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Procedia Engineering 207 (2017) 1725–1730

Procedia Engineering

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

A unique spinning method for grain refinement: repetitive shear spinning

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Abstract

Grain refinement is an effective way to improve the strength of non-heat treatment aluminium alloy. To obtain much refined grains in the spun parts made of 3003 aluminium alloy, a unique spinning method, i.e., repetitive shear spinning, is proposed. The new process is composed of two shear spinning passes conducted along the two sides of sheet metal sequentially. By using finite element (FE) simulation and physical experiment, the grain refinement in the repetitive shear spinning is investigated. The results indicate that, under the same thickness reduction ratio, both the larger equivalent plastic strain and the larger shear strain can be obtained in the repetitive shear spinning than those obtained in the traditional single-pass and two-pass shear spinning processes. Meanwhile, the density of plastic dissipation energy (DPDE) in the repetitive shear spinning process is larger than that in two-pass shear spinning and doubled compared with that in single-pass shear spinning. This makes more deformation energy to be transformed into the stored energy thus provides more driving force for grain refinement. The observation of microstructure indicates that after the repetitive shear spinning, a great number of refined grains are generated with the average grain size refined from 48.6μm of the initial microstructure to 3.77μm, which is smaller than the grain size of 7.17μm and 4.91μm in single-pass and two-pass shear spinning, respectively. With the grain refinement, the micro hardness and its homogeneity of spun part after repetitive shear spinning is improved obviously. Compared with the average standard deviation of micro hardness obtained by the single-pass and two-pass shear spinning, it is decreased by 70.27% and 61.41% under the same thickness reduction ratio. The developed repetitive shear spinning process thus has the good capability for grain refinement and enhancement of mechanical properties of the spun parts and the promising application potential in industries.

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

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1877-7058
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.929

Keywords: Repetitive shear spinning; Grain refinement; Shear strain; Micro hardness.

1. Introduction

Shear spinning is one of the metal spinning processes that transforms flat sheet metal blanks into hollow shaped parts, usually with thin walled section and axis-symmetric profiles. During the process, both the mandrel and blank rotate while one or more rollers contact the blank and progressively induce a wall thickness determined by the initial thickness and the inclined angle of mandrel following the Sine Law. Due to nature of the localized deformation of material, shear spinning has the inherent advantages, such as low forming force, simple tooling and high material utilization. Consequently, lightweight spun parts have been increasingly used in aviation, aerospace and automotive industries [1,2]. On the other hand, 3003 aluminium alloy (3A21 aluminium alloy in China) is a typically non-heat-treatable Al-Mn alloy and commonly used for high-end applications for its advantages of versatile properties, good rust resistance and economical benefit. The low strength of the spun part made of 3003 aluminum alloy, however, limits its industrial applications [3]. Therefore, it is necessary to develop an efficient spinning method to improve the strength of the spun parts using 3003 aluminum alloy.

For 3000 series aluminium alloys, cold working is generally an available way to improve the strength of its part [3]. Zhan et al. [4] revealed that the strength of spun part made of 3003 aluminium alloy by shear spinning was improved due to grain refinement resulted from the formation of deformation band (DBs). Lee et al. [5] found a good correspondence between grain size and the magnitude of shear strain in the accumulative roll-bonding (ARB) of pure aluminium. The contribution of shear strain in grain refinement include the roles by the equivalent strain, strain gradient and strain path. Naseri et al. [6] reported in cross accumulative roll-bonding (CABR) of AA1050 aluminium alloy, refined grains are obtained by rotating the sheets with 90° around the normal direction axis in each cycle. And the CABRed parts exhibit superior tensile properties due to the change in strain path. Thus, for the strengthened spun parts made of 3003 aluminium alloy, the critical issue is how to generate more refined grains.

In this study, a unique spinning method, i.e., repetitive shear spinning, is proposed. During the spinning process, the equivalent strain, shear strain and the density of deformation energy are studied via FE simulation and they are compared with those in single-pass and two-pass shear spinning processes. The grain refinement in the new process is verified and the effect of grain refinement on micro hardness is examined via physical experiment.

2. Research method

The repetitive shear spinning is composed of two shear spinning passes along the two sides of sheet metal sequentially. The FE model for modeling of the repetitive shear spinning is established based on ABAQUS/Explicit platform. The simulation is done in three steps using two sets of mandrel and rollers, as shown in Fig. 1. In the first step, the outer surface of the blank is spun under the action of rollers Ⅰ and mandrel Ⅰ. Then the rollers Ⅰ are withdrawn in the second step. In the third step, the fillet radius is spun by the rollers Ⅱ along the inner surface first, then the wall of part is spun with thickness reduction. The trace of roller in the third step is shown in Fig. 1(d). In the FE model, rollers and mandrels are treated as rigid bodies. The blank is considered as a deformable body and meshed by 8-noded first-order reduced integration continuum elements (C3D8R). The hourglass control technologies are employed to control the zero-energy mode. The main forming parameters are listed in Table 1.

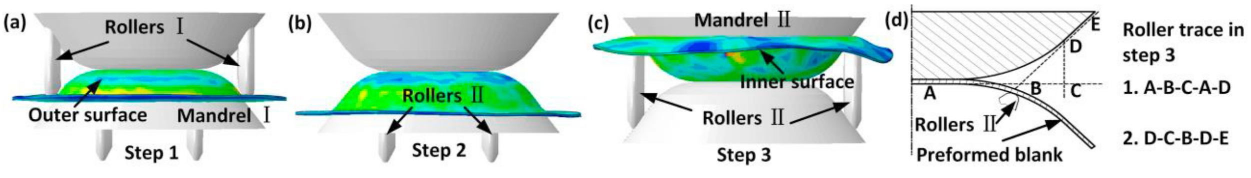

Fig. 1. (a)-(c) The FE model of repetitive shear spinning and (d) trace of rollers in the third step of repetitive shear spinning.

The initial blank in this study is a rolled sheet of 3003-O aluminium alloy with a nominal thickness of 6 mm. For comparison, the same forming conditions are adopted in single-pass and two-pass shear spinning except for the dimension of the mandrel. The fillet radius of mandrel adopted in the repetitive shear spinning is larger than that in single-pass and two-pass shear spinning to avoid the fracture in this area, as shown in Fig. 2. For two-pass and repetitive shear spinning, the gap t_1 between mandrel and rollers in the first pass is 3.86mm. The gap t_2 is 3mm in the second pass, which is equal to the gap t in single-pass shear spinning. The final thickness reduction ratio of the three processes is 50%. The spinning experiments are conducted in CZ900/CNC spin forming machine. The microstructure of spun parts is observed by optical microscope and electron backscatter diffraction (EBSD) technique in Rolling-Normal plane (R-N plane), as shown in Fig. 2. In addition, micro hardness of the spun part is measured in R-N plane at a load of 200g in a HX-1000TM/ LCD machine along thickness (Normal) direction.

Table 1. Main forming parameters.

Forming parameters	Values
Diameter of performed blank (mm)	290
Thickness of the initial sheet (mm)	6
Thickness reduction ratio	50%
Nose radius of the forming roller (mm)	10
Attack angle of roller (°)	30
The outer diameter of roller (mm)	200
Rotation speed of mandrel (r/min)	100
Roller feed rate (mm/r)	1

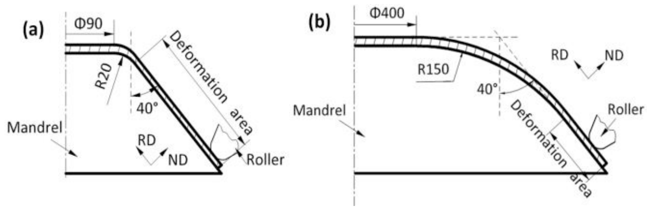

Fig. 2. Mandrel dimensions of for (a) single-pass and two-pass shear spinning; (b) repetitive shear spinning.

3. Results and discussion

3.1. Characteristics of strain in repetitive shear spinning

Considering that the variation of grain size is related to strain during the deformation, the equivalent strain in these three processes is analyzed first. Fig. 3 illustrates the distributions of the equivalent strain in these three processes. It can be found that in the repetitive shear spinning, the equivalent strain in the deformation area is larger than that in the other areas of spun part. Compared with the single-pass and two-pass shear spinning, the magnitude of the equivalent plastic strain in the repetitive shear spinning is close to that in the two-pass shear spinning, and the equivalent plastic strain in these two processes is greater than that in the single-pass shear spinning. These mean that under the same amount of deformation, the equivalent strain is increased with the spinning pass increasing.

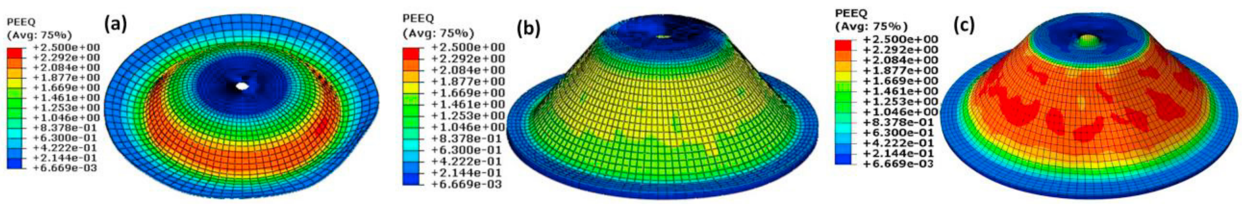

Fig. 3. Distributions of the equivalent strain in (a) repetitive shear spinning; (b) single-pass shear spinning and (c) two-pass shear spinning processes.

To investigate the reason for the increasing of equivalent strain in the repetitive and two-pass shear spinning, the three main strain components, i.e., strain in rolling direction, strain in thickness direction and shear strain in R-N plane of the three processes are obtained, as shown in Fig. 4. It is found that, in all the processes, the largest strain component is the shear strain, which is generated by transmission of torsional moment when the blank rotates with the mandrel [7]. Compared with the single-pass shear spinning, it can be found that in the deformation area, the magnitudes of strain components after the first pass of repetitive shear spinning is less than those in the single-pass shear spinning. However, the strain components after the second pass are larger than those in the single-pass shear spinning. Meanwhile, the variations of strain components in the repetitive shear spinning are close to those in the two-pass shear spinning, except that the shear strain in the second pass of repetitive shear spinning is slightly larger than that in the two-pass shear spinning. These results indicate under the same thickness reduction ratio, with the increase of spinning pass, the strain components are increased to a certain degree after each pass, which results in the increase of the equivalent strain in the two-pass and repetitive shear spinning processes. In addition, in repetitive shear spinning, more shear deformation is generated, which is beneficial for grain refinement.

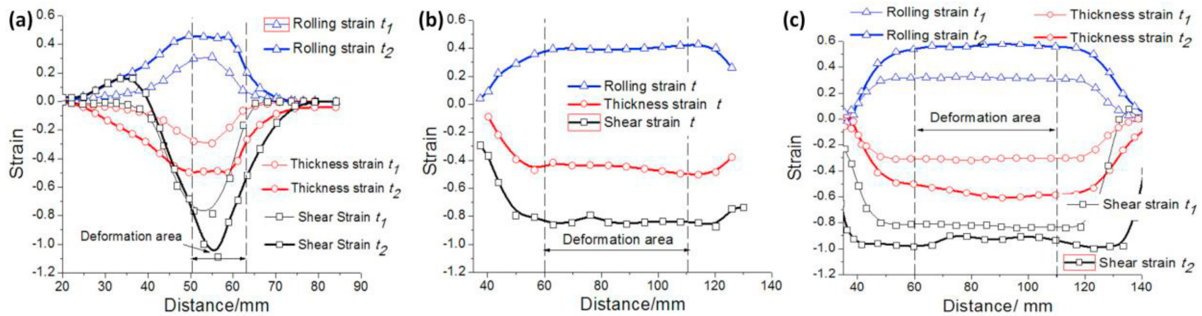

Fig. 4. Strain components in (a) repetitive shear spinning; (b) single-pass shear spinning and (c) two-pass shear spinning processes.

3.2. Characteristics of density of plastic dissipation energy

In ABAQUS platform, the external work is composed by internal energy, viscous dissipation energy, friction dissipation energy as well as kinetic energy. The internal energy is stored in the deformation body and provides driving force for microstructure evolution, which includes elastic strain energy, plastic dissipation energy, pseudo-variable and creep dissipation energy [8]. Due to the plastic deformation mainly occurring in shear spinning, the density of plastic dissipation energy (DPDE) is also used to investigate the potential of grain refinement. Fig. 5 shows the variation of DPDE of a certain element with the spinning stage. In the figure, the increase of DPDE means the generation of plastic deformation of the element in this stage. It is found that the DPDE in the repetitive shear spinning and two-pass shear spinning are close to each other after the first pass spinning, which are smaller than that in the single-pass shear spinning. After the second pass, the DPDE in both repetitive shear spinning and two-pass shear spinning are increased. The DPDE in the repetitive shear spinning process is larger than that in two-pass shear spinning and doubled compared with that in the single-pass shear spinning. The increase of DPDE in the initial stage of the second pass in repetitive shear spinning is resulted from the compatible plastic deformation of the fillet area. This means that in repetitive shear spinning, more deformation energy can be transformed into the stored energy, thus providing more driving force for grain refinement.

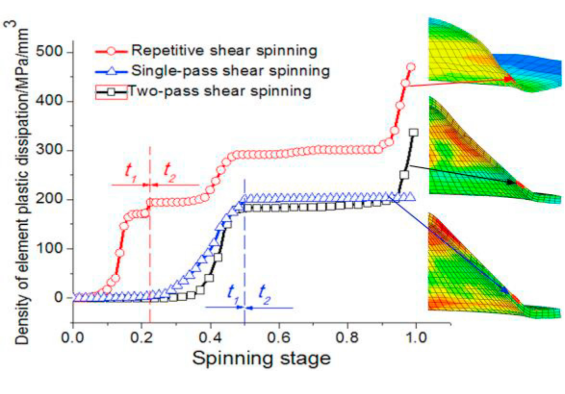

Fig. 5. Density of element plastic dissipation energy in repetitive, single-pass and two-pass shear spinning processes.

3.3. Verification the potential of grain refinement in repetitive shear spinning

Fig. 6 shows the microstructures in repetitive, single-pass and two-pass shear spinning. The microstructures obtained by the optical microscope indicate that, after shear spinning, grains are elongated in the rolling direction and compressed in the normal direction. Compared with the grains single-pass and two-pass shear spinning, grains in repetitive shear spinning are compressed and elongated more. Based on the EBSD images, it can be seen that the grain boundaries in repetitive and two-pass shear spinning are formed along the geometrical necessary boundaries (GNBs) to fragment the grains. In repetitive shear spinning, a large number of small subdivided grains are formed, as shown in Fig. 6(d). While in the single-pass shear spinning, there are small misorientation angles among the GNBs in the DBs which subdivide grains, particularly coarse-grains, into the regions of different orientations during the deformation and are often observed on in aluminium and its alloys [9]. Upon measurement of the average grain size in the three processes, it is found that both the average grain and the maximum grain sizes are decreased in the repetitive shear spinning process (Fig. 7(a)). The average grain size in the repetitive shear spinning is refined to 3.77μm from 48.6μm of the initial microstructure [4]. It is smaller than the grain size of 7.17μm and 4.91μm in single-pass and two-pass shear spinning, respectively. The dramatically decrease of the average grain diameter is mainly due to the generation of the new grains. These results verify the potential of grain refinement in the proposed repetitive shear spinning. The reason for the grain refinement in this unique shear spinning is due to the larger shear strain obtained on one hand, on the other hand, the change of loading directions in the repetitive shear spinning lead to the intersection of GNBs and formation the high angle grain boundaries [4, 10].

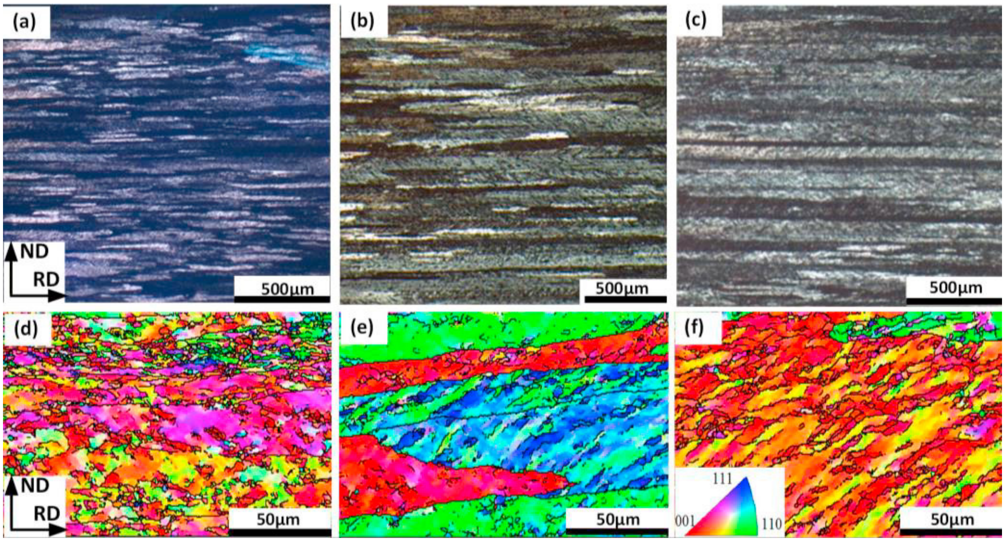

Fig. 6. Optical images in (a) repetitive shear spinning; (b) single-pass shear spinning and (c) two-pass shear spinning; EBSD images in (d) repetitive shear spinning; (e) single-pass shear spinning and (f) two-pass shear spinning

To evaluate the improvement of strength of spun part, micro hardness of spun parts along thickness direction of these three processes is measured, as shown in Fig. 7(b). It can be seen that, the values of micro hardness in the repetitive shear spinning are higher than those in single-pass and two-pass shear spinning process, which is resulted from the severe grain refinement. The average micro hardness is increased by 13.22% compared with that of the initial aluminium sheet with micro hardness of 62.5HV [4]. Meanwhile, the homogeneity of micro hardness after repetitive shear spinning is improved obviously. The average standard deviation of micro hardness [4] obtained by repetitive shear spinning can reach 0.22, which is decreased by 70.27% and 61.41% compared with the average standard deviation of micro hardness with 0.74 and 0.57 obtained by the single-pass and two-pass shear spinning processes, respectively. In addition, in repetitive shear spinning, the higher micro hardness is obtained both in the inner and outer surface. These imply that under the same thickness reduction ratio, the through-thickness grain refinement can be obtained in repetitive shear spinning process.

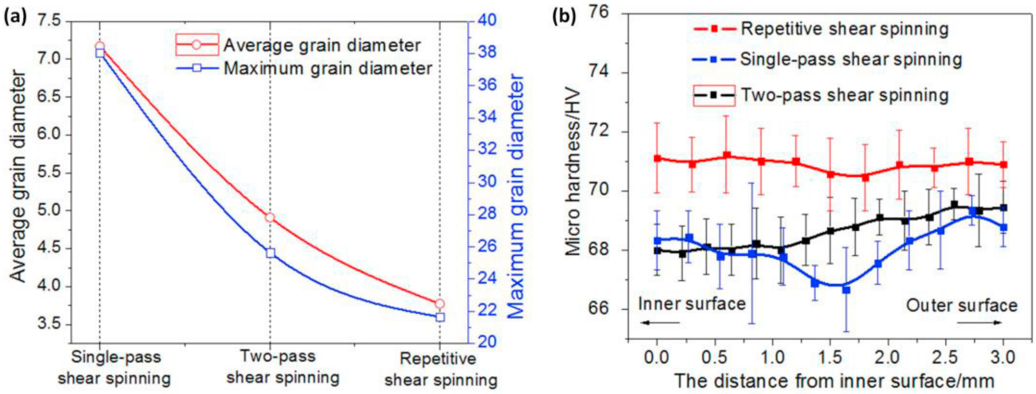

Fig. 7. (a) Average and maximum grain diameter and (b) micro hardness in repetitive, single-pass and two-pass shear spinning processes

4. Conclusions

In this study, a unique spinning method, i.e., repetitive shear spinning, is proposed to improve the strength of spun parts by grain refinement. Based on the FE simulation and experiment, grain refinement in the repetitive shear spinning is investigated. The main concluding remarks include: (a) Under the same thickness reduction ratio, larger equivalent plastic strain, shear strain and density of plastic dissipation energy (DPDE) can be obtained in the repetitive shear spinning compared with those in the single-pass and two-pass shear spinning processes. (b) After repetitive shear spinning, a large amount of refined grains can be obtained due to the larger shear strain and the change of loading direction. (c) With the grain refinement, the micro hardness and its homogeneity of spun part after repetitive shear spinning is improved obviously. Compared with the average standard deviation of micro hardness obtained by the single-pass and two-pass shear spinning processes, it is decreased by 70.27% and 61.41% under the same thickness reduction ratio. It is a promising approach to increasing the mechanical properties of the spun parts.

Acknowledgements

The author would like to acknowledge the support from the National Science Fund for Distinguished Young Scholars of China (Project 51625505), Key Program Project of the Joint Fund of Astronomy and National Natural Science Foundation of China (Project U1537203), and the Research Fund of the State Key Laboratory of Solidification Processing (Projects 118-TZ-2015, 97-QZ-2014 and 90-QP-2013).

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