Comparison of alternative approaches of single point incremental forming processes

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\textbf{ABSTRACT}

Incremental sheet metal forming is becoming an attractive technology for fast prototyping and small batch production of sheet metal parts. The majority of investigations are focused on the use of a rigid tool to incrementally form the sheet metal into a final shape. An interesting alternative is to substitute the rigid tool with a high velocity water jet (WJ). The comparison between using a rigid tool and a WJ shows that each method has its advantages and disadvantages. This investigation is aimed to identify the most influential parameters affecting the forming process through experimental comparison of the two observed methods. Technological windows based on non-dimensional values and relevant process parameters like force on the rigid tool and water pressure were defined.

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\textbf{1. Introduction}

Modern production requires manufacturing processes, which are flexible and adaptable in order to fulfil the requirements of new products. An important aspect of developing new products is the possibility to produce functional prototypes in a time and cost effective way. In case of sheet metal products, incremental sheet metal forming represents a reliable fabrication method for prototypes and small batch production as described by Jeswiet et al. (2005). Incremental sheet metal forming is a process in which a simple geometry tool moves along an arbitrary trajectory over a sheet metal workpiece. In this way locally controlled plastic deformations are inserted until the target geometry is achieved. The majority of investigations in this field are focused on the use of a rigid tool, as for instance the investigations made by Jeswiet et al. (2005) and Petek et al. (2005). Nevertheless, alternative principles like the use of a laser described by Geiger and Vollertsen (1993) and Kim and Na (2003) or a high velocity water jet (WJ) reported by Iseki (2001) and Jurisevic et al. (2003) instead of a rigid tool have been considered as well.

The aim of this investigation is to compare rigid tool single point incremental forming (RTSPIF) and water jet single point incremental forming (WJSPIF). In case of RTSPIF the main tool is a rod-shaped punch with a smooth hemispherical head, while in case of WJSPIF the main tool is a high velocity WJ as shown in Fig. 1.

Both processes are compared by means of technological windows, which show the optimal operating area depending on workpiece material properties and part geometry requirements.

A similar comparison has been carried out by Jurisevic et al. (2004), in which both processes were evaluated qualitatively, without any experimental verification. The results of that study showed some advantages of using a WJ as the main tool. The tool workpiece interface conditions, equipment costs and process flexibility are better comparing to the case when a rigid tool is applied. On the other hand the use of a rigid tool
allows better forming accuracy and reduces the machining time.

2. Principles of RTSPIF and WJSPIF processes

In the presented research two relatively new and innovative metal forming technologies, namely RTSPIF and WJSPIF are observed and compared. Both methods are capable of forming sheet metal parts of complex unsymmetrical shape without the need of a dedicated die.

The main difference between RTSPIF and WJSPIF is in the forming mechanisms. During RTSPIF the position of the tool against the workpiece is defined with the process kinematics. Therefore, the force acting on the workpiece depends on the tool path and is the result of the forming process itself. In case of WJSPIF the situation is inverted. The available force of the tool (a high velocity WJ) is defined mainly with the water pressure and nozzle characteristics (diameter and type). Therefore, the forming force is not a consequence of the process but is rather defined by the operator through the process parameters. The working principles and the most relevant process parameters of RTSPIF and WJSPIF are presented in Fig. 2.

2.1. Experimental setup for RTSPIF

Experimental work in case of RTSPIF has been executed on a CNC milling machine using specially adapted tooling. In this process the rod-shaped punch with a smooth hemispherical head of diameter \( d_{RT} \) 1.6 mm is clamped into the spindle of the milling machine. Because of superior tribological properties the rotation of the spindle is taken into account (rotation speed, \( v_R = 30 \) rpm). The metal plate is fixed and positioned on a specially designed blank holder, which is placed into the worktable of the milling machine. The CNC milling machine Mori Seiki with the FANUC MSC-521 control system for three-axis positioning and linear interpolation as well as two axis circular interpolation has been used. The blank holder remains in place during the entire forming process in which the punch presses and deforms the plate by inserting locally controlled plastic deformations. The tool path strategy is defined as increments in horizontal and vertical direction \( \Delta y \) and \( \Delta z \), respectively. Phases of single point incremental forming with rigid tool are shown in Fig. 2. In order to avoid any undesired issues arising from friction between the tool and the workpiece the SYLAC Al 46 lubricant oil was used.

2.2. Experimental setup for WJSPIF

Experimental work concerning WJSPIF has been carried out on a specially developed machine consisting of three main components: high-pressure unit, working table and controlling system. The main component of the high-pressure unit is the pump itself, a three plunger design, which is capable of reaching water pressures up to 20 MPa and water volume flow up to 50 l/min. Besides the pump the unit is fitted with a filtering system and a 500 l water tank, which enables to reuse the same water. During the forming process the workpiece is placed into the working table inside the same workpiece holder used in RTSPIF, while the forming head moves along a predefined arbitrary trajectory. The forming head contains a water nozzle through which the WJ is generated as the main tool. During the investigation the forming head was positioned 20 mm above the workpiece, presented as the standoff distance \( h_{SO} \) in Fig. 2. Process kinematics is controlled with a...
was a 0.23-mm thick aluminium alloy plate of size 125 mm x 125 mm.

Material properties of aluminium alloy obtained by a uniaxial tensile test are shown in Table 1.

Table 1 – Material properties of aluminium alloy

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength coefficient, C (MPa)</td>
<td>139.12</td>
</tr>
<tr>
<td>Strain hardening exponent, n</td>
<td>0.025</td>
</tr>
<tr>
<td>Material anisotropy, r0, r60, r90</td>
<td>0.25, 0.62, 0.57</td>
</tr>
<tr>
<td>Young's modulus of elasticity, E (GPa)</td>
<td>70</td>
</tr>
<tr>
<td>Density, ρ (kg/m³)</td>
<td>2750</td>
</tr>
<tr>
<td>Initial workpiece thickness, t₀ (mm)</td>
<td>0.23</td>
</tr>
<tr>
<td>Tensile strength, Rm (N/mm²)</td>
<td>126</td>
</tr>
<tr>
<td>Yield strength, Ry (N/mm²)</td>
<td>120</td>
</tr>
</tbody>
</table>

In order to compare the observed forming processes, the same tool diameter (δWJ = δRT = 1.6 mm) and workpiece holder were used in both cases. During this investigation, a simple pyramidal shape has been formed. The final geometry depends on the applied process parameters. However, the base of the pyramid had a square side of 40 mm (A) and the top of 3 mm (a) as shown in Fig. 3.

During this investigation the forming time, forming accuracy and forming limits, have been observed, since they are very important for choosing the appropriate method, equipment and optimal process parameters.

Three of the most influential process parameters affecting the forming time and forming accuracy are selected on the basis of the previous investigations made by Petek et al. (2005) and Petek and Kuzman (2006) analysing the influence of various process parameters on the forming forces and deformations and Jurisevic et al. (2004) investigating the RTSPIF and WJSPIF process comparison aspects include forming time, forming accuracy, surface finish, strain distribution, flexibility, tooling needed and energy consumption on the technology level from part design to part production, but without any experimental verification. However, those three parameters are the traverse rate, horizontal step size and wall angle by RTSPIF and the traverse rate, water pressure and horizontal step size by WJSPIF. The above-mentioned process parameters also influence the forming limits, especially the horizontal step size and wall angle. Accordingly, the forming limit will be determined for both technologies taking into account these two.

Table 2 shows the selected process parameters for RTSPIF and WJSPIF, which are based on preliminary tests and available literature. During this study only horizontal step size was varied in WJSPIF, while horizontal step size and wall angle were varied in RTSPIF. The other process parameters from Table 2 were kept unchanged.

4. Results

In RTSPIF the predetermined tool path of the rigid tool defines the forming process in vertical direction. On the other hand in WJSPIF is still almost impossible to control the displacement of the workpiece material in vertical direction. In this case the forming tool is not rigid and the energy needed for the forming process depends on the water pressure, nozzle diameter and horizontal movement, what also influence the size of pyramid wall angle through the resulting force of the WJ. Therefore, the investigation was divided in two sections. In the first section the pyramid geometry were formed using WJSPIF, where the horizontal step size was varied. This results in achieving different pyramid wall angles. The biggest wall angles achieved in WJSPIF were used as the input in defining the plan of experiments for RTSPIF, where comparable process parameters adapted to RTSPIF were applied as listed in Table 2.

4.1. Influence of the wall angle and horizontal step on forming

The horizontal step size and wall angle are included in this contribution since they present two of the most influential process parameters affecting the forming limits chosen on the basis of the previous investigations made by Petek et al. (2005), where only the deformation or displacement in the perpendicular direction to the tool motion were investigated using graphometric analysis. To determine the influence of the horizontal step size (Δy) and the wall angle (α) on the forming process, four different horizontal steps were observed in WJSPIF, namely 0.4, 0.8, 1.2 and 1.6 mm and three horizontal steps were observed in RTSPIF (0.2, 0.4 and 0.8 mm). Other process parameters were kept unchanged according to the values listed in Table 2. In case of WJSPIF the size of horizontal step has a stronger influence on the wall angle compared to RTSPIF. If the horizontal step increases the wall angle decreases as shown in Fig. 4. The obtained results indicate that fracture occurs when the horizontal step is smaller than 0.8 mm, what corresponds to the maximal wall angle of approximately 26° for the applied workpiece material in this research. In case of smaller horizontal step the WJ passes several times over the same area of the workpiece what leads to the excessive material hardening and later on to fracture occurrence. A possibility to enlarge the slope of the pyramid is to use higher water pressure. Nevertheless, this is possible up to a threshold value, where erosion starts to appear on the workpiece.
Table 2 – Applied process parameters

<table>
<thead>
<tr>
<th></th>
<th>RTSPIF</th>
<th>WJSPIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall angle, ( \alpha )</td>
<td>26°, 44°, 50°, 60°</td>
<td>Defined with ( p_W ) and ( \Delta y )</td>
</tr>
<tr>
<td>Rotation speed, ( v_R ) (rpm)</td>
<td>30</td>
<td>–</td>
</tr>
<tr>
<td>Punch diameter ((d_{RT}))/water diameter ((d_W)) (mm)</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Traverse rate, ( v_T ) (mm/min)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Horizontal step size, ( \Delta y ) (mm)</td>
<td>0.2, 0.4, 0.8</td>
<td>0.4, 0.8, 1.2, 1.6</td>
</tr>
<tr>
<td>Lubricant</td>
<td>SYLAC Al 46</td>
<td>20</td>
</tr>
<tr>
<td>Standoff distance, ( h_{S0} ) (mm)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Water pressure, ( p_W ) (MPa)</td>
<td>–</td>
<td>10</td>
</tr>
</tbody>
</table>

In case of RTSPIF the forming force is directly related to the process parameters. However, the forming force is a consequence of the forming process itself and enables to detect the beginning of deformation and fracture area as reported by Petek et al. (2005). Hence, it follows that it could be useful to define the technological window for RTSPIF according to the relative tool diameter \( \kappa \) and forming force in vertical direction \( F_Z = F_{RT} \), as shown in Fig. 5.

The shape of the technological window presented in Fig. 5 is defined on the basis of numerous experimental results for three various materials (Al3003, \( t_0 = 1.23 \) mm; DC05, \( t_0 = 1 \) mm; aluminium alloy presented in Section 3). With the variation of \( t_0 \) and \( d_{RT} \) the various non-dimensional values \( \kappa \) and forming forces are observed and inserted into the diagram. In general, technological window presents two different areas, which are limited with the specimen fracture and area of no plastic deformation on the specimen, respectively. The first one describes the area where the sheet thickness \( t_0 \) is constant and the second one presents the area where the tool diameter \( d_{RT} \) is constant. It is worth pointing out that with the proportional enlargement or reduction of the values \( t_0 \) and \( d_{RT} \) (in order to keep the relative tool diameter \( \kappa \) constant) the areas move up and down, as schematically presented with arrows in Fig. 5. Finally, regarding to selected relative tool diameter \( \kappa \) the cross-section of the areas defines the technological window for RTSPIF, in which the part could be formed.

In order to evaluate the influence of various process parameters in case of both presented processes it is very convenient to observe the formability as a main criteria, which is defined as the case when plastic deformations are inserted into the work-

Fig. 4 – Forming limits for RTSPIF and WJSPIF depending on the horizontal step \( \Delta y \) and wall angle \( \alpha \).

Fig. 5 – Technological window defined for RTSPIF.
piece material without allowing defects like cracks, wrinkling, surface damage, etc. The optimal formability is obtained when the relative tool diameter is at its optimal value ($d_{RT}$ = 10). This value is defined on the basis of recommended tool diameter, which is defined according to previous experience reported by Matsubara (2001) and graphometric analysis based on maximal principle strains measuring, whereas tool diameter and material thickness were changed according to design of experiments. The technological window for RTSPIF, shown in Fig. 5, presents the technological window in case of optimal formability. This information can be used as a reference for setting optimal process parameter ($d_{RT}$, $t_0$ and other process parameters).

The technological window is also limited with the highest value of the relative tool diameter ($r_{max}$). This value depends on the size of the part, sheet thickness and tool diameter and usually differs from case to case. However, it defines the boundary between incremental forming, where the tool deforms the sheet metal with locally controlled plastic deformations, and other forming processes like deep drawing, stretching, etc.

Besides all mentioned, the position and size of the technological window (when $t_0 = constant$ and $d_{RT} = constant$) depends also on the type of the workpiece material. As for instance, high strength steel requires higher forming forces in contrast to aluminium alloys. This influences the vertical position of the technological window for RTSPIF. On the other hand some types of aluminium alloys have better incremental forming ability compared to high strength steel, what influences the size of the technological window.

In order to better evaluate the WJSPIF process, technological windows have been introduced in this case as well (Jurisevic et al., 2006a). The influence of the water pressure ($p_W$) as the most relevant process parameter on the formability is observed through the relative jet diameter ($s$). The technological window for WJSPIF shown in Fig. 6 is like the one for RTSPIF limited by two areas, one the top where damage occurs on the workpiece and the other on the bottom where no plastic deformation is inserted in the workpiece material.

As shown in Fig. 6 the technological window is defined on the top by the water pressure at which erosion starts to take place on the workpiece surface. In this case the pressure at the interface between the WJ and the workpiece exceeds the threshold value defined with the workpiece material properties. Furthermore, this upper limit does not depend on the sheet thickness. The other limit, which defines the area where no plastic deformation are inserted in the workpiece material depend on the workpiece material properties and its thickness.

Both technological windows presented in Figs. 5 and 6 are generic without any values on the axis, because actual values depend on the workpiece material properties. The aim of showing those two technological windows is to show the influence of process parameters to the forming process. Once that all mechanisms of both compared processes will be better understand, technological windows for various workpiece material will be accurately defined, what will help the operator to set optimal process parameters.

Nevertheless, it is very difficult to predict a process in which the tool attributes are not completely known and understand. In case of WJSPIF the tool is a high velocity WJ, which has been experimentally and numerically observed in previous investigations made by Jurisevic et al. (2006b). The numerical simulation is based on the continuity equation and Navier–Stokes equation for uncompressible fluid flow as shown in the following equations, respectively:

\[ \rho \cdot \frac{\partial \mathbf{v}}{\partial t} = \rho_0 \cdot \mathbf{f} - \mathbf{p}_i + \mu \cdot \nabla \cdot \mathbf{v} - \rho_0 \cdot (\mathbf{u} - \mathbf{v})_j \]

\[ \rho_0 \cdot \frac{\partial \mathbf{v}}{\partial t} = \rho_0 \cdot \mathbf{f} - \mathbf{p}_i + \mu \cdot \nabla \cdot \mathbf{v} - \rho_0 \cdot (\mathbf{u} - \mathbf{v})_j \]

Simulation results are in good agreement with the experiments, what represents a useful tool in future developments in this field.

6. Conclusions

The presented work is based on experimental observation of two incremental sheet metal forming processes, where the main difference is in the utilized tool. In one case the main tool is a rod-shaped punch with a smooth hemispherical head, what is addressed as RTSPIF. This process is compared with WJISMF, where the main tool is a high velocity WJ. Both processes are characterized with technological windows that show the optimal operational area according to the workpiece properties (sheet thickness and material properties).

Experimental work has been carried out on both observed processes. In this respect forming of a simple pyramidal shape out of 0.23 mm thick aluminium sheet has been observed. The diagram in Fig. 4 shows the forming results as a function of the horizontal step and wall angle. It is very interesting to observe, that the two processes are complementary according to the optimal range of horizontal step and wall angle. From the investigations made it could be concluded that, RTSPIF is more appropriate in cases of bigger wall angles and smaller horizontal steps, while WJSPIF performs better at larger horizontal steps and smaller wall angles.

A major difference between RTSPIF and WJSPIF is in the process controlling principle. In RTSPIF the main process parameter is the tool kinematics, which defines the loads acting on the workpiece. If they exceed the threshold value,
fracture of the workpiece occurs. During WJSPIF the main process parameter is the water pressure, which defines the loads on the workpiece. The standoff distance has also an influence on the WJ attributes at the interface with the workpiece. Ongoing investigations show that the water pressure is far more relevant to the process outcome.

Observations from previous comparison study between RTSPIF and WJSPIF reported by Jurisevic et al. (2004) have been confirmed. RTSPIF enables higher process accuracy and shorter machining time compared to WJSPIF.

REFERENCES