0,318	0,370	24,582	25,136	-0,462	0,09
4	+	+	-	-	25,214	25,137	0,088	0,164	24,497	25,131	-0,522	0,117
5	-	-	+	+	24,504	24,382	0,202	0,319	25,273	25,3	0,262	0,288
6	+	-	+	-	24,543	24,438	0,160	0,263	24,524	25,106	-0,491	0,097
7	-	+	+	-	24,522	24,432	0,180	0,270	25,212	25,238	0,19	0,209
8	+	+	+	+	24,431	24,348	0,271	0,353	24,501	25,092	-0,547	0,051
9	0	0	0	0	24,729	24,668	0,273	0,332	24,518	25,177	-0,51	0,133
Avg.					24,794	24,704	0,208	0,296	24,705	25,175	-0,324	0,145

The response of the DOE is summarized in Tab 3. The gap, G, is measured in the z-direction on the top and inside of the profile to the x-y symmetry plan at the centre of the profile. Just by considering the data in Tab 3, the two calibration methods show promising results in terms of reduced variation in dimension. One difference between the principal methods is the end effect observed in the springback simulation for the LC method. Upon unloading simulation, the bottom wall at the free end straightens, which leads to local inwards bending of the web. One can also observe from the response data of the LC method in Tab 3, that the springback results from run 5 and 7 give a much larger springback than the rest of the runs. This phenomenon occurs because the combination of the (-) B and (+) t_w yields no bending of the bottom wall, since this fits the inner die perfectly. The performance of the calibration methods is measured in how robust they are concerning minimum variation. To reduce variations, it should be evaluated if the LC method can be designed to always ensure bending of the bottom wall. Due to this phenomenon, the springback at the edge shifts from negative to positive.

Due to the end effect of the LC method, data from the centre measurements have been used to statistically compare the two methods. The Pareto plots in Fig 3 indicate the most influential factors concerning the final centre gap and springback. For the TC gap, the thickness variation of the web is most influential. This influence occurs because the profile is calibrated to the outer web wall, while the gap is measured from the inside. The thickness variation of the web then gives a direct influence on the gap. This observation is also the only finding which has a statistical significance with the confidence level of $\alpha = 0.05$, as indicated by the dotted red line in Fig 3 (a). The springback of TC is governed by the thickness of the bottom wall. The LC gap is mainly governed by the initial width of the profile, due to the same interaction effect between (-) B and (+) t_w as mention earlier. The AC interaction between the width and thickness of the web is also caused due to this phenomenon. The springback results show the same trend as the gap response, where the initial width of the profile and the AC interaction demonstrate the largest influence on the response.

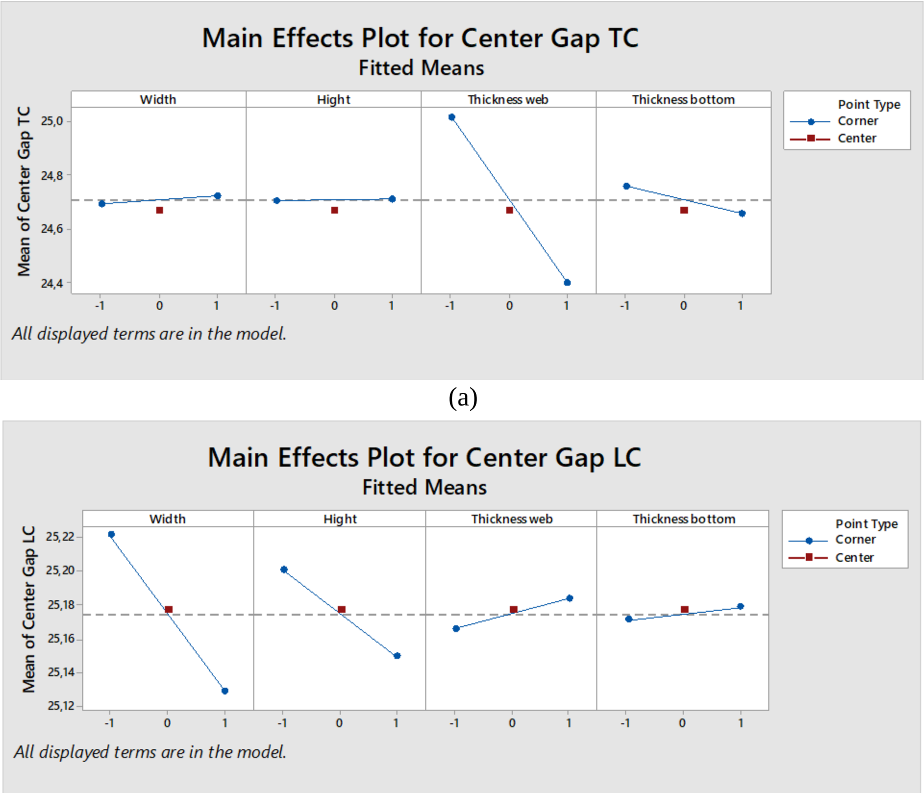
Figure 4 shows the effect plot of main factors for the centre gap TC and LC. There is no significant deviation between the centre points and corner points, which implies that there is no curvature in the data.



(a) (b)

(c) (d)

FIGURE 3. Pareto plots of the two calibration principals at the centre of the profile



(a)

(b)

FIGURE 4. Main Effect Plots of Center Gap, Transverse Calibration (a) and Longitudinal Calibration (b)

DISCUSSION AND CONCLUSION

Results from the LC show a higher average reduction of springback at the centre of the profile compared to TC. The consistent centre gap response with minimal variation is closely related to the desired gap opening of 50mm. This strategy can further be improved by ensuring bending of the bottom wall for all possible dimensional variations. Due to the longitudinal displacement, a local deformation at the end of the profile causes high and negative springback values. As a result of the local deformation, the deviation from the end gap and centre gap is more profound for the LC, than the TC. Another drawback with the LC is the need of two calibration steps. Multiple steps increase the cycle time of the process, which in return adds to the production cost. Also, practical considerations concerning the grip during the longitudinal stretching can be challenging in a high-volume production.

The TC demonstrates uniform results between the centre and the end of the profile, with only a small average deviation in final gap after calibration. Contrary to the LC, it is the end of the TC profile that shows the lowest springback response. This springback response also leads to a more accurate end gap compared to the final centre gap. The TC strategy has only one calibration step; this is highly beneficial when low cycle time reduces the manufacturing cost of the final part. Compared to the average centre gap of the LC process, the TC centre gap deviates slightly more from the desired 50mm gap. The gap variation is dominated by the web thickness, which has a direct influence on the final gap. By improving the control of the web thickness variations combined with adjustments in the calibration setup, even better results can be obtained by this strategy.

The gap variation is reduced by a factor of 0.52 for both strategies compared to initial extruded tolerances. The LC centre gap results indicate even higher reduction of gap variations. These reductions show that both calibration strategies have proven to reduce cross-sectional variations effectively. Even though the LC has a more profound reduction of variation at the centre gap, the TC is a more promising calibration strategy based on the uniform result and low number of calibration steps.

By these results, it is concluded that mechanical calibration is a viable low-cost alternative for aluminium parts that demand high dimensional accuracy.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from NTNU, NAPIC (NTNU Aluminium Product Innovation Centre) and the Value project.

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