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Simulation of incremental sheet metal forming for making U-channel in two light-weight alloys

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Abstract. Incremental sheet metal forming (ISMF) is a viable method for fabricating complicated three-dimensional structures from sheet metal. It is characterized by localized deformation and is effective for both rapid prototyping and low-volume manufacturing. ISMF technology is suitable for quick product development time with affordable tooling and for deforming difficult-to-form materials. Simulation of the process reduces costly hit-and-trial attempts for manufacturing an accurate product. This article presents the simulation for producing a U-channel made of aluminum (Al 6061-T6) and titanium (Ti-6Al-4V) alloys. A finite element method (FEM) package, ABAQUS®, has been used for simulation using shell elements. The effect of various parameters on the forming forces is discussed using two different tools, flat and hemispherical-end.

Introduction

For the past few decades, numerical simulations have been playing a vital role in understanding the underlying physics of various manufacturing processes. In processes where the machine operation and raw material costs are very high, simulation results assist in reducing the expensive hit-and-trial attempts. Sheet metal forming is a metal forming process where a sheet of metal is shaped into a product by deforming it plastically. Incremental sheet metal forming (ISMF) is one of the advanced and innovative techniques in sheet metal forming processes. This die-less process has gained popularity thanks to its high flexibility and cost-effectiveness for small-batch production. This process can form difficult-to-form materials such as titanium, aluminium, and magnesium [1]. Because of its capability to produce high geometric accuracy and surface finish, ISMF finds many applications in the automotive, aerospace, and medical sectors. Numerical modelling of the ISMF is an active area of research [2]. Modelling and simulation can provide all the information about the distribution of stresses and strains, which is crucial for finding out spring back and the possibility for defects. Many advanced finite element methods (FEM) software packages such as ABAQUS®, LS-DYNA, and PAM-STAMP are used to simulate ISMF. Among these packages, ABAQUS® /Explicit is a general-purpose package and hence, has wider availability in organizations. One can model the ISMF process using explicit or implicit dynamic methods [3].

A single-point incremental forming is an ISMF process wherein a tool presses the clamped sheet from the top without having any support from the bottom. The tool can be of different shapes, which is plunged into the sheet incrementally; path planning of the tool is also important. During the deformation, a very high reaction force is developed on the tool, depending on the sheet thickness and material. Arens et al. [4] developed a mathematical relation for the approximate prediction of axial force in ISMF. In the force prediction model, the axial force was the function of the tensile strength (not the yield strength) with other parameters. No effect of strain hardening was included. Chang et al. [5] highlighted that due to localized and step-wise deformation in the ISMF process, the axial forming force is drastically reduced compared to conventional sheet forming processes. They noted that elastic deformation of the sheet was the major cause of the axial force fluctuation.

Petek et al. [6] demonstrated that the forming force in ISMF is very small as compared to deep drawing and is independent of the size of the product. Forming angle, tool diameter, and step-depth were the major influencing factors for the force distribution during the ISMF process. The authors also observed that the rotation of the tool has no effect on the force, but it affects the surface quality of the product. Asghar et al. [7] observed a good agreement between the forces obtained from FEM and the experimental study. The axial force is greater than the radial force on the deep-drawn component; comparatively, the tangential component of force is much smaller. Hence, geometrical accuracy is mainly influenced by axial and radial forces.

ISMF process provides good formability, low surface roughness, and high geometric accuracy. Formability improvement is one of the major advantages offered by ISMF. Shamsari et al. [8] carried out a single and two-stage ISMF for 70° wall angle truncated cone. Two-stage forming provided 26% improvement in forming depth compared to a single stage; sheet thinning was also reduced by around 45%. The effect of a hemispherical-end and flat-end tool on deformation behavior was also studied. A straight tool path has been used for each simulation, with different step depths as per the number of stages. Najm et al. [9] observed that a flat-end tool with a small corner radius offered the best thickness distribution stability. Ziran et al. [10] found that as compared to hemispherical-end tools, flat-end tools provided greater profile accuracy and formability.

The primary objective of this work is to carry out FE simulations for the forming of Al 6061-T6 and titanium (Ti-6Al-4V) alloys. Although simulations of ISMF have been performed by several researchers; however, many research articles provide only partial information about the results. This work attempts to understand the efficacy of simulations for proper process planning of ISMF. Alloys chosen for simulations are used in the automobile, aerospace, and medical sectors. Simulations were performed for making U-channels and evaluating the effects of step depth and coefficient of friction between the tool and workpiece.

Problem Definition

The deformation in the ISMF process is due to the horizontal and vertical linear movement of the tool along the defined tool path over the workpiece. Due to the motion of the tool, plastic deformation takes place, resulting in the development of stresses, reaction forces, and strains in the workpiece. Fig. 1 shows a forming tool starting from its initial position and moving forward in a horizontal direction at a certain depth. After one pass, more depth is provided depending on step-size. Then the tool moves backward and reaches its original position. This process is continued till the desired form is produced. During the deformation of the workpiece, high reaction forces act on the tool, and thinning of the sheet also takes place. Fig. 1 shows the schematic of the process along with the tool path. Here a spherical-end tool is shown, but the simulations were carried out with a flat-end tool too.

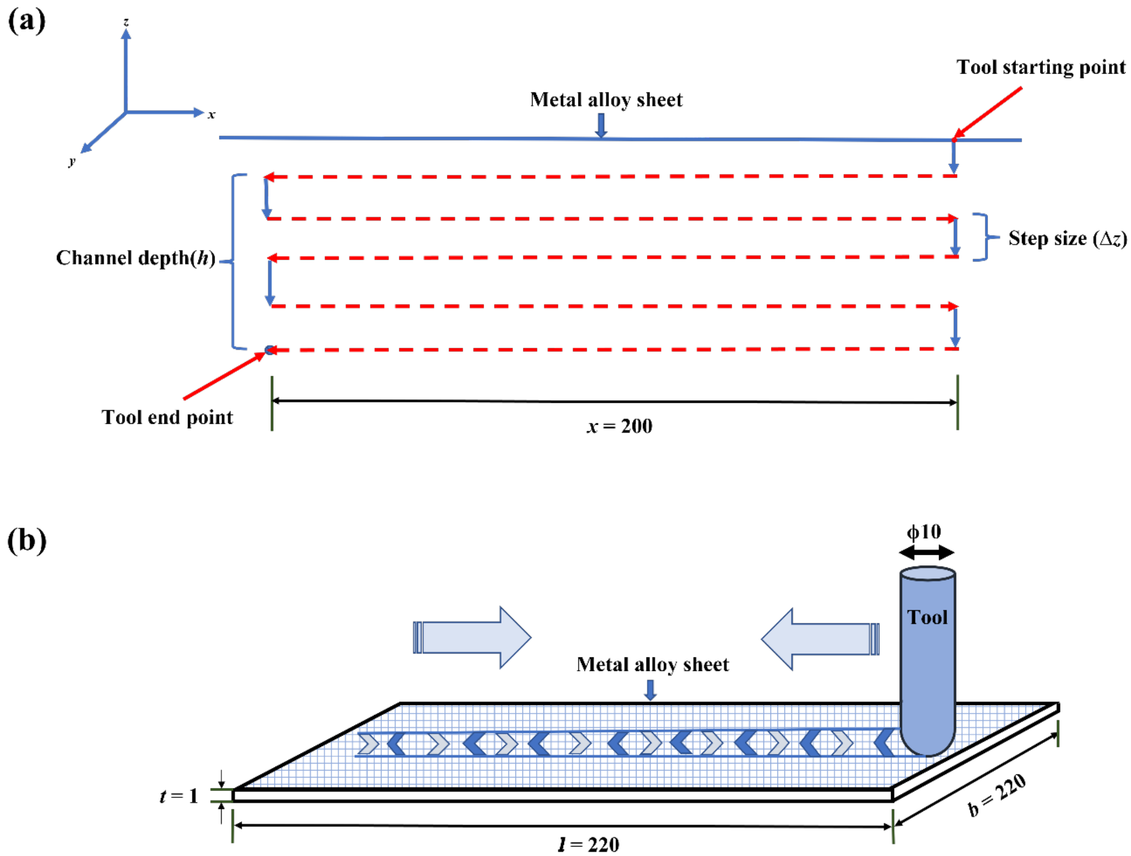

Fig. 1. Forming of U-channel: (a) tool path, (b) total imparted depth h = 5 mm with step size Δz = 1 mm. (All dimensions shown in the figure are in mm).

Numerical Simulation

Simulations were performed in ABAQUS®/Explicit FE software (SIMULIA™ by Dassault Systems®, France). Explicit analysis has been chosen because of its computational efficiency. Considering that strains are small and the sheet is already hardened, strain hardening has been neglected. The sheet blank of aluminum alloy Al 6061-T6 of thickness 1 mm was modeled. Considering the low thickness of the sheet, shell elements were chosen. The use of shell elements provided much less computational time than that required with solid elements [11]. The plasticity model used for numerical simulations for both materials is the 'Perfectly plastic isotropic hardening model based on von Mises yield criterion'. The S4R four-node square shell element was used to mesh the sheet. S4R is a 4-node double curved thin or thick shell with reduced integration, hourglass control, and finite membrane strains. For various parameters, the approximate element sizes of 1 mm, 2 mm, and 4 mm were taken. Simulations were performed to obtain different output parameters such as stress, strain, reaction force on the tool, the thickness of the sheet at different values of coefficient of friction between tool and workpiece, number of stages, and two different types of the tool.

Fig. 2 shows the hemispherical-end tool and the flat-end tool with a diameter of 10 mm. A corner radius of 2.5 mm was given to the flat-end tool. As the analytical rigid property was given to both tools, no material properties were assigned to them. Additionally, no rotational speed was given to the tool, as the effect of rotation was manifested in the form of friction.

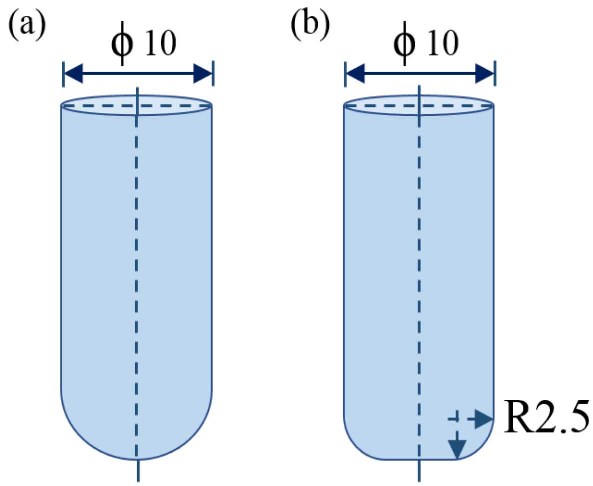

Fig. 2. Incremental sheet metal forming tools: (a) hemispherical-end, and (b) flat-end with chamfered edges. (All dimensions are in mm).

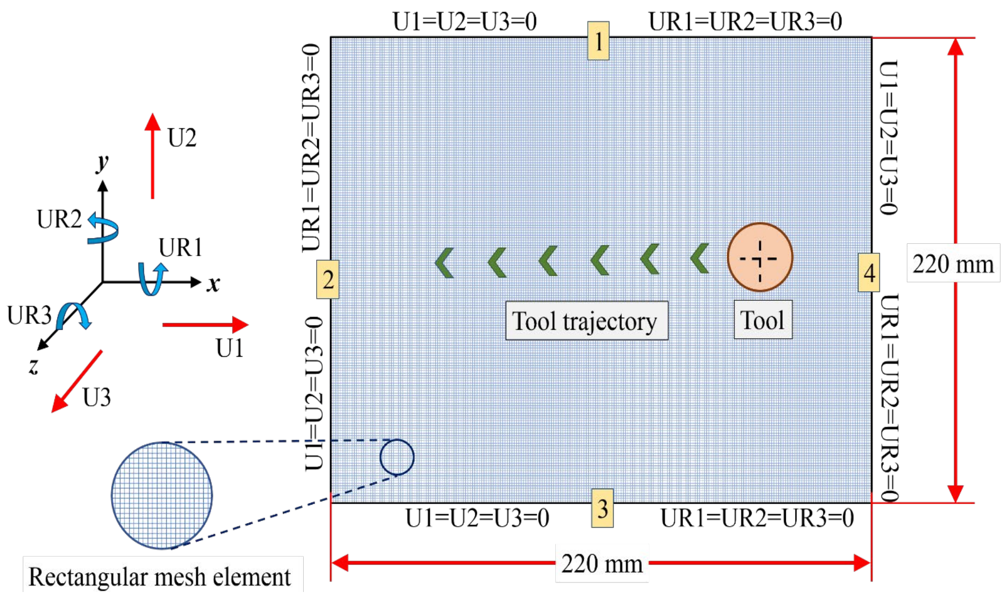

Fig. 3. Domain with boundary conditions. U1, U1, and U3 represent displacement, and UR1, UR2, and UR3 represent rotation about the x, y, and z axes, respectively. The sheet thickness is kept at 1 mm, and the edge length of the square mesh element is 2 mm.

Fig. 3 shows that the sheet was square in shape, with cross-sectional dimensions of 220 mm × 220 mm and a thickness of 1 mm. The sheet was modeled using a deformable, shell, planer type base feature. All edges of the blank sheet were fixed by applying an ENCASTRE (U1=U2=U3=UR1=UR2=UR3=0) boundary condition. In this type of displacement boundary condition sheet was clamped with all its edges. The translation and rotational motion along the *x*, *y*, and *z* axis were restricted. The boundary condition provided for the tool path was of amplitude type. In this type of boundary condition, the field variable varied with time. Co-ordinates of tool path were the field variables. Surface-to-surface explicit type contact property was given for dynamic explicit analysis. A master-slave algorithm was used to describe the frictional contact between tool and work. The tool moves from one edge to the other edge and repeated its path as per the number of stages provided.

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The mesh sensitivity analysis was performed. Square S4R shell elements of 1 mm, 2 mm, and 4 mm size were taken by considering the effect of friction. Reaction force was estimated with different mesh sizes. CPU time increased drastically as mesh size decreased. Simulation time was about 20 minutes, 85 minutes, and 225 minutes for the element sizes of 4 mm, 2 mm, and 1 mm, respectively, for one problem. The material properties of the different materials are listed in Table 1.

Table 1. Physical and mechanical properties of Aluminum 6061- T6 and Titanium Ti-6Al-4V [12, 13].

Properties	Aluminum	Titanium
Density [g/cc]	2.7	4.43
Tensile Yield Strength [MPa]	276	880
Ultimate Tensile Strength [MPa]	310	950
Poisson's Ratio	0.33	0.34
Modulus of Elasticity [MPa]	68900	113800

Results and Discussion

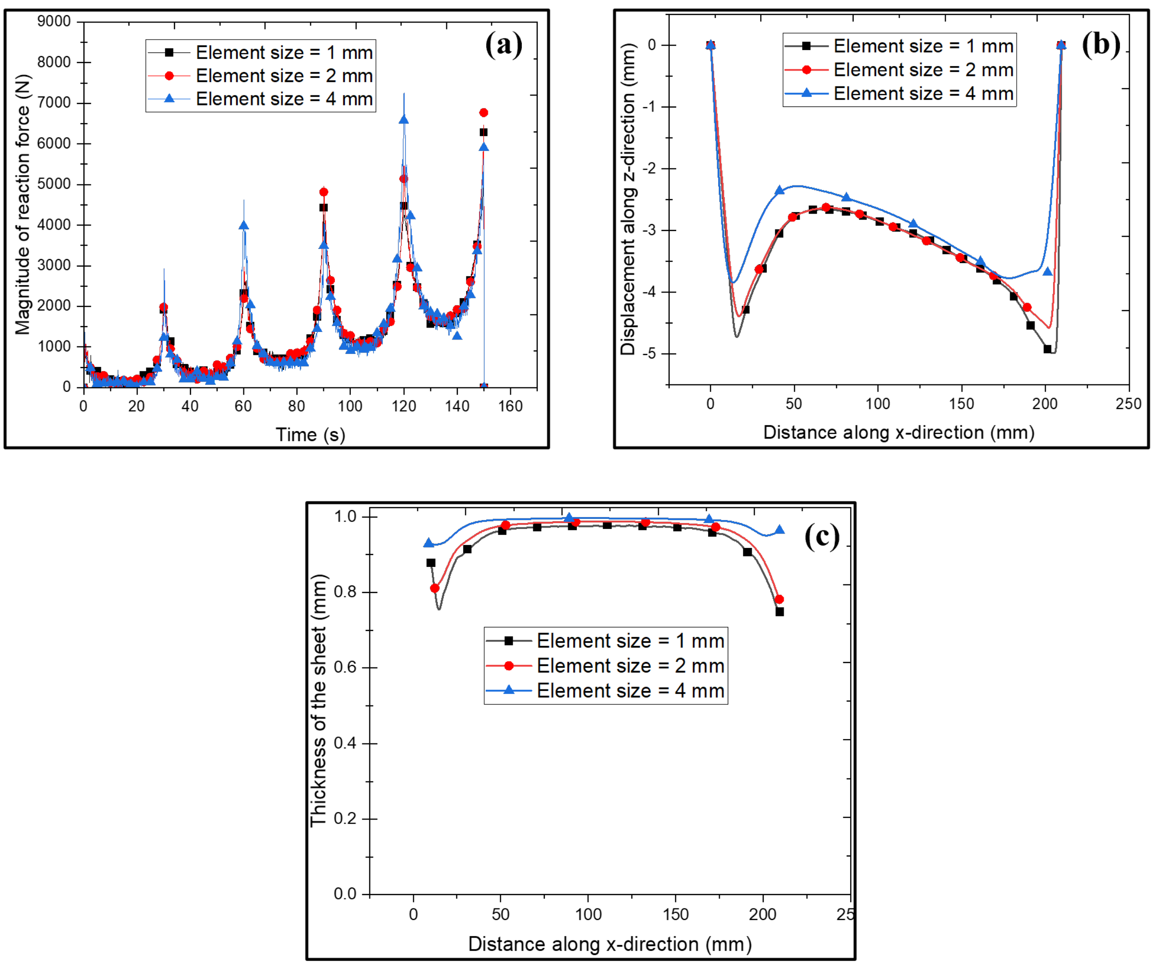

Fig. 4. Element size effect on (a) reaction force developed on the tool, (b) displacement achieved in the z-direction, and (c) thickness of the sheet after deformation.

Mesh sensitivity analysis.

For simulation, mesh size plays a vital role. In Fig. 4, an aluminium alloy has been used to investigate the mesh sensitivity. Smaller element size becomes too costly in terms of simulation time. Mesh sensitivity affects the magnitude of the reaction force developed on the tool, as shown in Fig 4 (a). Element size effect on the magnitude of reaction force developed was insignificant, but it affects the other process parameters significantly. Fig 4 (b) shows that with an element size of 1 mm, the spring back effect is high compared to the element size of 2- and 4-mm. Fig. 4 (c) showed that thickness distribution with larger element size was better, and low thickness reduction was observed. Considering a trade-off between accuracy and computational time, a 2 mm element size was chosen for subsequent parametric study. Fig. 5 shows the von Mises stress developed in aluminium alloy sheet.

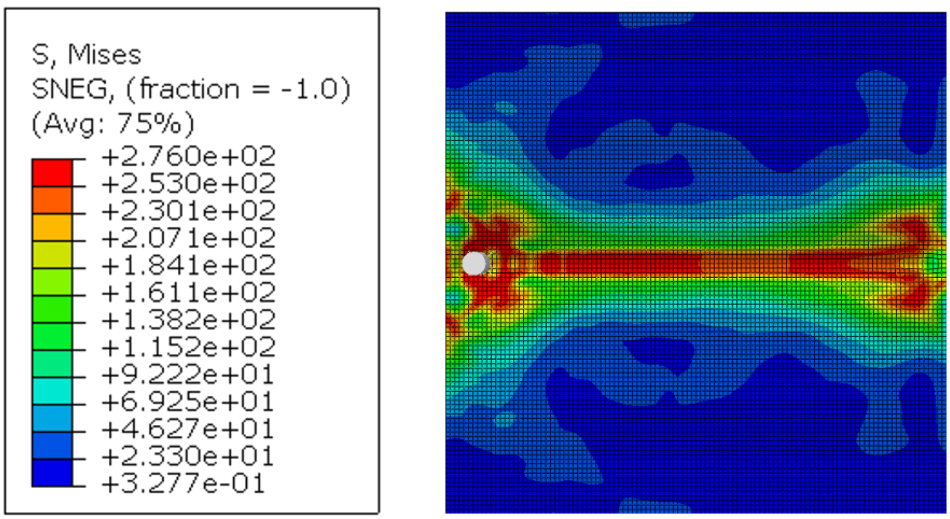

Fig. 5. Numerical simulation response of deformation with aluminium alloy.

Effect of different parameters on the reaction force.

In ISMF, the forming forces depend upon the tool path, and the feasibility of forming a reliable component also depends upon it. In the present case, the straight tool path was chosen for simulation, and forming forces were determined for different process parameters. One of the input process parameters was the coefficient of friction. The penalty-based condition with a hard contact surface was given between the tool and the workpiece.

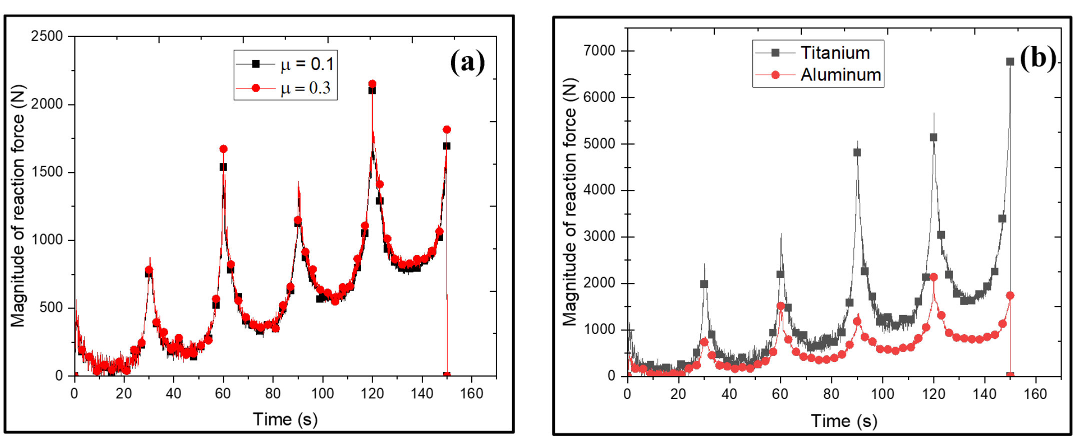

Fig. 6. Time-history plots of resultant reaction force with (a) different coefficients of friction values and (b) different materials.

Force was measured by taking every 0.1 s unit of time in field output request in the step module of ABAQUS. It was observed that the friction coefficient has very little influence on the reaction forces acting on the tool Fig 6 (a). A tool with a hemispherical-end was used by taking μ=0.1 and μ=0.3 with a 2 mm mesh size, i.e., (approximate global size). The observed magnitude of force was the same for these friction coefficient values. These results inferred that the coefficient of friction had an insignificant effect on the reaction force developed on the tool in any direction. When the tool stopped and reversed back during its motion along the assigned path and simultaneously moved in the *z*-direction in accordance with step size, it resulted in a sudden increase in reaction force. Thus, a sharp spike in reaction force was observed at the edges.

Fig. 6 (b) showed that the magnitude of the reaction force on the tool depends upon the type of material used. The developed reaction force with titanium alloy was more compared to aluminum alloy. It was due to the high tensile strength of the titanium alloy. For the same amount of deformation, by keeping all other parameters the same, force developed with titanium should obviously be high.

For making channels by ISMF process, different types of tools can be used, such as hemispherical-end tool, flat-end tool, and flat-end tool with corner radius. Simulation results suggest that the magnitude of reaction force required for making a channel is relatively less with the hemispherical-ended tool, as shown in Fig. 7.

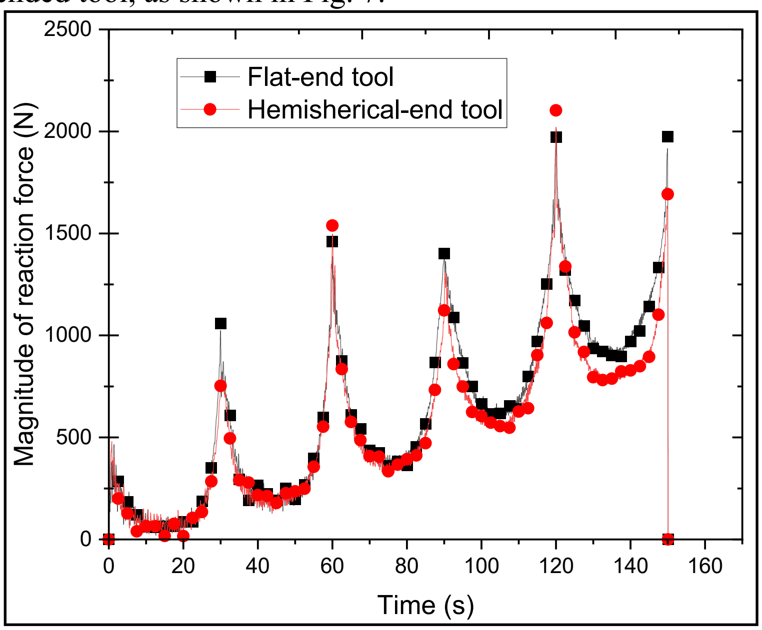

Fig. 7. Time-history plots of magnitude of resultant reaction force with different types of tools.

Effect of the step size.

The effect of step depth on different response parameters was investigated. Forming tool was treated here as a rigid body with no deformation. Reaction force developed on the tool, displacement achieved in the *z*-direction, and final thickness of the sheet were analyzed for two different step sizes. Fig 8 (a) showed that the reaction force developed was high with a large step size.

Sheet thinning is the major factor in sheet forming. Here, it was observed that with different step sizes, there was not much difference in the final thickness of the sheet. The spring back effect with a small step was more compared to a high step size, and the depth achieved in the *z*-direction was more with a large step size Fig. 8 (b), (c).

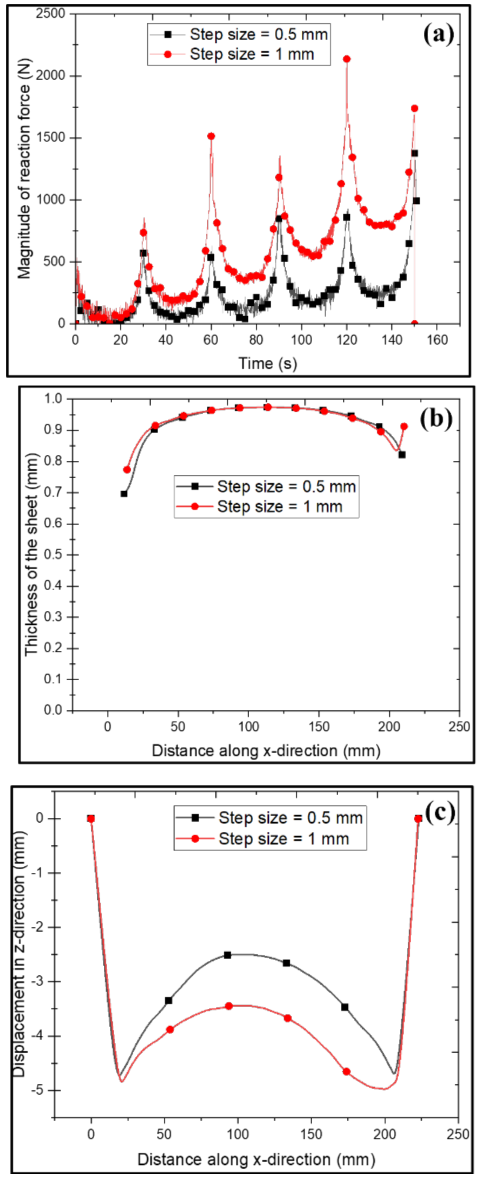

Fig. 8. Effect of step size on (a) reaction force developed on the tool, (b) thickness of the sheet after deformation, and (c) displacement achieved in the z-direction.

Experimental validation was carried out qualitatively from published literature. The trend of various parameters is observed to be in good agreement with numerical simulation data. It was observed that reaction force increases with an increase in step size [14]. From this reference, it is noted that the trend of force is in good agreement as it was done in the simulation in this article. Formability was higher with a large step size, but the thickness distribution was better with a low step size [15]. Strain hardening has a negligible effect on the force developed. There is less effect of the coefficient of friction on the formability and reaction force [16].

Summary

In recent years, the ISMF process has been intensively investigated using the FEM. In this work, numerical simulations were performed for ISMF in the U-channel model. Aluminum and titanium alloys were deformed with flat-ended and hemispherical-ended tools. To obtain a depth of 5 mm, simulations were performed with various step sizes. Based on the analysis of simulation results, the following conclusions can be drawn:

1. The size of the element has a significant effect on the resulting values of some output parameters. However, decreasing the element size makes the simulation computationally intensive, time-consuming, and cost-ineffective.
2. No significant difference was observed with different coefficient of friction values on reaction force.
3. It is observed that the reaction force developed on the tool was higher with high-strength alloy and the flat-end tool experienced a high magnitude of reaction force compared to a hemispherical end tool.
4. Step size affects the reaction force devolved on the tool and formability (measured in the form of depth achieved) but has little influence on the thickness reduction of the sheet.

Future work aims to validate the results with in-house experiments and study formability.

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