Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 2072–2077

Procedia Engineering

www.elsevier.com/locate/procedia

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

Size effect affected deformation characteristics in micro deep drawing of TWIP domed-bottom cups

N. Guo[a], C.Y. Sun[a,*] , M.W. Fu[b]

[a]*School of Mechanical Engineering, University of Science and Technology Beijing, Beijing, 100083, China*
b Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Abstract

The occurrence of size effect in micro-scale deep drawing leads to the geometrical uncertainties, which affects the deformation behavior, in process determination. Micro deep drawing of domed-bottom cups of Fe-30Mn-3Si-2Al-0.11C TWIP steel with different grain size and thickness size was investigated in this research to obtain the characteristics of micro-deformed sheet to study the size effect on deformation behavior, earing profile and defect formation of the micro-parts. Finite element simulation shows fracture in the place with the thinnest thickness of the micro-parts easily occurs around the punch corner. Deformation load decreases with the increasing grain size for each thickness size except the fracture case, while under the particular grain size the load increases with the increase of thickness. Earing easily occurs with the larger grain size and smaller thickness size in the well-formed domed-bottom cups. Inhomogeneous deformation leads to irregular geometry of the formed part. The research promotes the understanding of size effect on micro deep drawing and facilitates the development of micro forming process.

Keywords: Size effect; Earing; Twinning; TWIP steel; Micro deep drawing

* Corresponding author: Tel.: +86 10 62333695; fax: +86 10 62329145
E-mail address: suncy@ustb.edu.cn

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.1066

1. Introduction

Microforming, is referred to the fabrication of microparts or its geometrical feature with at least two dimensions in sub-millimeter range via micro-scaled plastic deformation, which plays a significant role in micromanufacturing field for its mass productivity, low cost and net-shape of the formed parts [1, 2]. Micro deep drawing is one of the focused technologies in microforming process. When the dimensions of formed parts are scaled down to micro scale, the occurrence of size effect lead to enormous changes of deformation behaviors, geometrical size and microstructural evolutions [3, 4]. Therefore, in-depth investigation and understanding of deformation behavior and process characteristics is critical in design and development of micro-formed parts.

As a kind of advanced high strength steel, TWIP (TWinning Induced Plasticity) steel is exhibits considerable elongation and high toughness due to the activation and evolution of twinning and its interactions with dislocations slip during forming [5]. In micro-scale level, the characteristics and evolution of deformation twins show a different performance as a result of the limited size of grain and geometry compared with macro-scaled parts [6]. However, few researches has focused on the combined effects of size effect and twins evolution on the material deformation behavior, tooling design and measurement of formed part geometry and simulation of micro deep drawing process.

Based on the abovementioned parts, tooling sets of micro deep drawing are designed in micro scale and the micro deep drawing tests are conducted on test specimen with different grain and thickness size on this testing platform. The purpose of this research is to investigate the size effect affected deformation behavior including deformation load, earing and thinning/defect formation of Fe-30Mn-3Si-2Al-0.11C TWIP steel.

2. Materials and experiments

2.1. Material preparation and tooling sets

A vacuum induction furnace was used to manufacture the investigated steel with the chemical composition 30Mn-3Si-2Al-0.11C (w.t., %). After cropping the top section of the ingot containing shrinkage, the remaining ingot was hot forged down to 8 mm thick slab, subsequently rolled down to 3.5 mm thick plate in four passes with the finish rolling temperature of 800 ^{o}C. The slab was then homogenized in an air furnace at 1150 ^{o}C for 1 h to remove any inhomogeneity. Subsequently, the above samples were cold rolled to 1.5 mm by 10-30 % reduction in thickness in several passes using a laboratory scale rolling mill. Finally, after several passes rolling, the steel sheets with the thickness of 0.5 mm were obtained. The circular workpieces with diameter of 3mm were firstly cutting out. And mechanical polishing technic was used to obtain the testing samples with different thickness (t=0.1-0.3mm), as shown in Fig. 1 (a). Then these samples were annealed at 600, 700 and 900 ^{o}C in a protective argon condition to avoid oxidation to obtain different grain sizes as shown in Table. 1. It shows that with the increasing of annealing temperature the grain size also increases.

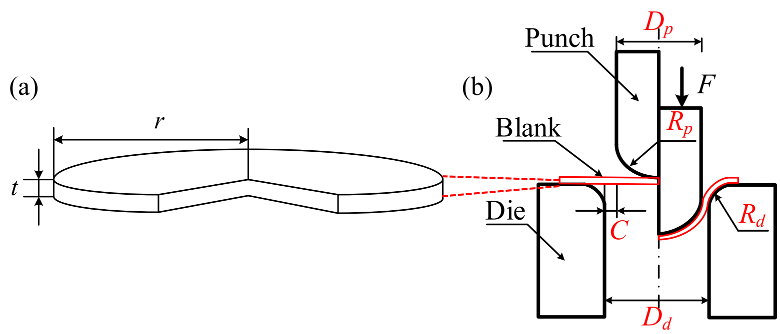

Fig. 1. (a) Schematic of testpieces and (b) Tooling sets in micro deep drawing process.

Table 1. Grain size at different material conditions.

Material conditions	Grain size (μm)
As-received	~5
Annealed at 600 °C	~25
Annealed at 700 °C	~30
Annealed at 900 °C	~50

Table 2. Dimensions and parameters of tooling sets.

Parameters	Meaning	Value (mm)
D_p	Diameter of drawing punch	1.3
D_d	Diameter of drawing die	1.7
R_p	Radius of drawing punch	0.65
R_d	Radius of drawing die	0.5
C	Unilateral drawing clearance	0.2
r	Radius of blank	1.5
t	Thickness of blank	0.1, 0.15, 0.2, 0.25, 0.3

The tooling sets of micro deep drawing for these samples are designed in Fig. 1 (b). The drawing punch diameter is 1.3 mm with domed bottom. The diameter of drawing die is 1.7 mm and the unilateral drawing clearance between punch and die is 0.2 mm corresponding sheet thickness. The detailed dimensions and parameters of tooling sets in micro deep drawing process are presented in Table 2.

2.2. Experimental set-up

The micro deep drawing experiments were conducted using a MTS testing machine with a load cell of 30 KN for measuring the deformation load and punch stroke, with the detailed schematic of testing platform shown in Fig. 2 (a) and (b) as well as the tooling sets and workpiece. It is noted that a low velocity of punch displacement is about 0.02 mm/s to guarantee the formability of defect-free micro cups. The interface between tooling and workpiece is lubricated with machine oil.

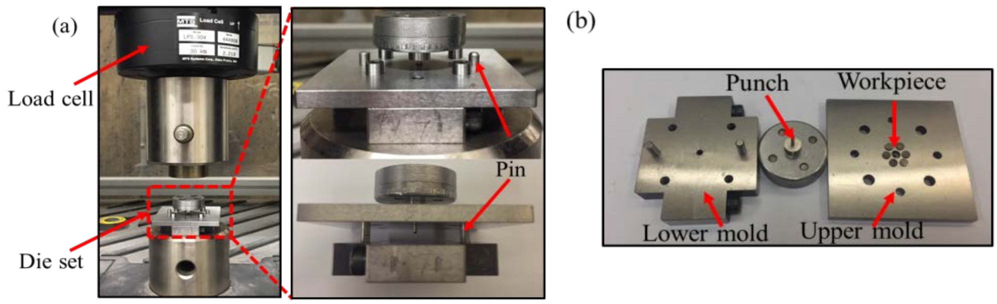

Fig. 2. (a) Testing platform and (b) Tooling set.

3. Results and discussion

3.1. Size effect on defect and earing

Size effect affected defect formation such as crack growth induced fracture could be observed in the samples and the scanning electron microscope (SEM) photograph of micro formed cups with any thickness at annealing temperature of 600 °C, 0.3 mm at 700 °C and 900 °C in Fig. 3 (a) and (b). It is noted that the fracture occur in the place near punch corner with thinnest thickness in the micro part, blanking from the sheet metal deserves to be considered as an important factor in micro deep drawing due to the residual stress induced in blanking process on the deformation behavior of micro part.

In Fig. 3 (b), it is noted that at the annealing temperature of 700 °C and 900 °C, earing profile at the end of formed parts could be observed for the thickness size from 0.01 to 0.2 mm. When the dimensions of testing samples are scaled down to millimeter, the grain size and geometrical size become the limit factor to hinder dislocation motion, leading to unusual evolution such as nucleation of twins. Furthermore, twinning reorientation caused by twin's evolution could affect the crystal orientation which has a significant influence on texture. Then earing is resulted from material anisotropy, viz., deformation texture components. In this research, the grain size and the thickness size to determine the occurrence of earing of TWIP steel mainly above 30 μm and below 0.2 mm, respectively. Earing easily occurs with the larger grain size and smaller thickness size in the well-formed domed-bottom cups.

To investigate the influence of size effect on defect formation, a finite element model of micro deep drawing is presented and the thickness variation of side wall of micro parts is simulated. The FE model of deep drawing process is shown in Fig. 4 (a) and its parameters are based on the table listed in Fig. 1(b). Since the twinning exists universally in the microstructural morphology of TWIP steel [7], the 2D Voronoi-based model with different thickness is presented to illustrate the circular samples. C3D4 element unit is adopted in the work piece in the model. The friction coefficient between punch and work piece is defined as 0, and the friction coefficient between the work piece and die, and that between work piece and binder plate have both been set as 0.1. In Fig. 4 (c), the maximum stress distribution appears at the end of micro parts due to the ironing effect [8]. Severe thinning occurs at the punch corner which leads to the fracture easily. Inhomogeneous deformation leads to irregular geometry of the formed part.

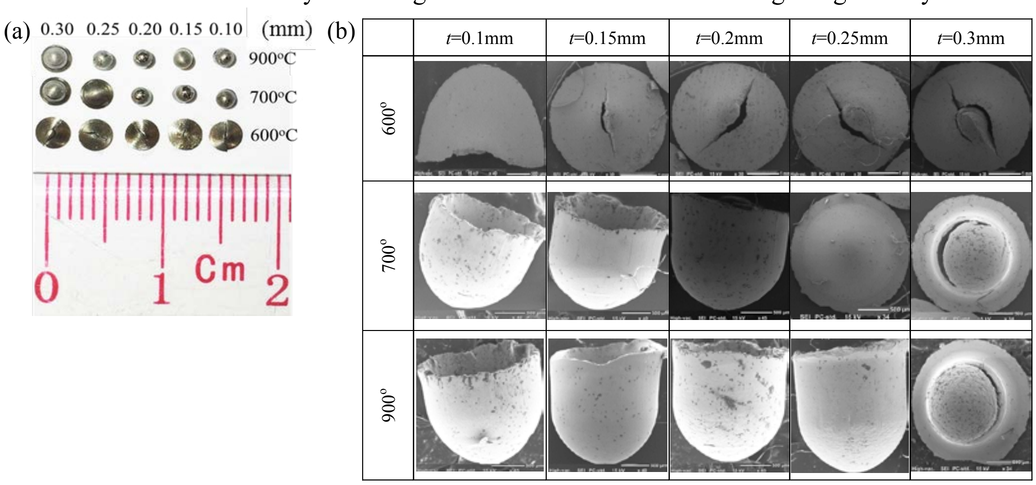

Fig. 3. (a) Comparison of the different thickness size-scaled cups with different annealed temperature, (b) SEM images of different scaled micro parts in micro deep drawing process.

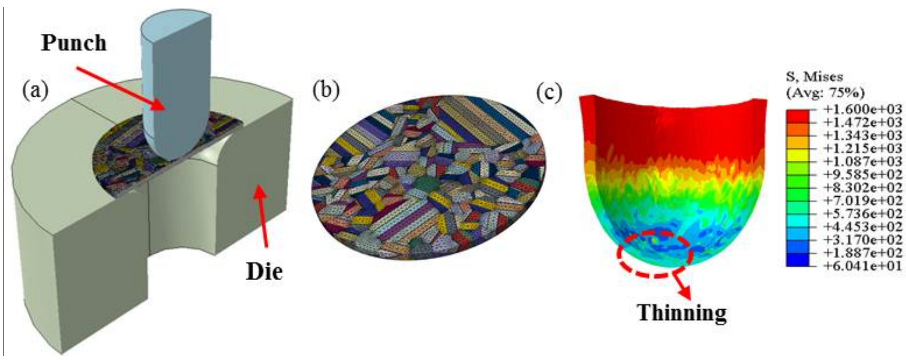

Fig. 4. (a) FE modeling of deep drawing process, (b) Voronoi based testing specimen and (c) Thickness thinning and stress distribution of micro part with grain size of 50μm and initial thickness size of 0.25mm.

3.2. Size effect on deformation load

Grain size and geometrical size also play a significant role in deformation behavior during the micro forming process of TWIP steel. Fig. 5 shows the micro deep drawing force and stroke curves with different thickness ranging from 0.1 to 0.3 mm. It could be observed that the tendencies and the shapes of these curves were similar although there are deviations between them.

It can be seen from the figure that the tendencies of the curves were the same, and there were two peaks in each curve. With the progress of the deep drawing process, the deep drawing force first increased and then decreased and the first peak occurred. In Fig. 5 (a), there was only one peak for all the curves with different thickness at the annealing temperature of 600°C and a sharp drop occurred followed the peak, which indicated the fracture happened. In Fig. 5 (b), it could be observed that there are two peaks in the curves at the thickness of 0.1, 0.15 and 0.2 mm, meanwhile, the deformation load increases with the increasing of thickness except two curves at the thickness of 0.25 and 0.3 mm which represents fracture. In Fig. 5 (c), except the thickness of 0.3 mm, the remaining load-stroke curves exhibit two obvious load peaks. The forming of the second peak was due to the blank thickening and wrinkles on the flange [9, 10]. The flange would be thickened and wrinkled if the applied blank holder force was not sufficient. Then the excessive materials pushed into the drawing die were more difficult to flow into the drawing clearance, which needed a higher deep drawing force to proceed. It could be conclude that deformation load in the deep drawing process decreases with the increasing grain size for each thickness size except the fracture case, while under the particular grain size the load increases with the increase of thickness.

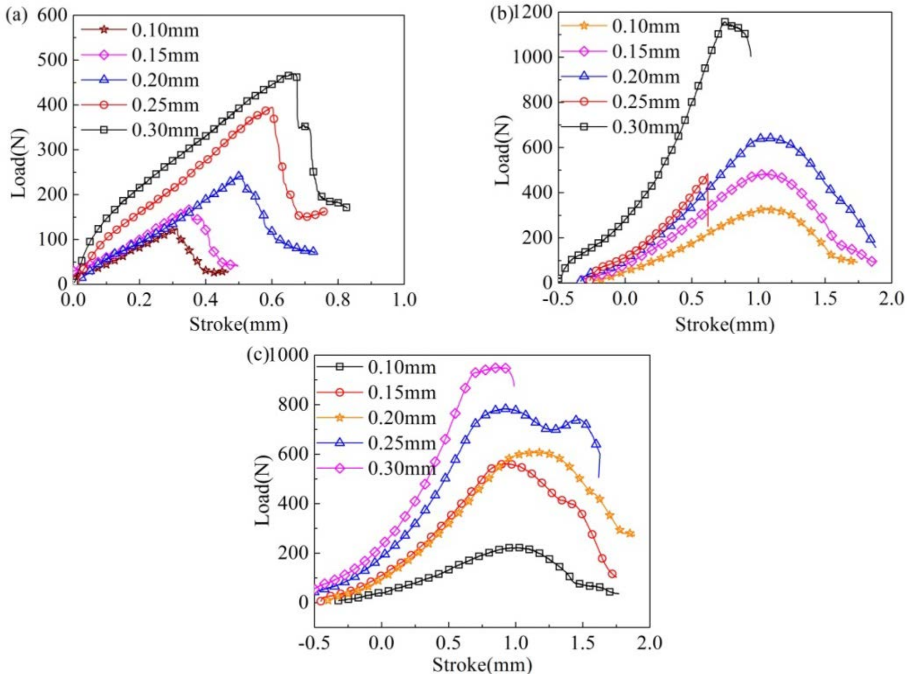

Fig. 5. Load-stroke curves under (a) 600°C annealing; (b) 700°C annealing and (c) 900°C annealing.

In Fig. 6, with the increasing of the thickness, the peak load expresses an increasing tendency for all the annealing temperatures. For TWIP steel, it is resulted that the majority of grains consist of twin lamellae which could hinder dislocation motion, leading to the strengthening of deformation load. It is noted that for the different annealing temperature from 700 to 900 °C, the peak load are almost the same at the thickness of 0.15 and 0.2 mm, viz., for the well-formed cups, the geometrical size plays a less important role than microstructural size on the deformation behavior in micro deep drawing process. However, at the thickness of 0.1 mm at different annealing temperatures, it is note that the peak load of annealing temperature of 700 °C is larger than that of 900 °C. It could be explained that the fraction of grain boundary increases with the decrease of grain size, which leads to the increase of deformation load, regardless of the fracture above the thickness of 0.25 mm.

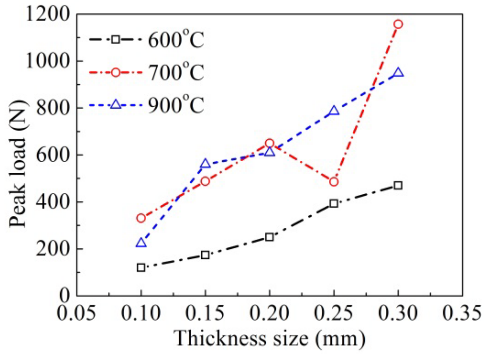

Fig. 6. Peak load- thickness size curves with different annealing temperatures.

4. Conclusion

In this research, micro deep drawing experiments of TWIP domed-bottom cups with different thickness and grain size were carried out to investigate the size effect affected deformation characteristics including deformation load, occurrence condition of earing and defect formation. The following conclusions are drawn based on the physical experiments.

(1) Deformation load increases with the increase of thickness size in micro deep drawing. For the well-formed cups, the fraction of grain boundary increases with the decrease of grain size, which leads to the increase of deformation load.

(2) With the increase of grain size, the fraction of twins lamellae increases, which leads to material anisotropy. Earing becomes severer at the larger grain size.

(3) Fracture occurs in the place with the thinnest region in the micro parts. The thickness of the formed cup increases gradually along the side wall from the bottom radius to the edge of the cup. The thinnest area appears at the bottom radius while the maximum stress was located at the rim of the cup.

Acknowledgements

The authors would like to thank the support to this research from the National Natural Science Foundation of China (No. 51575039) and the support from fund of Hong Kong Polytechnic University.

References

[1] M.W. Fu, B. Yang, W.L. Chan, Experimental and simulation studies of micro blanking and deep drawing compound process using copper sheet, J. Mater. Process Tech. 213 (2013) 101-110.
[2] W.T. Li, M.W. Fu, J.L. Wang, B. Meng, Grain size effect on multi-stage micro deep drawing of micro cup with domed bottom, Int. J. Precis. Eng. Man. 17(2016) 765-773.
[3] M.W. Fu, W.L. Chan, A review on the state-of-the-art microforming technologies, Int. J. Adv. Manuf. Technol. 67 (2013) 2411–2437.
[4] A. Molotnikov, R. Lapovok, C.F. Gu, C.H.J. Davies, Y. Estrin, Size effects in micro cup drawing, Mat. Sci. Eng. A 550 (2012) 312- 319.
[5] H. Idrissi, K. Renard, L. Ryelandt, D. Schryvers, P.J Jacques, On the mechanism of twin formation in Fe-Mn-C TWIP steels, Acta Mater 58(7) (2010) 2464-2476.
[6] M.W. Fu, J.L. Wang, A.M. Korsunsky, A review of geometrical and microstructural size effects in micro-scale deformation processing of metallic alloy components, Int. J. Mach. Tool Manu. 109 (2016) 94-125.
[7] C.Y. Sun, B. Wang, D. J. Politis, L.L. Wang, Y. Cai, X.R. Guo, N. Guo, Prediction of earing in TWIP steel sheets based on coupled twinning crystal plasticity model, Int. J. Adv. Manuf. Technol. (2016) doi:10.1007/s00170-016-9291-z.
[8] Jenn-Terng Gau, Sujith Teegala, Kun-Min Huang, Tun-Jen Hsiao, Bor-Tsuen Lin, Using micro deep drawing with ironing stages to form stainless steel 304 micro cups, J. Manuf. Process 15 (2013) 298-305.
[9] J. Ma F. Gong, Z. Yang, W.Q. Zeng, Microdeep drawing of C1100 microsquare cups using microforming technology, Int. J. Adv. Manuf.Technol. 82 (2016) 1363-1369.
[10] F. Gong, Q. Chen, Z. Yang, D.Y. Shu, S. Zhang, Micro deep drawing of C1100 conical-cylindrical cups, Procedia Eng. 81 (2014) 1457-1462.