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The effects of machining residual stresses on springback in deformation machining bending mode

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Abstract

Hybrid machining-forming technology is a combination of two thin-structural machining and incremental forming manufacturing processes. A group of complex geometry parts in which a thick region is connected to a thin wall region can be manufactured through this technology with certain advantages. The parts made by this technology require less raw material compared to the ones created by means of machining. The major problem with this technology is the dimensional and geometric inaccuracy of its products which is mainly due to springback. The main purpose of this research was to study the effects of machining parameters and residual stresses induced by the machining primary stage on the subsequent springback after the forming stage. It was found by experiments that the parameters of cutting speed, axial depth of cut, mode of milling and milling path had a minor effect on springback. However, the workpiece fracture during the forming stage was observed to be sensitive to the prior machining feed rate. Both finite element simulations and experimental results confirmed that the compressive machining residual stresses increased with an increase in the machining feed rate. The compressive residual stresses postponed the onset of fracture at the workpiece lower end during the forming stage. Therefore, we could approach the forming tool closer to the bottom of the wall during forming and, as a result, springback decreased considerably.

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Declarations

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1. Introduction

Parts with thin and integrated walls but complicated geometry are widely applied in different industries such as aerospace, automotive and marine. Being produced in an integrated way, such parts have higher strength and longer fatigue life compared to the assembled ones and, most importantly, this can postpone failure in critical regions. However, fabricating integrated parts with complicated and thin geometry while having logical costs and high quality is the main challenge in traditional manufacturing due to requirement for large equipment, flexible tools, and complicated dies[1]. In 2007, deformation machining was introduced by Smith et al. [2] in order to meet this challenge. Deformation machining is a process in which two processes, i.e. thin-wall machining and incremental forming, are combined together and performed on a single computer numerical control (CNC) machine. In this process, a raw material block is machined in order to create an integrated thin-wall

(vertical or horizontal). Afterwards, this thin-wall is incrementally formed into the desired shape using a hemi-spherical headed tool. This process offers several advantages compared to the traditional manufacturing processes such machining and forming processes. Monolithic structures can be made by this process and therefore this process may significantly reduce or eliminate the need for assembly. Besides, the monolithic components are generally stronger, lighter and less expensive than the sheet metal assemblies. In comparison with metal forming processes, this process requires much less expensive tooling and dies. In spite of its advantages, the dimensional accuracy of the products made by the deformation machining bending mode may not be satisfactory due to springback.

Thin-wall machining is a special machining technique to create a workpiece with a very small thickness. Using this technology, the parts that previously made by jointing steel plates can now be produced in an integrated way. This is one of the advantages of thin-wall machining. Cost reduction and higher accuracy of thin-wall machining is outstanding and these integrated parts are being used in different industries [3-6].

Incremental forming is a flexible sheet metal forming process in which one small section of a sheet is formed at a time [7]. In this process, the forming tool travels through a specific path and forms the fixed sheet. Complex shapes can be made with this forming technique due to the local forming nature of the process [8]. This process has attracted a lot of attention due to its flexibility, low cost of tooling for batch production, small forming forces, and greater formability under localized deformation [9-13].

In deformation machining bending mode, a thin and integrated vertical wall is machined and a hemi-spherical headed tool then bends the wall perpendicular to the tool axis. Figure 1 shows a schematic illustration of the deformation machining bending mode.

Figure 1. Schematic of deformation machining bending mode

Smith et al. [2] found that the bending force of thin walls was comparable to the cutting forces generated during machining. Therefore, the incremental forming process can be performed on CNC machine tools in terms of the required force. Ziegert et al. [14] investigated the repeatability and fatigue life of the products made by the deformation machining process. Singh and Agrawal [15] studied the effect of surface residual stresses for the deformation machining. They indicated that compressive residual stresses were induced during machining, and tensile residual stresses were created during forming. They also reported that the machining parameters had a significant influence on the residual stresses of the final workpiece. The residual stress distribution within the workpiece at the end of forming determines the amount of springback. Obviously, the machining residual stresses is expected to influence the stress distribution at the end of the forming stage. To the best of authors knowledge, however, the effect of residual stresses induced by the primary machining process on the springback that occurs after the forming stage has not investigated in the literature.

In the present study, the effect of the machining parameters on the subsequent springback after forming was investigated. To this end, a series of experimental tests with different machining parameters were conducted and the springback after forming was measured. In order to estimate the distribution of residual stresses within the workpiece and to understand the influence of machining parameters such as cutting speed, feed rate and depth of cut on the distribution of residual stresses, the machining process was simulated using ABAQUS/Explicit finite element package. The predicted residual stresses were then imported as an initial stress field into a new part and the forming stage was simulated with ABAQUS/Explicit. The subsequent unloading stage was simulated using ABAQUS/Standard to predict springback. The predicted results by the finite element analysis and the experimental findings were finally analyzed to understand the influence of machining parameters on springback. Finally, a strategy was suggested to reduce springback through selection of the machining parameters.

2. Materials and methods

The material used in this study was AA-7075-T651 aluminum alloy. This material is considered a high-strength aluminum alloy and therefore it has a high ratio of flow stress to elastic modulus. Thus, this material generally exhibits a large springback during unloading. Samples were mounted on a 3-axis CNC vertical milling machine and the deformation process was carried out. The initial dimensions of the raw blocks were 5x10x50 mm. The main reason for selecting a small sample was the reduction of the computational cost of simulation of the machining process. The initial block was machined to create a 1 mm thick wall, as shown in Figure 2. Afterward, this wall was incrementally bent to 45° using a hemi-spherical headed tool.

Figure 2. Geometry of the workpiece: a) initial block, b) after machining and c) after forming

Several factors affect springback and dimensional accuracy in this process. As the influence of machining process on springback is investigated in this study, the machining parameters such as revolution speed, feed rate, depth of axial cut, type of machining (climbing and conventional), and milling tool direction (side milling and plunge) were chosen as the study parameters. The width of cut was 4 mm, and it was kept constant in all the tests. High speed steel (HSS) end mill tool with a diameter of 19.05 mm was used as the machining tool. The tool had 3 flutes and a high helix angle to generate a smooth force during cutting. The workpiece was also supported by a relatively-rigid flat plate at the back of the workpiece wall during machining to prevent vibrations of the thin wall during machining.

The forming parameters, as shown in Table 1, were kept constant during all the tests because the purpose of this work was to investigate only the machining parameters. Figure 3 defines the initial distance of the forming tool from the bottom of the workpiece. The tool

initial distance is defined from the bottom of wall up to the first contact point of the tool with workpiece at the beginning of the incremental forming process. Figure 4 shows the forming tool path. The tool initial distance was 10 mm unless otherwise stated. At the end point, the forming tool leaves the workpiece and springback occurs.

Figure 3. The forming tool initial distance from the bottom of the workpiece wall

Figure 4. Illustration of the forming tool path

Table 1. The incremental forming process parameters

Tool material	Tool diameter	Feed rate	Incremental depth	Bending angle
HSS	18 mm	50 mm/min	1.4 mm	45°

3. Results and discussion

The influence of different machining parameters on the subsequent springback after forming is discussed in this section.

3.1. Influence of machining parameters

Five parameters, including revolution speed, feed rate, depth of axial cut, type of milling, and direction of tool travel were chosen as the machining parameters. Table 2 shows the effect of these parameters on springback. These results showed that the direction of milling, type of milling, and depth of cut parameters had a minor influence on springback. Therefore, these parameters were excluded from the next experiments. The followings parameters were chosen for the upcoming experiments: depth of axial cut: 2mm; type of machining: side milling; type of milling: climbing. Among the machining parameters, the feed rate and revolution speeds had the biggest influence on springback. In order to study the effect of these parameters in a wider range, the minimum and maximum possible values for the feed rate and revolution speed were chosen as shown in Table 3. This table shows that springback reaches its minimum value at maximum feed rate (0.3 mm/tooth). Therefore, the springback decreases with an increase in the machining feed rate. The results also show that, at 0.01 mm/tooth feed rate, the workpiece fractured from the bottom of the wall during the forming stage. This is a very important observation because it indicates that a higher machining feed rate postpones the onset of fracture. Therefore, if the machining process is carried out at a higher feed rate, a smaller tool initial distance can be used during forming. As shown in the next section, a smaller tool initial distance also reduces the springback. This means that as the machining feed rate increases, not only the springback decreases but also we can reduce the tool initial distance and further reduce springback. Therefore, we can conclude that the machining feed rate is the most effective machining parameter on springback. The results also show that springback changes by approximately 5% with the change in the revolution speed. This observation indicates that the revolution speed has more influence on springback than

the depth of cut, machining type, and milling type; however, its effect is negligible in comparison with the feed rate.

Table.2. Influence of machining parameters on springback

Type of machining	Type of milling	Revolution speed (rpm)	Feed rate (mm/tooth)	Axial depth of cut (mm)	Transverse depth of cut (mm)	Angle of wall after springback	Springback percentage
Side milling	Climb	500	0.1	2	-	21.1	53.1
Side milling	Climb	2000	0.1	2	-	22.1	50.8
Side milling	Climb	1000	0.05	2	-	20.4	54.6
Side milling	Climb	1000	0.25	2	-	22.3	50.4
Side milling	Climb	1000	0.1	2	-	21.7	51.7
Side milling	Climb	1000	0.1	5	-	22.2	50.6
Side milling	Conventional	1000	0.1	2	-	22	51.1
Side milling	Climb	1100	0.15	2	-	22.5	50
Plunge mill	Climb	1100	0.15	-	2	22.1	50.8

Table.3. Influence of revolution speed and feed rate on springback

Revolution speed (rpm)	Feed rate (mm/tooth)	Angle of wall after springback	Springback percentage
1000	0.01	failed	-
1000	0.3	23.1	48.6
100	0.1	19.8	56
2500	0.1	21.9	51.3

3.2. Influence of machining feed rate on springback

Experimental results presented in previous sections indicated that the machining feed rate had a considerable effect on springback, while the other machining parameters had a minor effect on springback. It was also observed that the minimum feed rate during machining led to a workpiece fracture during the forming stage. In other words, a higher machining feed rate delays the onset of fracture during the forming stage. To find the minimum safe tool initial distance, a series of experimental tests were designed at three different levels of machining feed rate, i.e. 0.01, 0.15, and 0.3 mm/tooth. The machined workpieces were then formed at different tool initial distances. The tool initial distance was reduced until the workpiece fractured during the forming stage. A summary of results is shown in Tables 4-6 for the machining feed rates of 0.3, 0.15, and 0.01, respectively. The

machining conditions in these tests were side-milling and climbing type with a 2 mm depth of axial cut and rpm of 1,000.

Tables 4-6 show that springback decreases as the tool initial distance is reduced. As the forming tool approaches the bottom of the wall, the bending radius decreases during forming, and the magnitude of plastic strain increases, which in turn results in decrease of springback. At the maximum feed rate of 0.3 mm/tooth, the minimum initial tool distance was obtained to be approximately 8 mm and the springback was at minimum of 44.2%. On the other hand, under the minimum feed rate of 0.01 mm/tooth, the minimum tool initial distance was found to be 11 mm, and the springback reached its maximum of 56.8%. Therefore, under the conditions of this study, the machining feed rate had the potential to decrease springback by 12.6%.

Figure 5 shows the minimum tool initial distance for the forming stage as a function of the machining feed rate. The region beyond the curve is considered a safe zone for production of a workpiece with the target angle of 45°. It is noted that to have a general diagram for a range of bending angles; a few more experimental curves should be plotted for a few more specified target bending angles. An interpolation can then be performed to obtain the minimum initial tool distance for the target angles that were not already obtained by the experiment.

Table 4. Tool initial distance and springback percentage for the feed rate of 0.3 mm/tooth

Tool initial distance (mm)	Angle of wall after springback (degree)	Springback percentage
10	22.4	50.2
9	23.6	47.5
8	25.1	44.2
7	Workpiece failed	-

Table 5. Tool initial distance and springback percentage for the feed rate of 0.15 mm/tooth

Tool initial distance (mm)	Angle of wall after springback (degree)	Springback percentage
10	21.5	52.2
9	23.1	48.6
8	Workpiece failed	-

Table 6. Tool initial distance and springback percentage for the feed rate of 0.01 mm/tooth

Tool initial distance (mm)	Angle of wall after springback (degree)	Springback percentage
11	19.4	56.8
10	Workpiece failed	-

Figure 5. Minimum tool initial distance versus machining feed rate

3.3. Influence of residual stress on springback

The results presented in the previous section showed that the machining feed rate had a considerable effect on the fracture and springback of the workpiece during the forming process. To understand the reason for this observation, the effect of the workpiece machining residual stresses is studied in this section.

In order to study the effect of residual stresses, two specimens were machined with the feed rates of 0.01 and 0.3 mm/tooth. Subsequently, the specimens were heated up to 345 °C and then cooled down in the air to remove the residual stresses after machining [16]. Afterward, the T651 heat treatment process was carried out on the specimens to restore the original properties of the material. The heat treatment process was carried out as follows: (a) the specimens were heated up to 480 °C, (b) they were kept in the furnace for 35 minutes, (c) the specimens were quenched in water, (d) they were put into the furnace under the temperature of 120 °C for 24 hours, and (e) the specimens were finally cooled down in the air to return back to the ambient temperature [17]. In order to make sure the heat treatment process was carried out correctly, a tensile specimen was also heat-treated using the above-mentioned heat treatment procedure. The tensile test was then carried out on the heat-treated specimen, and its stress-strain curve was compared with that of the as-received material. As shown in Figure 6, the maximum discrepancy between the stress-strain curves of the two samples is less than 10.5%. The experiment is shown in Table 7.

Table 7. Forming experiments on the stress-relieved workpieces

Feed rate (mm/tooth)	Tool initial distance (mm)	Angle of wall after springback (degree)	Springback percentage
0.01	11	19	57.8
0.3	10	21	55.3

Figure 6. Comparison between the original sample and the heat-treated sample

Tables 4 and 7 show that when the tool initial distance from the bottom of the wall is 10 mm, the wall angle after springback for the workpiece with machining residual stresses and the stress-relieved workpiece is 22.4° and 21° , respectively. Thus, the residual stresses have a small influence on the wall springback.

To observe the influence of residual stresses on fracture, another experiment was designed, as shown in Table 8. A few parts were first machined with a feed rate of 0.01 mm/tooth. The parts were stress-relieved and then heat-treated according to the T651 heat treatment procedure. The parts were then incrementally formed with an initial distance of 10 mm. According to Table 5, if the residual stresses are not to affect the fracture behavior of the workpiece, the workpiece must be fractured. However, the experiment here showed that the parts were successfully formed without fracture. The initial distance was even further reduced, and it was found that the stress-relieved workpieces could be successfully formed up to an initial distance of 8 mm. Therefore, the residual stresses do not seem to have a significant impact on springback; however, they profoundly affect the minimum initial distance that is set to form the workpiece. This observation helps us to move the forming tool

towards the bottom of the wall and reduce the springback for the workpieces that have been machined at higher feed rates. Table 8 shows that springback reduces approximately 8% when the initial distance goes from 10 mm to 8 mm.

Table 8. Springback for the stress-relieved parts formed with different tool initial distances

Feed rate (mm/tooth)	Tool initial distance (mm)	Angle of wall after springback (degree)	Springback percentage
0.01	10	21.5	52.2
0.01	8	25	44.4

4. Simulation of the deformation machining process

Finite element simulation can provide a deeper insight into the process and also helps us analyze the experimental results. Therefore, the deformation machining process was simulated using ABAQUS finite element package. The main goal of simulation was to find out how the residual stress distribution through the wall thickness, created by the machining stage, affects the deformation and springback.

4.1. Finite element model

For the machining simulations, the cutting tools was modeled as a rigid body and was meshed using 4-noded bilinear quadrilateral rigid elements, known as R3D4 in ABAQUS. The workpiece was meshed using three-dimensional first-order solid elements, denoted by C3D8R in ABAQUS. While a very fine mesh is generally required in the machining area of the workpiece, a coarse mesh would suffice elsewhere. Therefore, to save the computational cost, the mesh density was increased in the machining zone for each machining pass as shown in Figure 7. The mesh size for the fine mesh region was 0.2 mm. As shown in Figure 7, the workpiece was fixed at the bottom in the region placed in a vice. A constant friction coefficient of 0.3 was defined between the tool and the workpiece. 15 passes of the machining process were simulated using ABAQUS/Explicit to create a 1 mm thick wall. After each machining pass, the part was transferred into ABAQUS/Standard solver to damp out the stress oscillations caused by an explicit solver.

For the incremental forming simulations, the forming tool and the workpiece were meshed using rigid R3D4 and continuum C3D8R elements, respectively. The predicted stress field at the end of machining simulations were defined as an initial stress field for the workpiece. Again, the explicit solver was used to simulate the forming stage. A constant mesh size of 0.2 mm was used for the workpiece. The tool was allowed to freely rotate about the tool axis according to the experiments. A frictionless condition was assumed between the tool and the workpiece because of the free rotation of the tool as well as lubrication during the forming process. Upon completion of the forming process simulation, the part was imported into ABAQUS/Standard and was allowed to reach the final equilibrium configuration.

Figure 7. The mesh and boundary conditions for the machining simulation

Johnson-Cook plasticity model was used to define the mechanical behavior of the material. The equivalent stress σ is defined as follows:

$$\sigma = (A + B\varepsilon^n) \left[1 + c \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right) \quad (1)$$

where A is the initial yield stress, B the hardening modulus, c the strain rate dependency coefficient, n the work-hardening exponent, m the thermal softening coefficient, ε the equivalent plastic strain, $\dot{\varepsilon}$ the equivalent plastic strain rate, $\dot{\varepsilon}_0$ the reference plastic strain rate, T_{room} the room temperature, T_{melt} the melt temperature and T the current temperature. Identification of the material parameters for Johnson-Cook model requires several experimental tests at a range of temperatures and strain rates. In this work, the material parameter obtained by Brar et al. [18] for AA 7075-T651 were used in the simulations of the machining process.

A chip separation criterion is also needed to model the chip formation in the machining process. Johnson-Cook damage model was used to model the damage in the material. The damage scalar parameter D is defined as the sum of the ratio of increments in the equivalent plastic strain $\Delta\varepsilon$ to the equivalent strain at the beginning of fracture ε_{fi} , as follows [19]:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon_{fi}} \quad (2)$$

In Eq. (2), the equivalent strain at the time of fracture beginning ε_{fi} is gained from Eq. (3) [19]:

$$\varepsilon_{fi} = \left[D_1 + D_2 \exp\left(D_3 \frac{p}{\sigma}\right) \right] \left[1 + D_4 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \right] \left(1 + D_5 \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right) \right) \quad (3)$$

where p denotes the hydrostatic pressure, σ is von Mises equivalent stress, and D_1 to D_5 are material parameters that are given in Table 10 for AA7075-T651 [18].

Table.9. Johnson-cook material parameters value for AA7075 - T651 [18]

A(MPa)	B(MPa)	n	C	m	T_{room} (°C)	T_{melt} (°C)	$\dot{\varepsilon}_0$
527	575	0.72	0.017	1.61	25	520	1

Table.10. Johnson-cook failure parameters for AA7075-T651 [18]

D_1	D_2	D_3	D_4	D_5
0.11	0.572	-3.446	0.016	1.099

Table.11. Material properties for AA7075-T651 [20]

Elastic Modulus (GPa)	Poisson's ratio	Density (kg/m ³)
71.7	0.33	2810

4.2. Simulation results

Simulations with different machining parameters were run to study the effect of the residual stresses induced by machining on springback. Table 12 lists the machining parameters for each simulation. The CPU time required to run the simulations of the machining stage was 4 to 7 days per each machining pass with a 2.1GHz processor and 16GB RAM. Figure 8 shows the residual stress distribution after the machining stage for the test number 7 at Table 12. After each machining pass, the largest residual stress region occurs at the bottom of the machined wall.

Figure 9 shows the contour of von Mises stress on the part at the last increment of the forming stage for the test number 7 in Table 12. The figure shows that the stress is maximum at the bend radius where the maximum deformation occurs. Therefore, the distribution of stress in this region is expected to have the most significant influence on springback. Figures 10-a&b show the predicted configuration of the part at the end of the forming and springback stages, respectively, for the test number 7 in Table 12.

Table.12. The machining parameters for the simulations

Simulation number	Revolution speed (rpm)	Feed rate (mm/tooth)	Axial depth of cut (mm)	Type of milling
1	2000	0.1	2	Climb
2	500	0.1	2	Climb
3	1000	0.05	2	Climb
4	1000	0.25	2	Climb
5	1000	0.1	2	Climb
6	1000	0.1	5	Climb
7	1000	0.3	2	Climb

Figure 8. The distribution of longitudinal residual stress after machining

Figure 9. Stress distribution within the workpiece at the end of the forming stage

Figure 10. The deformed configuration: a) before springback b) after springback

The distribution of longitudinal stress through the wall thickness plays the most significant role on springback. Figures 11-13 show the effect of machining parameters on the residual stress distribution in the longitudinal direction through the thickness after machining. In these figures, layers 1 and 5 denote the outermost and innermost layers of mesh through the wall thickness, respectively. It is emphasized that maximum deformation takes place in the vicinity of the bottom of the wall. Therefore, the average residual stress within this region is shown Figure 14 for each simulation.

Table 13 shows the predicted and experimental wall angle after springback. The results show that the springback is underpredicted. The simulation results will improve if the decrease of elastic modulus during unloading with plastic deformation is taken into account [21]. As the purpose of this work was not focused on the accurate prediction of springback, this phenomenon was taken into account in the simulations. Comparison between simulation numbers 1 and 2, and between simulation numbers 5 and 6 demonstrate that the revolution speed and axial depth of cut have a negligible effect on springback because, as shown in Figure 14, the discrepancies among the distributions of residual stresses created in those tests are small.

Figure 11. The effect of machining feed rate on the longitudinal residual stress distribution

Figure 12. The effect of depth of cut on the longitudinal residual stress distribution

Figure 13. The effect of machining speed on the longitudinal residual stress distribution

Figure 14. Average residual stress in the first wall layer of mesh

Table 13. Comparison of the predicted and experimentally measured wall angle after springback

Number of simulation	Predicted wall angle after springback (degree)	Measured wall angle after springback (degree)	Relative error (%)
1	26.9	22.1	17.8
2	27	21.1	21.9
3	26.6	20.4	23.3
4	27.5	22.3	18.9
5	27.2	21.7	20.2
6	26.8	22.2	17.2
7	27	22.4	17.0

To study the effect of residual stress on springback through simulations, one simulation was run with the parameters shown in Table 14. Another simulation was also run in which only the forming and springback stages were modeled. In other words, the initial stress-free configuration was the workpiece geometry at the end of the machining stage. The predicted springback changed approximately 4% when the residual stresses were neglected in the simulation. Therefore, the simulation results confirm that the machining residual stresses have a minor influence on springback.

Figures 11-13 compare the distribution of longitudinal residual stress for different layers of the workpiece mesh. These figures show that the highest compressive stress occurs in the first layer of mesh, i.e. the outermost layer during subsequent bending. As shown in Figure 14, the compressive residual stress increases as the machining feed increases.

However, it does not considerably change with the matching speed and depth of cut. Therefore, the machining feed has the most pronounced effect on the residual stress in the first layer of the workpiece mesh. This layer is subjected to the largest tensile stresses during the forming stage. Higher compressive stresses in this layer help neutralize the induced tensile stresses during the forming stage. Consequently, this postpones the failure in the vicinity of the bottom of the wall.

In order to explain why a smaller tool initial distance can be used for the stress-relieved part, the stress distribution at the bottom of the wall during a 45° bending is investigated. Figure 15 compares the longitudinal stress at the end of forming for workpieces with and without machining residual stresses. According to this figure, tensile longitudinal stress at the bottom of the wall for a part without residual stress is approximately 11% smaller than that of the unrelieved part. Therefore, when the stress-relieved part is submitted to tension in bending, lower tensile stresses develop within this region. This reduces the chance of crack growth and fracture at the bottom of the wall.

Figure 16 shows the effect of machining feed rate on the minimum springback that could be achieved with the smallest tool distance from the bottom of the wall during the forming stage. The compressive residual stresses in the longitudinal direction on the sidewall increase as the machining feeding rate increases during machining. As a result, the tool initial distance can be reduced in the forming stage without the risk of workpiece failure. Consequently, this results in springback reduction after the forming stage.

Table.14. Comparison of springback between workpiece with and without the machining residual stresses

Revolution speed (rpm)	Axial depth of cut (mm)	Feed speed (mm/tooth)	Tool initial distance (mm)	Angle of wall after springback (degree)	Springback percentage
1000	2	0.3	10	27	39.9
-	-	-	10	25.1	44.1

Figure 15. Longitudinal stress distribution through the wall thickness at the bottom of the wall

Figure 16. The effect of machining feed rate on the minimum springback percentage

5. Conclusion

In this work, the effect of the machining process parameters and the residual stresses induced by machining on the subsequent springback after forming in the deformation machining process was studied. It was found during the experimental tests that four machining parameters i.e. revolution speed, depth of axial cut, type of milling and direction of tool travel had a minor effect on springback. However, the machining feed rate had a

considerable effect on the fracture failure of the part during the forming stage. As the machining feed rate increased, the tool initial distance could be reduced during forming. As a result, the springback considerably decreased. The results showed that the springback could be decreased by 12.6% through a proper choice of the machining feed rate. Finite element simulation was also used to analyze the experimental results. From the simulations, it was confirmed that the residual stresses induced by machining did not directly affect the springback after forming. The simulation results also showed that the longitudinal residual stress were compressive on the outermost layer of the workpiece at the end of the machining stage and it raised with an increase in the machining feed rate. The compressive stresses prevented the crack growth at the bottom of the workpiece wall and allowed us to use a smaller tool initial distance which helps the springback to reduce.

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Figures

Figure 1

Schematic of deformation machining bending mode

Figure 2

Geometry of the workpiece: a) initial block, b) after machining and c) after forming

Figure 3

The forming tool initial distance from the bottom of the workpiece wall

FORMING TOOL PATH

Figure 4

Illustration of the forming tool path

Figure 5

Minimum tool initial distance versus machining feed rate

Figure 6

Comparison between the original sample and the heat-treated sample

Figure 7

The mesh and boundary conditions for the machining simulation

Figure 8

The distribution of longitudinal residual stress after machining

Figure 9

Stress distribution within the workpiece at the end of the forming stage

Figure 10

The deformed configuration: a) before springback b) after springback

Figure 11

The effect of machining feed rate on the longitudinal residual stress distribution

Figure 12

The effect of depth of cut on the longitudinal residual stress distribution

Figure 13

The effect of machining speed on the longitudinal residual stress distribution

Figure 14

Average residual stress in the first wall layer of mesh

Figure 15

Longitudinal stress distribution through the wall thickness at the bottom of the wall

Figure 16

The effect of machining feed rate on the minimum springback percentage