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Tool dynamics during single point incremental forming process

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Abstract

The single point incremental forming manufacturing process has become increasingly used because of its flexibility in manufacturing single pieces. There exist in the literature many research works that focus on studying the different phenomena observed during the single point incremental forming process of sheet metal blanks such as material fracture criterion, forming limit diagram, friction and force effects, mechanics of deformation, material spring-back, optimization processes, among others. However, the tool and the experimental set up dynamic effects that could influence the single point incremental forming process have not been addressed. Therefore, the aim of this research focuses on studying the dynamics interaction among the tool, the experimental set up and the sheet blank during the forming process. To quantify these effects, we have dynamically characterized the process response behavior and used finite element simulations to identify the resonance vibrational frequencies as well as the magnitude of the maximum von Mises stresses and found that if we want to avoid undesirable vibrational effects that could affect the final formed part, we need to have a robust experimental set up.

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Keywords: SPIF process; System dynamical response; Forming tool natural frequencies; Resonance forming tool and spindle frequencies

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1. Introduction

Modern manufacturing processes have integrated methods that allow the customization of metal and plastics prototype components. In this sense, the single point incremental forming manufacturing process has become increasingly used because of its flexibility in the manufacturing of single pieces such as automotive body panel, reflectors, housing and fairings for aerospace, medical applications (Ambrogio et al., 2005; Jeswiet et al., 2005; Emmens, 2010), to say a few. There exist in the literature many research works that focus on studying the different phenomena observed during the single point incremental forming process of sheet metal blanks such as material fracture criterion (Cockcroft and Latham, 1968; Brozzo et al., 1972; Ko et al., 2007), forming limit diagram (Keeler and Backofen, 1963; Bael et al., 2007; Filice et al., 2002), friction and force effects (Tisza et al., 2001; Podgornik et al., 2004; Duflou et al., 2007; Bagudanch et al., 2013a), mechanics of deformation (Emmens and van den Boogaard, 2009), material spring-back (Vahdati and Vahdati, 2011), optimization processes (Ceretti et al., 2002), energy consumption (Bagudanch et al., 2013b), among others. However, the tool dynamic effects that could influence the material response behavior during the single point incremental forming process have not been addressed. Fig. 1(a) shows that during the forming processes, the dynamic forces between the tool and the workpiece tends to increase with the forming depth. At any interval time of the forming loop, the exerted forces do not remain constant, as shown in Fig. 1(b). The variation of the force is mainly due to the contact area of the tool (Duflou et al., 2007), that leads the vibration effects. In manufacturing process three vibrational type effects could arise: free vibrations, forced vibrations (Elías-Zúñiga et al., 2009) and chatter (Hamilton, 2010), as occurred during the milling cutting processes where forced vibrations are mainly due to gear contact forces, bearing imbalance, transmissibility of the workshop floor, and the entrance and exit of the tool (Quintana and Ciurana, 2011). These vibrations could also influence the final shape of a manufactured part by incremental sheet forming therefore, it is important to establish design criteria's for the selection of the forming tools that will allow us to manufacture good quality parts. The aim of this work focuses on discussing the dynamic effects that the forming tools have during the single point incremental forming process on sheet metallic parts as well as its influence on the maximum stress magnitude values. In this sense, experimental data were collected by considering the real shape formed part at each depth as well as the transmitted acceleration values reached during the forming process. Then, the finite element technique was applied to determine the influence of the vibrating effects of the forming tool on the blank metallic sheets.

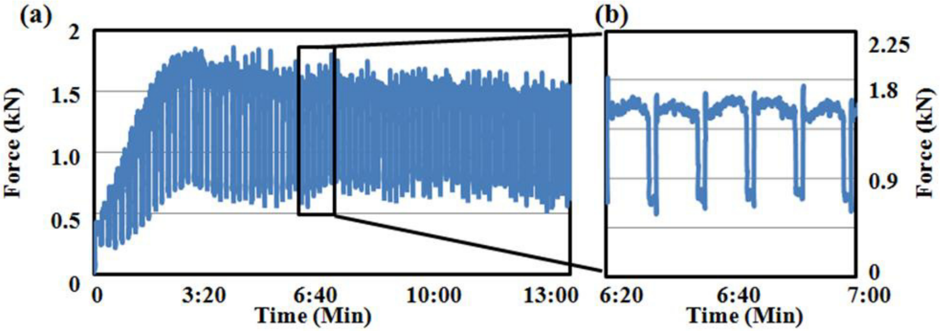

Fig. 1. Experimental forming force, (a) full process; (b) five step down loops.

2. Experimental Set up and Tested Materials

The experiments were carried out in a Kondia® HS1000 3-axis milling machine with the single point incremental forming experimental set up, that includes a top plate, a clamping plate, four supports, a bottom plate and a sheet blank, as shown in Fig. 2(a). These sheet blanks have the dimensions of 150 x 150 mm with an effective working area of 120 x 120 mm in Fig. 2(b) that allow us to manufacture the formed part shown in Fig. 2(c). Between the experimental set up and the working table, a table-type dynamometer Kistler 9257B was put to measure the forming forces that occur during the manufacturing process. The forces were acquired on a computer based data acquisition systems by using a DaqBoard 505 data card and the DaqView 9.0.0 software. The acceleration during the forming process in the *z*-direction was measured by a PCB 352C22 accelerometer with a 0.5 gr. of weight. This accelerometer was fixed on the formed part as illustrate in Fig 2(d). Stainless steel AISI 304 blanks with a sheet thickness of 0.8 mm were used to collect the vibrational effects on their forming process. We selected the forming tool with a 10 mm hemispherical tip made from tool steel and clamped rigidly. To reduce friction effects during the single point incremental forming process, we used the metal forming lubricant Houghton TD-52.

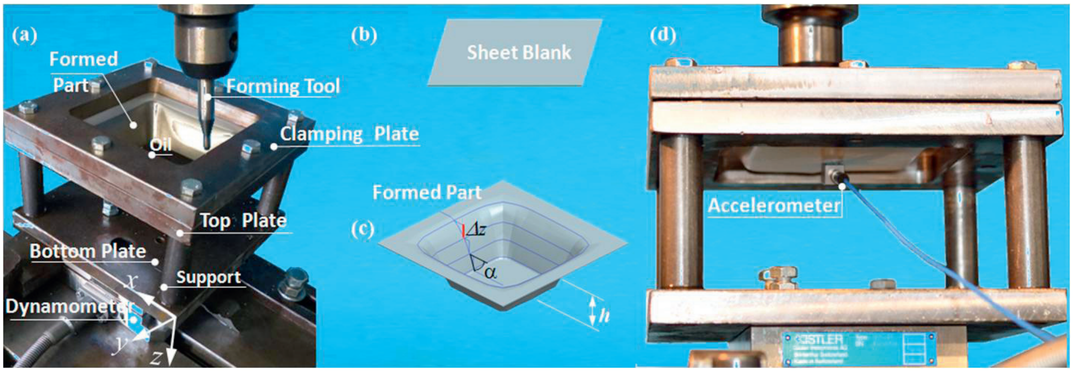

Fig. 2. (a) Single point incremental forming experimental setup mounted on a Kondia CNC milling machine, (b) sheet blanks, (c) formed part with a depth of 41 mm and (d) accelerometer mounted on the formed part.

3. Experimental method and computer simulation.

We select a quadrangular pyramid form and follow square loops tool paths to form the metallic sheets that have an initial square length trajectory of 95 mm and forming angle α of 65º. Tool forming step down was Δz = 0.5mm, Fig. 2(c), the spindle speed of 1000 RPM and feed rate of 50 mm/s (Bagudanch et al., 2013a). These parameters avoid 'orange peel' effects generated by the friction interaction between forming tool and the formed part (Hamilton, 2010), however there was a temperature increase in the formed part at higher spindle speed, that enhance the sheet formability (Durante et al., 2009; Hamilton and Jeswiet, 2010). Six metallic sheet pieces were manufactured by considering the following depths, *h*, of 15mm, 23mm, 31mm, 35 mm, 39 mm and 41mm. Afterwards, the computer simulations were run to characterize the dynamical response during the incremental forming process, starting by modeling the formed part at different depths by using the 3D Handyscan EXAscan laser class II with a resolution of 0.050 mm and accuracy up to 0.040 mm. This process can help us to identify the true geometry of the formed part, like thickness thinning, to get their real corresponding computer-aided design (CAD) representation with the help of Creo 2.0 computer program. Fig. 3(a) illustrates an example of a formed part with a 41 mm depth, while Figs. 3 (b) and (c) represent respectively, the scanned geometry and their geometric computer model obtained from the Creo 2.0 computer program. To predict the dynamical response behavior of the experimental setup during the forming process, we modeled it on the Creo 2.0 program, as shown in Fig. 3(d), and then we followed a discretization process, as shown in Fig. 3(e), to determine the natural vibration frequencies of the system and the stress distribution field.

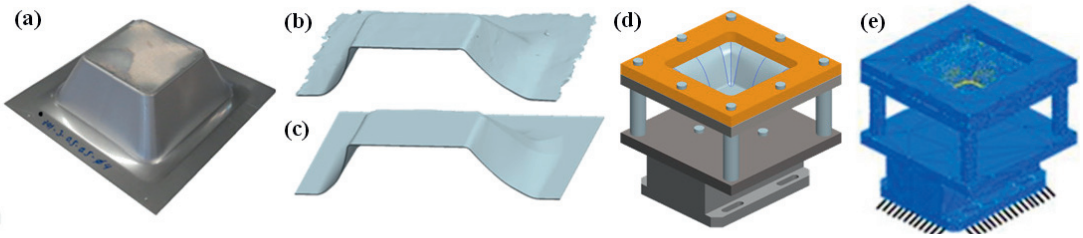

Fig. 3. (a) Formed part, (b) laser scanned formed part, (c) computer geometric model, (d) experimental setup model and (e) discretized model.

4. Experimental and numerical results

Initially, during the forming process, the maximum attained force attained was 1.83 kN as shown in Fig. 1, while the maximum acceleration values in the z-direction on the formed part, are illustrated in Fig. 4(a). To capture possible dynamical effects, we used the acceleration fast Fourier transform to identify the dominant frequencies induced in the formed part during its manufacturing process. The collected peaks acceleration values shown in Fig. 4(b) were: 1.29, 1.77, 3.93, 11.56, 14.48 and 3.55 m/s^2, corresponding with the frequencies values of 2.84 kHz, 2.87 kHz, 3.24 kHz, 3.65 kHz, 4.05 kHz, and 4.46 kHz, that corresponds, respectively, to the points I through VI. The two maximum acceleration values occurred at the frequencies of 3.65 kHz and 4.05 kHz. We next characterized the forming tools dynamically. In this case, we performed the corresponding measurements by using a laser vibrometer system (Polytec OFV 505) with an impact hammer PCB 086C03 in conjunction with the analyzer system OROS OR35 to collect the output signals. The collected measurements were integrated throughout the NV Gate 6.7 software platform. These provided the forming tool natural frequencies values of 1.45 kHz, 2.18 kHz and 2.41 kHz, from A to C in Fig. 4(c).

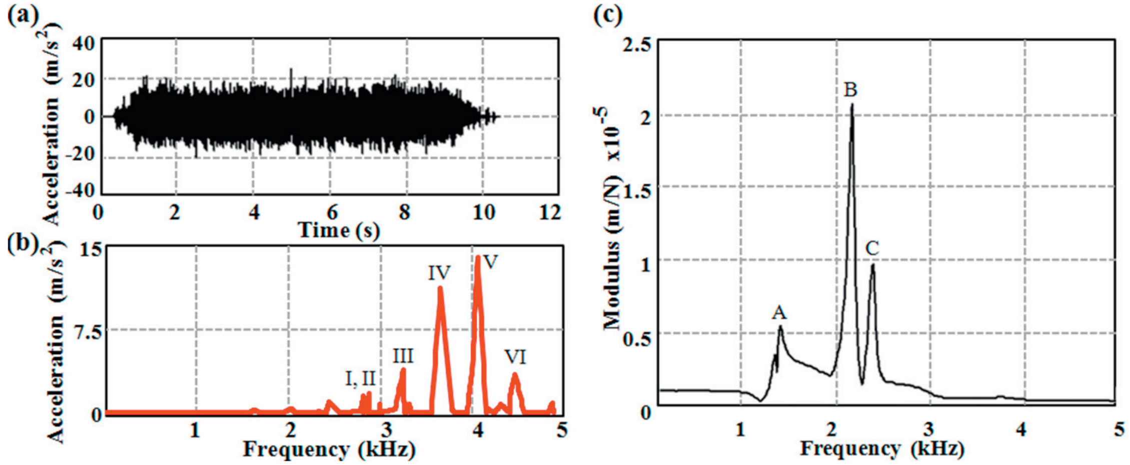

Fig. 4. (a) Acceleration spectra of the formed part, (b) the corresponding fast Fourier transform (FFT), and (c) forming tool oscillatory frequencies.

The excitation acceleration signal shown in Fig. 4(b) was considered to identify the natural frequencies and the stress levels by using the geometric element analysis (GEA). The CAD´s experimental setup has been discretized into geometric elements to map the structure geometry by considering 14,317 tetrahedral elements and 17,477 elements with 34,900 edges and 36,740 faces, with a minimum edge value of 15.00 and maximum edge angles of 160°. During the analysis, we assumed an elastic modulus of 199 GPa for the experimental setup with a Poisson coefficient value of 0.3, while for the formed part, the values of 193 GPa and 0.3 were used. To define the boundary conditions, we assumed that the base of the experimental setup was completely restrained as shown in Fig. 3(e). The numerical computation provided the natural frequency values, the vibrational modes of the experimental setup system, as well as the maximum von Misses stresses over the formed part at different tool depths under 5 kHz. Fig. 5 shows the evolution of the maximum von Misses stress at different tool depths by considering the acceleration profile of Fig. 4(b) for all cases. With a depth h =15mm, the maximum computed stress value was 0.1 MPa, at the frequencies of 4.44 kHz in the point *i*, as shown in Fig. 5(a). As the tool depth was increased, the excitation frequencies were changed. For the second formed part at the tool depth h =23mm, the estimated maximum stress value values was 0.04 MPa at the frequency of 4.47 kHz, which corresponds to the point *ii* of Fig. 5(b). At the tool depth value of h =31mm, the highest stress values were 0.20 MPa and 0.04MPa at the frequency values of 3.63kHz and 4.4 kHz, respectively, as indicated by the points *iii* and *iv* shown in Fig. 5(c). At the tool depth value of h =35mm, the computed von Misses stress values were: 1.04 MPa (3.62kHz), 0.19 MPa (4.10 kHz), and 0.89 MPa (4.44 kHz), as shown by the points *v*, *vi* and *vii* of Fig. 5(d). At h = 39 mm, the maximum predicted stress value was 0.04 MPa at 4.48 kHz which corresponds to point *viii* of Fig. 5(e). Finally, at *h* = 41 mm, we obtained the maximum von Mises stresses values of 0.02 MPa, 0.11 MPa, 0.19 MPa at the vibrational frequency values of 2.42 kHz, 3.69 kHz, 4.50kHz, that corresponds to the points *ix*, *x* and *xi* shown in Fig. 5(f). Based on these results, we can conclude that during the evolution of the forming process, different vibrational frequencies are excited which is mainly due to the geometry changes experienced by blank sheet that affects the dynamics setup response.

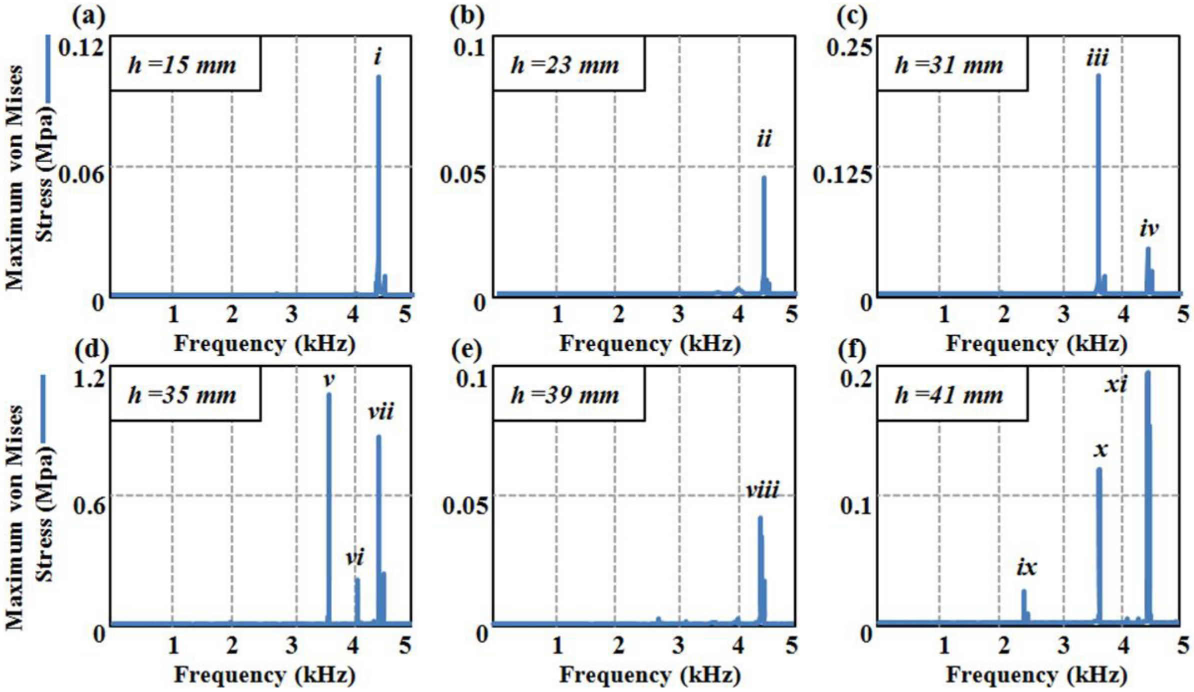

Fig. 5. Maximum von Misses stress values at different depths: (a) *h* = 15 mm, (b) *h* = 23 mm, (c) *h* = 31 mm, (d) *h* = 35 mm, (e) *h* = 39 mm, and (f) *h* = 41 mm.

5. Conclusions

In this work we have studied the dynamical response of the formed part during the single point incremental forming process by performing several experimental measurements not only of the forming tool but also in the experimental set up. According to the experimental frequency measured values, we can conclude that under the manufacturing machine parameters used to process the metallic sheet blanks, resonance forming tool behavior do not appear, as shown in Fig. 5. However, the fast Fourier transform plotted in Fig. 4(b) shows that the system experimental setup has a dynamical response that is closed to the recorded frequency values of the formed part. In fact, the von Mises stress peak values that are induced in the sheet blanks at each step occur at the experimental set up modal frequency values, as illustrated in Fig. 5 in which the maximum values of these computed stresses are lower than 1.2 MPa. Furthermore, we have observed from the computer simulations that the experimental set up remains fixed when the deformed part oscillates close to the modal frequency value of 4.88 kHz. Therefore, if we want to transfer all the energy to the forming process, we need to guaranty that the experimental set up is rigid enough to avoid vibrations that could produce geometrical inaccuracies in the final part.

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