Investigating the Effect of Rotation Speed and Ultrasonic Vibrations in the Incremental Forming Process

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Abstract: Incremental forming is one of the forming methods that is considered because of no need to specific die, especially for rapid prototyping. In this study, the incremental forming process is carried out by using a rotating tool and assisted ultrasonic vibration. Purpose of this research is to investigate the effect of rotation speed and ultrasonic vibrations in the incremental forming process. According to the obtained results, mean and maximum values of forming force reduced by using a rotating tool and applying ultrasonic vibrations. The results of surface roughness tests demonstrated that by increasing rotational speed, the surface roughness improved 44% and applying ultrasonic vibrations with tool rotation can reduce surface roughness about 74%. Applying ultrasonic vibrations lead to increase micro-hardness up to 84%, but, by increasing rotational speed, surface hardness slightly reduces. Results of straight groove test determined ultrasonic vibrations with the rotating tool can increase stretching limit up to 41.79% due to the affect on the sheet plasticity behavior.

Keywords: Formability, Incremental Forming, Rotating Tool, Surface Roughness, Ultrasonic Vibrations

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1 INTRODUCTION

Incremental forming is one of the sheet forming processes, which has advantages as low cost, high formability and more flexibility than traditional forming processes that is because of no need to specific die, especially for batch and job producing and rapid prototyping. In the incremental forming process, sheet is fully constrained and formed in different directions using ball nose tool. In these years, many attempts have been made to improve this process for producing complicated specimens.

Fracture mechanism, deformation forces, tool design, route direction and surface roughness are issues that investigated on this process. Micari et al. [1] showed by this method can produce car body parts. Also, other pieces such as art parts, music instruments, kitchen tools, wheel disks and clutch plates can be produced by this method [2-5]. In 1980, Iseki et al. [6] introduced single point incremental forming and produced an asymmetric part with manual X-Y table.. Asghari et al. [7] investigated on the metal deformation mechanism in two-point incremental forming and presented that increase in step down and wall angle has a negative effect on the quality of the surface and formability of the sheets. Song et al. [8] studied on decreasing necking phenomenon in incremental forming process and they found that stress fields in the top, middle, and bottom of the surfaces do not have an effect on the forming limit simultaneously and each layer has a various effect on the necking phenomenon. Raoji et al. [9] simulated the incremental forming process and measured spring back on the thin-walled steel tube and showed that 2D and 3D FE simulation can be applied for estimating the part geometry and spring back. Yanli et al. [10] simulated conic incremental forming and could reach good agreement between experimental forming force and the analytical solution. Araghi et al. [11] investigated the combination of incremental forming and stretch forming and concluded that the combination of these two processes has a positive effect on sheet metal forming. Evaluation of Laser beam assistant incremental forming and electrical incremental forming showed the combination of the laser beam or electrical current with incremental forming has a positive effect on deformation of low formability materials due to creating heat in the forming zone [12-13]. Jiahoo et al. performed electromagnetic incremental forming and found that flat die, discharge voltage and rotation angle of the electromagnetic core are influential parameters on the surface roughness [14]. Investigation of water jet assistant incremental forming demonstrated that hybrid process is suitable due to the preventing metal to metal contact between tool and sheet [15]. Also, two new incremental forming tools introduced, in the name of the tool with surface texture made by the laser beam, and tool with an oblique roller, to improve lubrication conditions and reduce friction coefficient between tool and sheet [16-17]. Ebrahimzadeh et al. [18] studied formability of friction stir welded aluminum blank in two-point incremental forming process and found step down, and the rotational speed of the tool are the two effective parameters on the critical thickness of the sheet. According to the literature review, rotating tool with ultrasonic vibrations have not been utilized in the incremental forming process. So, in this research, incremental forming was carried out using a rotating tool with ultrasonic vibrations, and the effects of rotational speed and ultrasonic vibrations on the forming force, hardness, surface roughness, and formability limit of the incremental formed sheet were evaluated.

2 MATERIAL AND METHODS

In this study, experiments performed on 1050 aluminum sheet with 1 mm thickness. This alloy has good wear resistance, high thermal and electrical conductivity, and good formability that is used in the automotive industry. Experimental tests accomplished by universal milling machine with 0.001 mm movement precision, ultrasonic transducer with 20500 Hz frequency, and a ball nose tool with 12 mm diameter which it is made by heat treated CK45 steel. Before starting experiments, spindle rotational speed was controlled by a DT-2234B digital tachometer. Also, forces along forming procedure were measured via the Kistler 9257B piezoelectric dynamometer with 2000 HZ sample rate. The experimental setup is illustrated in “Fig.1”.

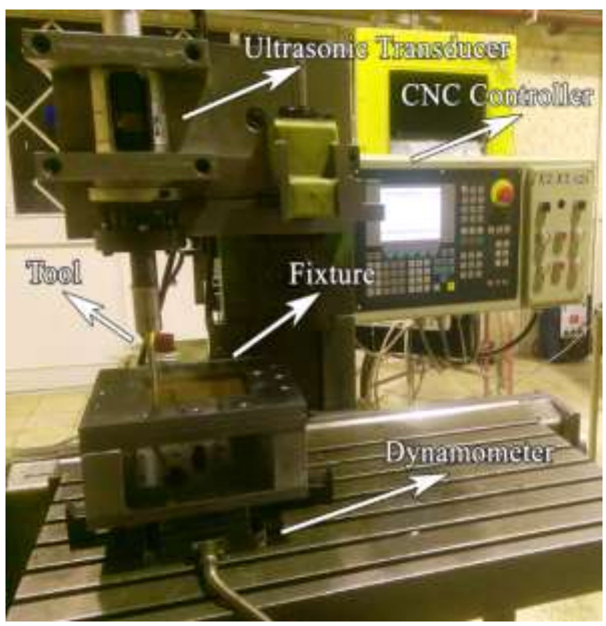

Fig. 1 The experimental setup for the incremental forming process.

To evaluate the effect of rotational speed and ultrasonic vibration on incremental forming, two sets of experiment were designed. The first series Include six experiments with three rotational speeds (0, 520, 1068 rpm) and two levels of vibrations (with and without ultrasonic vibrations) with 800 (mm/min) feed speed. Purpose of this design of the experiment is an investigation of rotational speed and ultrasonic vibrations on the forming forces, hardness and surface roughness. Tool moves on the plate to construct a pyramid geometry with a square section. Initial side length, the incremental depth and wall angle of the parts are 30 mm, 0.5 mm and 45º respectively. The tool motion path was a single direction pattern in these experiments. Figure 2 illustrates the sample geometry and direction of the tool path.

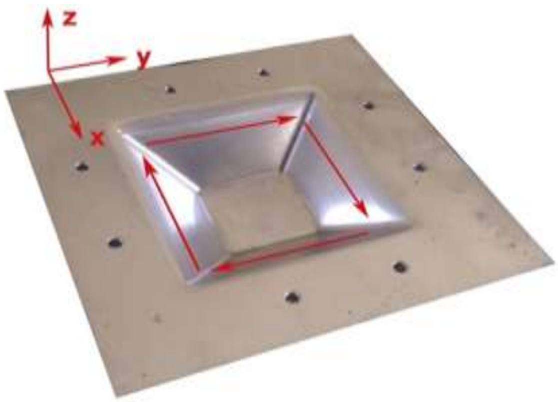

Fig. 2 Sample geometry and tool path.

In order to investigate the effects of rotational speed and ultrasonic vibration on the sheet formability limit, another set of experiments was carried out. This set includes 4 test series which their parameters are two rotational speeds (0, 520 rpm) and two levels of vibrations (with and without ultrasonic vibrations) with 800 (mm/min) feed speed, that all of them were performed by straight groove die. In these experiments, tool had perpendicular contact to the sheet and had reciprocating motion in a straight direction with 100 mm length and 0.1 mm down step in each 100 mm movement.

Lubrication was done with 60-grade oil in all of the experiments and tool head was completely immersed in the oil.

3 RESULTS AND DISCUSSION

The measured forces during experiments are presented in “Table 1”. According to the results, maximum and mean values of forming forces reduced by increasing rotation speed. Although decreasing the mean values are very slight and ignorable but maximum force value decreased by about 10%. It is because of local contact between tool and sheet that by friction, the temperature of the contact area increases and causes facilitation of deformation and reduction of forces [19-20]. Due to the tool symmetry movement, forces neutralize in X and Y directions. Figure 3 illustrates the force-time diagram for X and Z directions.

Table 1. The forming force and surface roughness results of the first set of experiments

Test No	Rotation speed (rpm)	Feed speed (mm/min)	Ultrasonic vibrations	Average force (N)	Maximum force (N)	The surface roughness (Rz) (µm)	The surface roughness (Ra) (µm)
1	0	800	Off	498.47	797	12.97	1.8
2	520	800	Off	495	753.4	8.27	1.11
3	1068	800	Off	490.5	718	6.86	1
4	0	800	On	474.3	790.8	8.01	1.51
5	520	800	On	437.71	684	4.52	0.82
6	1068	800	On	436.43	673.3	3.89	0.46

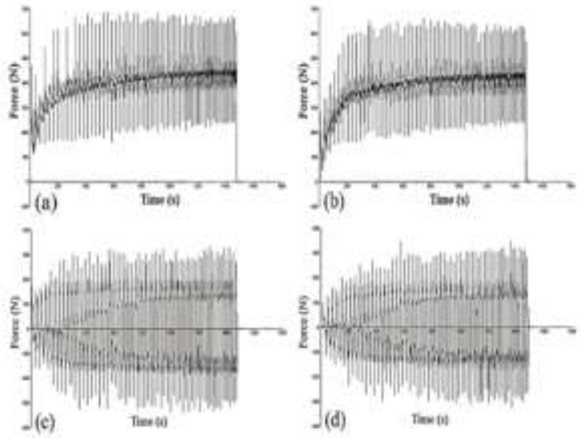

Fig. 3 Force-Time diagram, a) Z axial force without rotation and ultrasonic vibrations, b) Z axial force without rotation and with ultrasonic vibrations, c) X axial force without rotation and ultrasonic vibrations, d) X axial force without rotation and with ultrasonic vibrations.

Figure 4 shows a comparison of forming forces according to the rotational speed and ultrasonic vibrations. Study of the results demonstrated that ultrasonic vibrations reduced forming force. It could be due to the following reasons: with ultrasonic vibrations, contact of tool and sheet reduces and therefore friction force decreases, also, dynamic effects of the ultrasonic vibrations change material flow behavior [21].

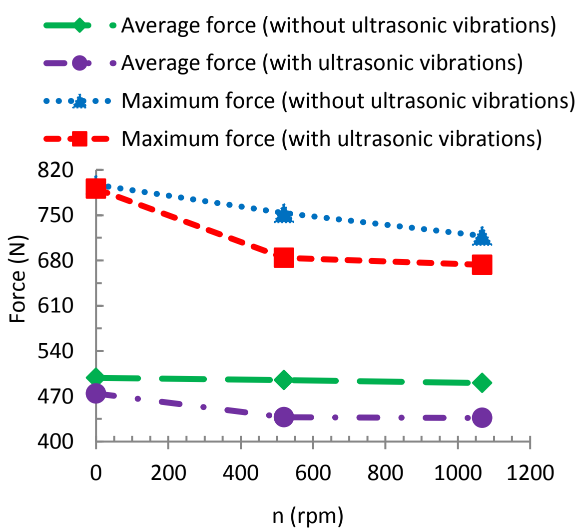

Fig. 4 Comparison of forming force according to the rotational speed and ultrasonic vibrations.

Utilization of tool rotation and ultrasonic vibrations together could reduce the mean and maximum values of forming force about 12.4% and 15.5% respectively, in comparison to the condition without rotation and ultrasonic vibrations. According to the Force-Time diagrams, in all cases, at first, forming force increased with high gradient and then remained stable. The initial increase in the forming force is affected by the bending mechanism [22] and stabilized force in the following procedure can be caused by superposition of two factors, wall thinning which reduces the force and work hardening which increases the force [23].
Figure 5 shows the surface topography of the samples.

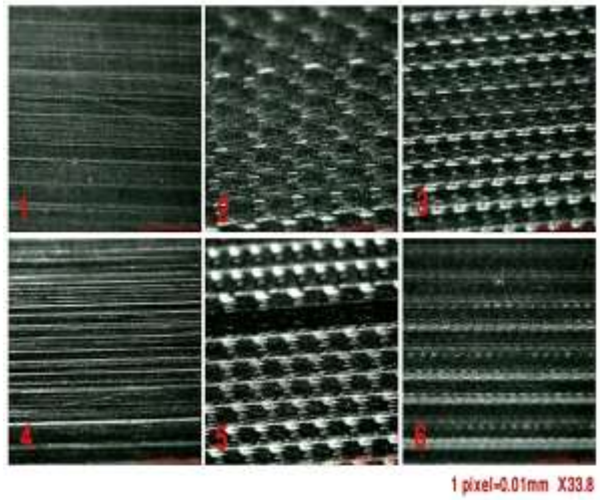

Fig. 5 Effect of rotational speed and ultrasonic vibrations on the surface topography (picture number is coordinate with test number in Table 1).

The number of pictures in "Fig. 5" conforms to the number of experiments in "Table 1". Investigation of surface topography, "Figs 5(1), 5(2), and 5(3)", illustrate tool effect on the surface by increasing rotational speed changes from surface scratch to the regular plastic deformation pattern; since by tool rotation, sliding friction converts to rotating friction and improves the tool movement and sheet deformation. Also via increasing rotational speed, local heat is created in tool and sheet contact zone and it facilitates the sheet plastic deformation. Figures 5(4), 5(5), and 5(6) demonstrate the effect of rotational speed with ultrasonic vibrations on surface topography. As it is evident in figure 5(6), using a combination of ultrasonic vibrations and high rotational speed could create regular plastic deformation with a smaller pattern.
Figure 6 shows the effect of rotational speed and ultrasonic vibrations on surface roughness. According to results in "Table 1", increasing rotational speed leads to decreasing surface roughness and improving surface quality. Also, using ultrasonic vibrations in the process induces surface knocking and reduces unevenness peak and roughness. Evaluation of surface roughness results indicated that by increasing rotational speed, the maximum surface roughness (R_z) and average surface roughness (R_a) improved by 47% and 44.4% respectively. Also, the combination of ultrasonic vibration and high rotational speed together can reduce R_z and Ra up to 70% and 74.5% respectively.

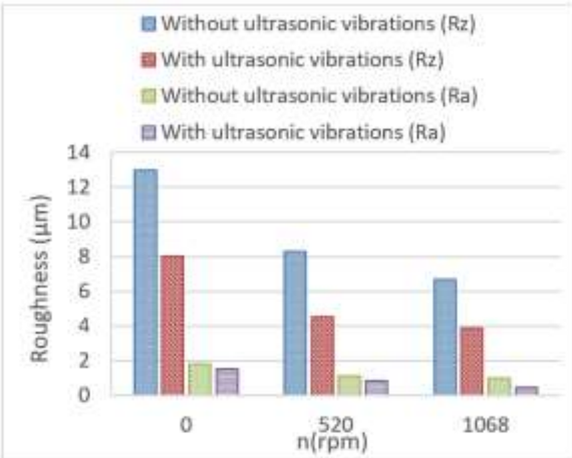

Fig. 6 Effect of rotational speed and ultrasonic vibrations on the surface roughness.

Plastic deformation in the room temperature causes to increase in strain hardening, strength, and hardness [24]. In the incremental forming process, hardness increasing occurs as the result of sheet tension. In addition, by using ultrasonic vibrations, hardness more increases due to local surface deformation, increasing dislocations density and compressive residual stress on the surface [25]. Figure 7 shows the effects of ultrasonic vibrations and rotational speed on surface hardness.

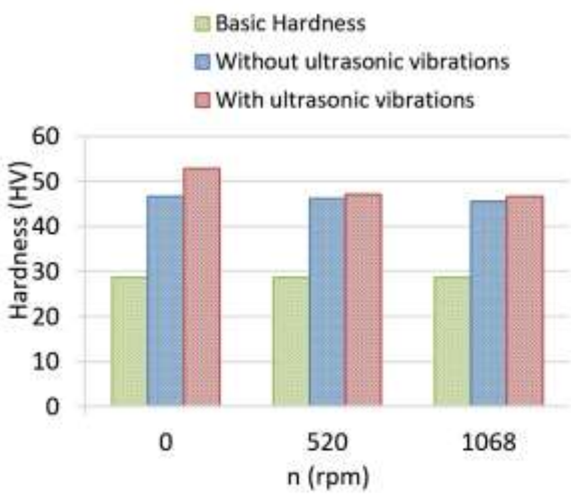

Fig. 7 Effects of ultrasonic vibrations and rotational speed on the surface hardness.

As seen in "Fig. 7", maximum hardness happens when only ultrasonic vibrations were utilized and it increased the hardness 84%. Increasing rotational speed reduces the hardness because increasing rotational speed induces heat in the contact zone and due to the increasing temperature, dislocations and therefore hardness decrease.

To investigate stretching limit, straight groove test was carried out. In this test, tool reciprocating motion continues until the first crack occurs in the sheet. Since the stretching operation is conducted in critical condition (90º contact angle), the maximum stretching limit of the sheet can be evaluated. In the incremental forming process, deformation occurs as plane strain. Stretching limit of the sheet in the incremental forming is larger than traditional forming. It is because of the low strain rate that reduces the effect of strain hardening in each step of the process [26].

The straight groove test sample is shown in "Fig. 8". Due to the results of the straight groove test, it was observed that the rotating tool and ultrasonic vibrations increase the stretching limit, but rotational speed is more effective than ultrasonic vibrations. Because, the frictional condition improves as a result of higher rotational speed and also, plastic deformation get better due to heat generation. The results showed stretching limit improved up to 41.79% using a rotating tool and ultrasonic vibration together. Figure 9 shows the result of stretching limit tests.

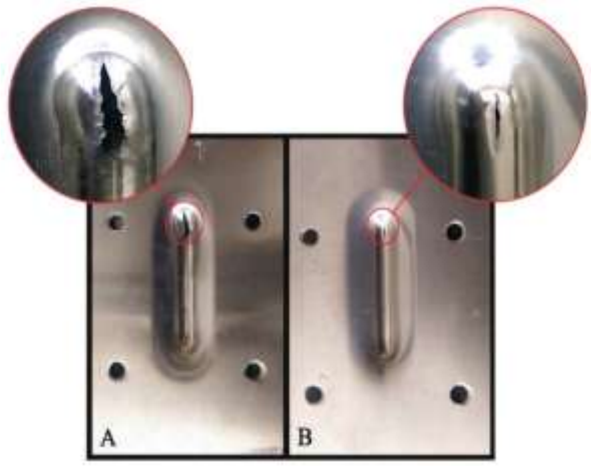

Fig. 8 Samples of the stretching limit test: (A): 520 (rpm) rotational speed with ultrasonic vibrations and (B): without rotation and ultrasonic vibrations.

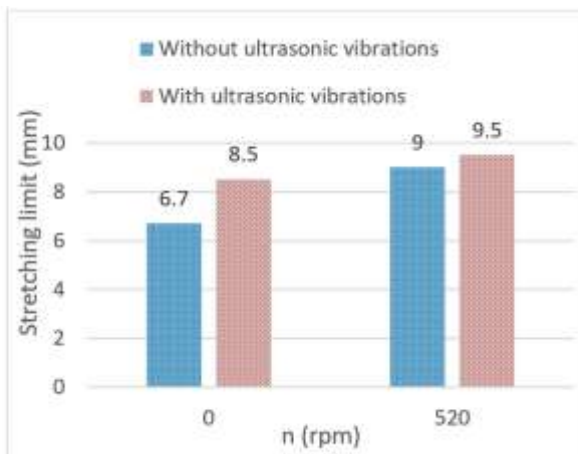

Fig. 9 Results of stretching limit in straight groove test.

4 CONCLUSIONS

In this study, the effects of rotational speed and ultrasonic vibrations on forming force, surface roughness, hardness and stretching limit in the incremental forming process were evaluated and the results are summarized as follow:

- Increasing rotational speed reduces forming force due to generating local heat between tool and sheet. Also, ultrasonic vibrations decrease forming force due to reducing the friction coefficient between the tool and sheet.
- By increasing rotational speed or applying ultrasonic vibrations, surface roughness reduced, and surface topography improved. Increase in rotational speed decreases Rz and Ra up to 47% and 44.4% respectively, and rotating tool with ultrasonic vibration can reduce Rz and Ra up to 70% and 74.5% respectively.
- Ultrasonic vibrations, due to inducing work hardening, increase surface hardness while increasing rotational speed decreases sheet hardness. Incremental forming without tool rotation and only by exerting ultrasonic vibrations on the tool, could increase surface hardness up to 84%.
- According to the results, using the rotating tool and ultrasonic vibrations together can increase the stretching limit up to 41.79%.

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