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Procedia Engineering 207 (2017) 795–800

Procedia Engineering

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International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Microstructure refinement by tool rotation-induced vibration in incremental sheet forming

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Abstract

This paper presents a study of employing tool rotation-induced vibrations in incremental sheet forming (V-ISF) to produce sheet metal parts with laminated ultrafine-grained structures. Non-axisymmetric tools were developed to generate tool vibration and surface shear deformation of sheet material during forming. Using the V-ISF process, magnesium sheets of AZ31 were formed to the hyperbolic cones and laminated ultrafine grains with higher micro hardness were obtained by tool generated low frequency vibrations with large amplitudes. To further investigate surface shear deformation induced during processing, the hole-deformation analysis of samples cut from the formed hyperbolic cones was performed. This study found that large surface shear deformation of the sheet and the tool vibration during incremental forming are the two key factors for the formation of laminated ultrafine grains. The developed V-ISF process has a great potential to produce sheet metal parts with refined grains and greater micro hardness.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: Incremental sheet forming, tool vibration, surface shear deformation, laminated ultrafine grains

1. Introduction

Superimposing vibrations during material processing provides a possible route for microstructure refinement to improve mechanical properties of a manufactured part. The vibration imposed on the forming tool will apply an additional stress field in the material to be deformed, thus enhance the dislocation density and cause the alignment

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Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.831

of dislocations eventually [1]. The vibration-assisted approach has been widely used in the material processing technologies such as casting [2] and welding [3]. In metal forming, vibrations have also been employed in processes such as high-pressure torsion [4] and surface rolling [5] to achieve ultrafine or nano grained structures. In these studies, ultrasound with high frequencies and relatively low amplitudes has been employed as a means of imposing vibration. However, the effect of low frequency vibration with larger amplitudes on microstructure refinement has yet to be fully studied.

Metal forming processes with severe plastic deformation, such as equal-channel extrusion [6], high pressure torsion [7] and tube spinning [8], have shown a good potential in attaining ultrafine grains. However, these processes could only be used to produce bulk or tubular parts. No feasible approach has been proposed to generate large deformation for sheet metal parts due to their small thicknesses. In recent years, incremental sheet forming (ISF) with added tool rotation has been developed to process "hard-to-form" materials without using additional heating devices [9]. The analysis of through-thickness shearing effect on formability in ISF was reported [10]. However, those studies have mainly focused on improving the material formability but not on studying microstructure refinement. The process potential on generating refined microstructures in ISF using tool vibration has yet to be explored.

Focusing on producing sheet parts with ultrafine grained microstructures, this work developed the tool rotation-induced vibration in ISF (V-ISF), based on novel designs of ISF rotation tools, aimed to generate tool vibration and large surface shear deformation of the deforming sheet at the same time. Magnesium alloy (AZ31) sheets were deformed to produce laminated ultrafine grain microstructures by using the V-ISF. The study of material deformation of the formed sheet suggested that the combined effect of large surface shear deformation and vibration during forming of the magnesium sheets were the two major factors for the formation of laminated ultrafine grains. The V-ISF process shows a potential to manufacture sheet metal parts with ultrafine grain microstructures.

2. Tool Development and Experimental Design

To facilitate the proposed idea of rotation-induced tool vibration in ISF, new forming tool designs are developed as shown in Fig. 1. The conventional tool (T1) with a ball head radius of 5 mm, Fig.1 (a), is used as a benchmark tool for comparison with the newly designed vibration tools. No vibration can be generated by T1 as the head geometry of the tool is axisymmetric. To generate the vibration, a single offset vibration tool T2, shown in Fig.1 (b), is developed. This tool has a smaller ball head, comparing to T1, with a radius of 4.5 mm. Instead of designing the tool head aligned with its central axis, the tool head is offset from the rotational axis by 0.5 mm. When rotating, the tool head will create cyclical impacts on the sheet surface to generate variations of the forming force by tool vibration. However, by using this tool, both the frequency and amplitude of the vibration is depended on the rotational speed of the tool. To increase the vibration frequency, a double-offset vibration tool T3, shown in Fig.1(c), is developed. This tool has an elliptical head with its major radius being 5 mm and minor radius being 4 mm. Using this tool, within one tool revolution, the tool head will impact on the sheet surface twice, which could double the vibration frequency, comparing to that of using T2. Comparing to the conventional ultrasonic method to induce tool vibration, the proposed approach could generate relatively low frequencies of vibration but with higher amplitudes. Furthermore, no additional vibration device is required in material processing thus simple to implement in ISF process.

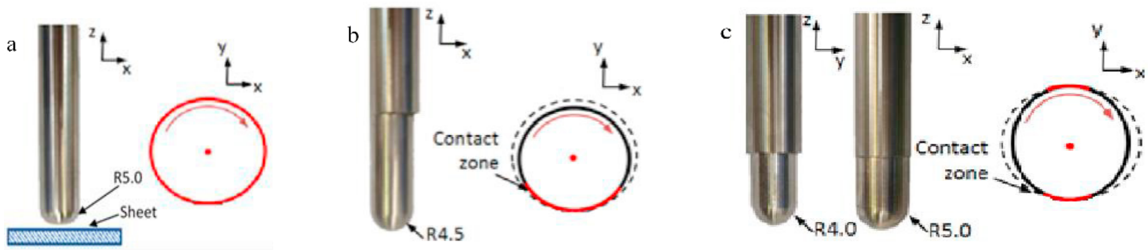


Fig. 1. Forming tools: (a) Conventional ball-nose tool; (b) Single-offset vibration tool; (c) Double-offset vibration tool.

Using the developed forming tools, ISF experiments are conducted on a 3-Axis CNC machine. Magnesium sheets of AZ31 with initial thickness of 1.5 mm are deformed to produce a hyperbolic cone shape. To record the forming force history a 3-axis load cell is placed under the fixture; a thermal camera is used to monitor the sheet temperature variation during processing, as shown in Fig. 2 (a) and (b). From a previous study on ISF of AZ31 sheets, it concluded that the material exhibited an excellent ductility at 250°C [11]; thus, a targeted forming temperature was set to be 250°C in this study. However, due to the different tool geometries, it results in variations of contact area during ISF processing, as shown in Fig.1, T1 may generate greater frictional heating in one revolution than that generated by T2 and T3. To achieve the same targeted temperature, a lower rotating speed of 3000 rpm is used for T1 while a higher rotational speed of 4000 rpm is used for both T2 and T3. The key process parameters used in the experimental tests are given in Table 1. After the experiment, samples are cut from the formed hyperbolic cone at the inclined wall, located near the bottom edge of the cone at both inner and outer sides of the sheet thickness, as shown in Fig. 2(c). The microstructures of these samples are examined by optical microscope and micro hardnesses are measured by Vickers test with a force of 100g.

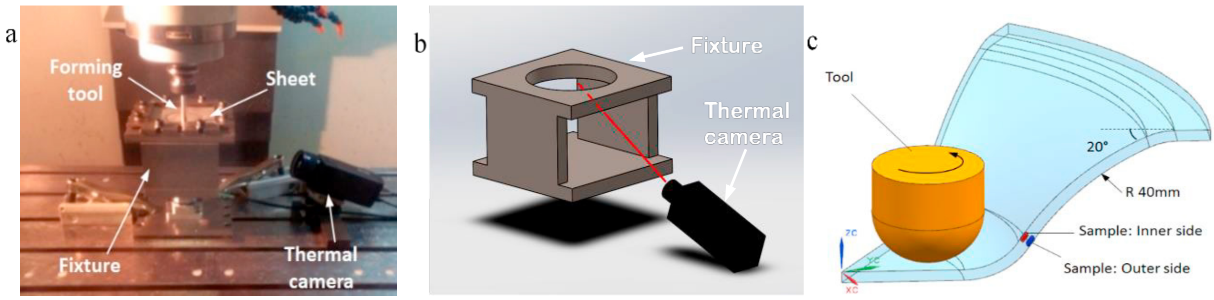


Fig. 2.V-ISF Tests: (a) Experimental setup; (b) Position of thermal camera and fixture; (c) Samples cut from formed hyperbolic cone.

Table 1. Experimental testing cases.

No.	Tool	Frequency (Hz)	Rotational speed (rpm)	Feed rate (mm/min)	Lubricant
Case 1	T1	50	3000	1000	No
Case 2	T2	66.7	4000	1000	No
Case 3	T3	133.3	4000	1000	No

3. Results and Discussion

Using three different tools, ISF tests are performed. Fig. 3 shows variations of vertical and horizontal tool forces and temperature respectively. Using the axisymmetric tool T1, a smoother vertical force history is observed. For T2 and T3, although smooth vertical force histories are recorded at the initial forming stage, obvious variations are observed after 200 seconds, when the angled wall of the hyperbolic cone is formed therefore the non-axisymmetric tool geometry takes its effect to impact on the sheet, creating force vibrations cyclically. In addition, the frequency of vertical force variations generated by T2 is the half of that by T3, while the amplitude of vertical force variations generated by T2 is slightly higher, as shown in the enlarged image in Fig. 3(a). The horizontal forces generated by T2 and T3 are lower than that by T1. Applying different tool rotational speeds, the forming temperature could eventually reach the targeted 250°C. However, the final forming temperature reached by using T1 is slightly higher than that by using T2, while the forming temperature by using T3 is the lowest. The differences in horizontal force and temperature may be explained by the varied contact zones of the individual tools as illustrated in Fig. 1, which affect the frictional heating thus the horizontal tool force and forming temperature. Compared to a non-friction warm ISF process with a constant forming temperature at 250°C, where a stable force history was maintained [12], the vertical tool force in V-ISF was generally lower, especially after 200 seconds when the tool vibrations took effect in the tests using T2 and T3. This reflects the effect of tool vibration on the reduction of vertical tool force.

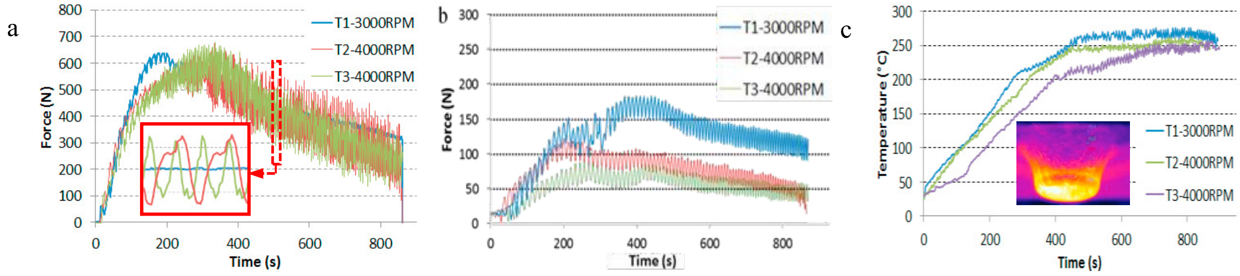


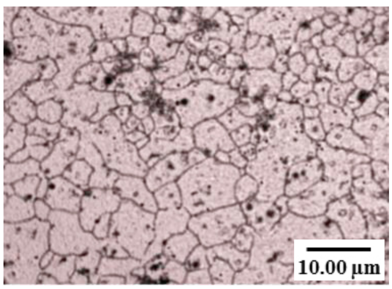
Fig. 3. Time histories of tool forces and forming temperature: (a) Vertical force; (b) Horizontal force; (c) Temperature.

To investigate microstructure refinement, samples are taken from the inner and outer sides of the sheet of the formed hyperbolic cone. Their microstructures are examined by using optical microscope and results are shown in Table 2 and Fig.4. The initial average grain size of the sheet is about 5μm. After forming, the grain sizes at the inner side of the hyperbolic cone are obviously refined in all test cases, suggesting the effect of surface shear deformation on the top surface layer to induce microstructure refinements. Particularly, for the samples produced in Cases 2 and 3, ultrafine grains are observed with an average size of 0.9~1μm on the inner side of the formed cone, showing the effect of cyclic vibrations on microstructure refinement, in addition to the surface shear deformation. However, no obvious difference in microstructures can be found between Cases 2 and 3, which suggests that the microstructure refinement of AZ31 sheets is not very sensitive to the low frequency range of tool vibrations between 66.3 and 133.3 Hz as used in the tests. For samples taken from the outer side of the formed cone produced by T2 and T3, although the grain sizes are more refined when compared to that of Case 1, they are much coarser when compared to that of the inner side. The observed coarser grain sizes of outer side samples of the formed cone in all cases show that a thickness-dependent gradient microstructure was formed indicating that the surface shear deformation is essential to enable microstructure refinement of the inner side. Liu et al. performed studies of surface mechanical grinding treatment and concluded that the formation of laminated structures, similar to this study however at nanometre-scale, was attributed to the large shear deformation with very high strain rates and high gradients in the top surface layer of the tested samples [13]. The micro hardness measurement results given in Table 2 show that the ultrafine grains at the inner side of samples in Cases 2 and 3 have 39.4% to 46.5% higher surface hardness than that of the original sheet. However, for Case 1, although the micro hardness increases 30.6% at the inner side of the deformed sheet surface, no increase of micro hardness can be observed at the outside surface of the sheet.

Table 2. Measured average grain sizes and average hardnesses.

	Average Grain size (μm)		Average Hardness (Hv)	
Case No.	Inner	Outer	Inner	Outer
Initial	4.9	4.9	60.4	60.4
Case 1	2.6	4.1	78.9	58.1
Case 2	1.0	3.7	84.2	68.0
Case 3	0.9	3.4	88.5	69.2

a



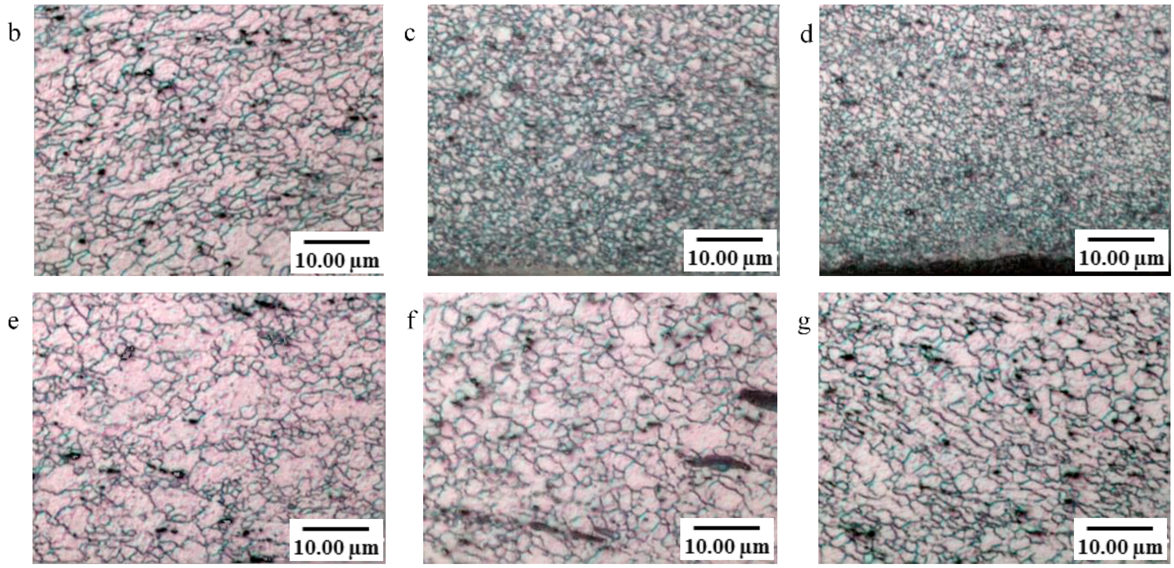
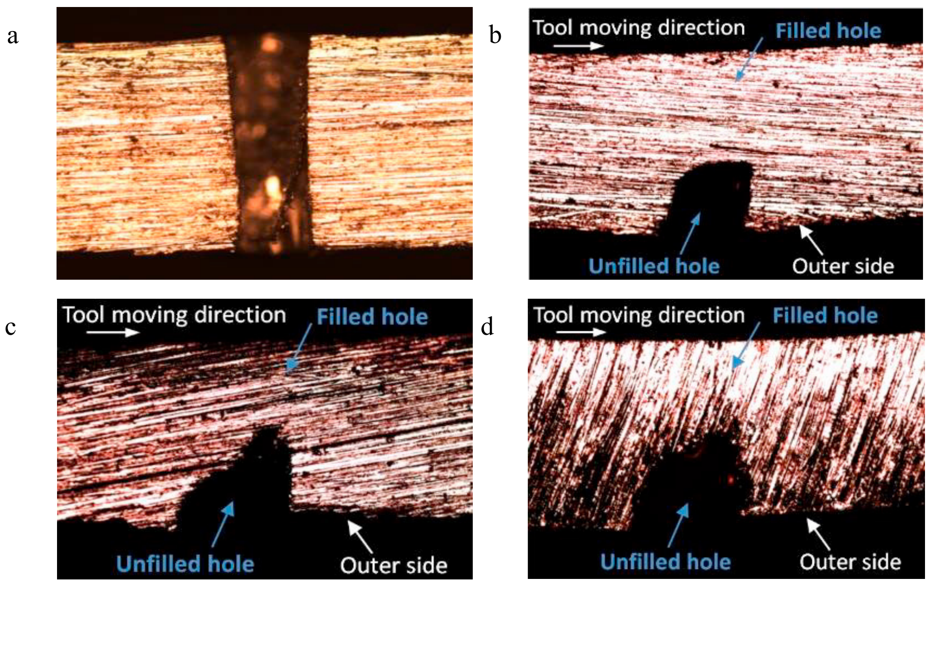


Fig. 4. Sheet microstructures before and after forming: (a) Original; (b) Inner side by T1; (c) Inner side by T2; (d) Inner side by T3; (e) Outer side by T1; (f) Outer side T2; (g) Outer side by T3.

To further investigate the material deformation during V-ISF, small holes are drilled through the thickness of magnesium sheets before they are deformed, as shown in Fig.5 (a). After forming, the deformed holes for Cases 1, 2 and 3 are examined using optical microscope, as shown in Fig. 5(b), (c) and (d) respectively. In all cases, the top half of the holes has been filled with material pulled from the surrounding area, which suggests a considerably surface shear deformation at the inner side of the formed cone. The hole is still visible at the outer side of the sheet but surface shear deformation at inner side can be observed along the tool moving direction. The large surface shear deformation of the sheet may be explained by the illustration shown in Fig. 5(e). This result implies that the surface shear deformation is another important factor for the formation of ultrafine grains. However, ultrafine grains can only be formed under sufficient surface shear and tool vibration generated by sufficiently large amplitudes of force variation. If only surface shear deformation is induced on the sheet as that in Case 1, the grain sizes are obviously larger than that of Cases 2 and 3, due to the absence of tool vibration effect.



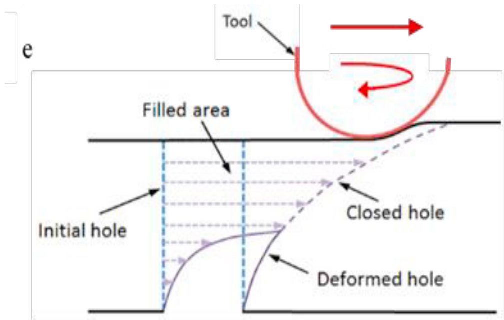


Fig. 5. Hole deformation analysis: (a) Initial hole; (b) Deformed hole by T1; (c) Deformed hole by T2; (d) Deformed hole by T3; (e) Illustration of large surface shear deformation at inner side of the sheet thickness.

4. Conclusions

The V-ISF process developed in this work is able to generate tool vibration resulting in cyclic forming force variations and large surface shear deformation at the same time when deforming the magnesium sheets. Using this new approach, hyperbolic cones with laminated ultrafine grains and higher micro hardness are obtained at the inner side of the formed cones. The following conclusions may be drawn:

- Tool vibration and large surface shear deformation of the sheet in the developed V-ISF process are the two major factors to achieve the laminated ultrafine grain microstructures of the magnesium sheet.
- Comparing to conventional high frequency vibration approach by employing ultrasound, low frequency vibrations with large amplitudes can also achieve the microstructure refinement.
- The laminated ultrafine grains obtained in this work can achieve 46.5% higher micro hardness at the inner side of the formed hyperbolic cones, comparing to that of the original magnesium sheet.

Acknowledgements

The authors would like to acknowledge their appreciations to Jamie Booth of Department of Mechanical Engineering, the University of Sheffield, for performing the experiments. We also acknowledge financial supports from EU FP7 Marie Curie Actions: FLEXFORM Project (FP7-PEOPLE-2013 IIF 628055 & 913055) and MatProFuture Project (FP7-PEOPLE-2012 IRSES 318968).

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