Available online at www.sciencedirect.com

ScienceDirect

Manufacturing Letters 2 (2014) 8–11

www.elsevier.com/locate/mfglet

Research Letters

A preliminary study on the fatigue behavior of sheet metal parts formed with accumulative-double-sided incremental forming

Rui Xu [a], Xiaoting Shi [c,a], Dongkai Xu [b,a], Rajiv Malhotra [a], Jian Cao [a,*]

[a] *Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208-3111, USA*

[b] *Department of Plasticity Technology, Shanghai Jiao Tong University, 1954 Huashan Road, Shanghai 200030, PR China*

[c] *Shanghai Key Laboratory of Materials Laser Processing and Modification, School of Materials Science and Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, PR China*

Received 25 October 2013; accepted 29 October 2013
Available online 13 November 2013

Abstract

Accumulative-double-sided incremental forming (ADSIF) is a newly developed die-less sheet metal forming process, which can form complex freeform sheet metal parts without using any part-shape-specific tooling. This preliminary study investigates the fatigue life of parts formed with ADSIF, on a AA2024-T3 sheet material. It is shown that the material formed with ADSIF has a longer fatigue life than the virgin material. Micrographs of the fracture surface obtained using a scanning electron microscope (SEM) is used to examine the mechanism of failure after the fatigue test. The areas of future work on fatigue life of parts formed with incremental forming are also discussed.

Keywords: Accumulative-double-sided incremental forming; Fatigue behavior; Fracture surface; AA2024-T3 alloy

Single point incremental forming (SPIF), a die-less sheet metal forming process, has been shown to result in significant advantages for low volume production and rapid prototyping of sheet metal parts [1–3]. In SPIF, a completely peripherally clamped metal sheet is locally deformed by a single, small hemispherical ended tool moving along a pre-programmed toolpath. The sum total of the local deformations adds up to give the global desired shape to the sheet metal. Although SPIF results in higher sheet formability than conventional forming [4], the process suffers from inherently poor geometric accuracy due to the lack of a backing die. This has led to the development of double-sided incremental forming (DSIF) which uses two tools, one on either side of the sheet. One tool acts as the forming tool and the other acts as a local supporting tool to concentrate the sheet deformation into the tool-sheet contact region. Malhotra et al. [5] demonstrated that while DSIF can improve the geometric accuracy of formed parts as compared to SPIF, the loss of contact between the sheet and the bottom tool still results in inadequate geometric accuracy of the formed part. A novel toolpath trajectory was developed to overcome this issue by Malhotra et al. [7], thus creating the accumulative-double-sided incremental forming (ADSIF) process.

While a lot of work has gone into toolpath planning for formability and geometric accuracy in DSIF and ADSIF, there is very little work on examining the fatigue life of the formed parts. This is especially important since one of the most promising applications of incremental forming is in low volume production and prototyping of aerospace parts. In these applications the elimination of part-shape specific dies can lead to large reductions in manufacturing costs and lead time. At the same time, since fatigue life is a major design constraint, especially for aerospace parts, it is critical to examine the fatigue behavior of parts formed with ISF. Agrawal et al. [6] studied the fatigue life for a 90 degree bent part formed by conventional bending, SPIF and the deformation machining process, which is a hybrid process combining machining of thin-wall structures and

* Corresponding author.
E-mail address: jcao@northwestern.edu (J. Cao).

2213-8463/$ - see front matter
http://dx.doi.org/10.1016/j.mfglet.2013.10.009

SPIF. The reported fatigue life showed that under bending loads SPIF parts have significantly longer fatigue life, compared to parts fabricated with deformation machining and conventional bending.

In this work we examine the fatigue life of parts formed with the ADSIF process, on AA2024-T3 sheets, since this sheet material has particular relevance in the aerospace industry. ADSIF is chosen as the process since it has been shown to result in significantly better geometric accuracy as compared to other forms of incremental forming [7]. The fatigue life of the deformed material is compared to that of the virgin material and the fracture surfaces are examined using SEM micrographs. Finally, areas of future work to further examine and establish the results seen in this paper are discussed.

1. Experimental procedures

The sheet material used in the present study was 0.5 mm thick AA2024-T3 with a yield stress of 345 MPa. The fatigue behavior of the sheet material was investigated in two distinct conditions, referred to henceforth as (i) virgin material, implying the as-received material and (ii) deformed material, implying the material after being formed with ADSIF. A pyramidal part (Figure 1a) was formed using the ADSIF toolpath strategy with tool diameters of 5 mm and incremental depth of 0.1 mm. The specimens for the fatigue test were then cut out from the walls of the pyramid and the fatigue test samples (Figure 1b) were machined from these specimens to shape and dimensions specified by ASTM Standards [8].

The fatigue tests were carried out in a MTS7 Servo-Hydraulic fatigue test machine under uniaxial stress-controlled tensile conditions. To examine the fatigue resistance of the material under a relatively high stress condition, the maximum stress was chosen as $\sigma_{\max} = 328$ MPa, which is 95% of the yield strength of AA2024-T3. The stress ratio, $R = \sigma_{\min}/\sigma_{\max}$ was specified as $R = 0.5$ to compensate for a high oscillation frequency at 44 Hz. Therefore, the stress amplitude and the mean stress for the fatigue tests were $\sigma_a = 82$ MPa, $\sigma_m = 246$ MPa, respectively.

2. Results and discussion

2.1. Experimental results

The numbers of cycles before failure, for the virgin material and the deformed material, are shown in Figure 2. The trends indicate that the material deformed with ADSIF has a similar or slightly higher fatigue life as compared to the virgin material. To understand this better one must consider the mechanics of the ADSIF process. In ADSIF, the bottom tool does not just act as a local support for the top tool, but also produces a squeezing effect on the sheet [5]. This results in a fairly uniform distribution of compressive residual stresses along the component wall, which might explain the higher fatigue life observed for deformed material as compared to virgin material.

2.2. Fractured surfaces

To investigate the characteristics of material fracture in the fatigue test, the fracture surface was examined under a scanning electron microscope (SEM). In ductile failure, microscopic voids nucleate, enlarge, coalesce and link with each other till the reduction in load carrying area is so large that the material breaks under applied loads. On a macroscopic scale, the material in such regions necks, shears and eventually fractures. Ductile failure is characterized by dimple like structures left on the fracture surface when observed under a SEM.

From Figure 3(a), it can be seen that the overall morphology of the fracture surface for the virgin material comprises mostly of ductile failure regions, which is as expected for a ductile metallic material. An examination of the fracture surface at higher SEM resolution (Figure 3b) reveals a population of voids of varying size and shape distributed through the fracture surface, indicated by the dimple struc-

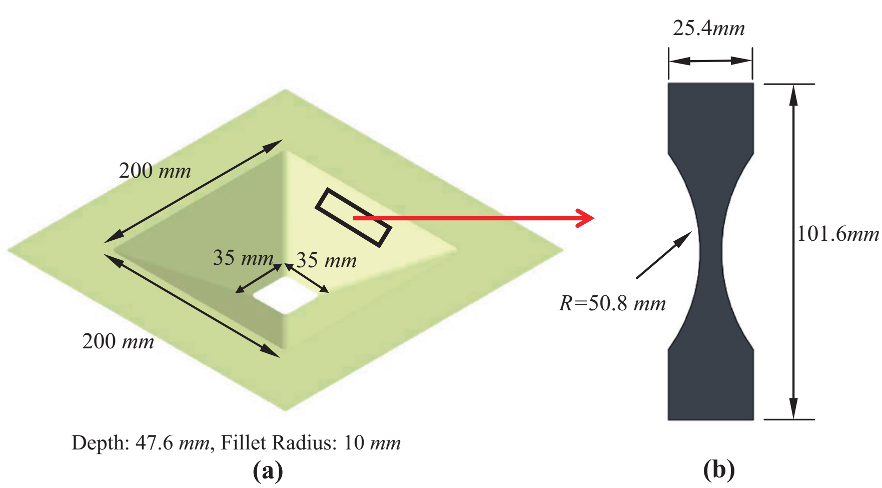


Figure 1. The shape and dimensions of pyramid and fatigue test specimen, (a) pyramid, (b) fatigue test specimen.

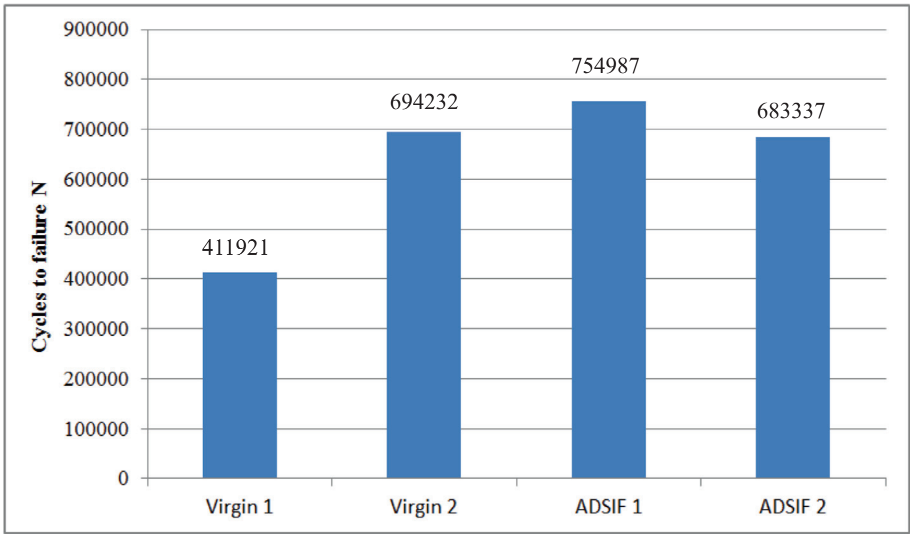
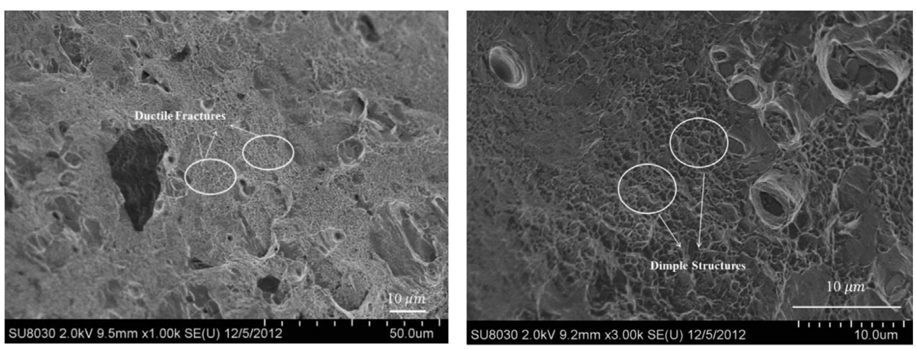
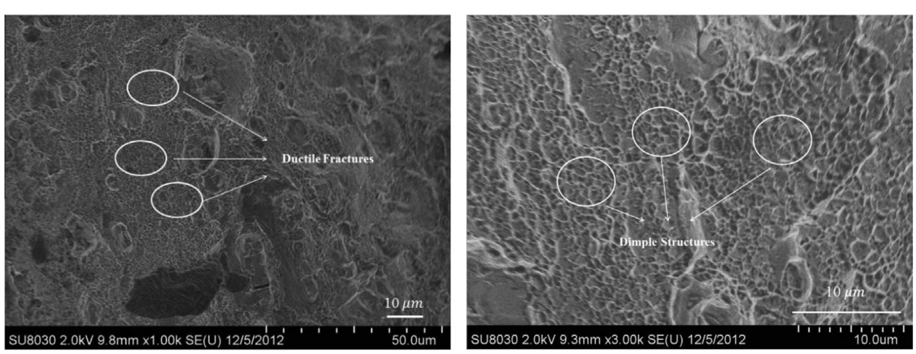


Figure 2. Comparison of limit fatigue cycles.



(a) (b)

Figure 3. SEM micrographs of fracture surface features of virgin materials after tensile fatigue test at (a) low resolution, (b) high resolution.



(a) (b)

Figure 4. SEM micrographs of fracture surface features of deformed materials (ADSIF) after tensile fatigue test at (a) low resolution, (b) high resolution.

tures. This means that the failure mode of the virgin AA2024-T3 material is dominated by ductile fracture.

The SEM micrographs of the deformed material are shown in Figure 4. The overall morphology shows features similar to that of the virgin material, i.e., a population of fine microscopic voids of varying sizes and shapes and dimple structures. However, at a higher resolution (Figure 4b), it is obvious that more dimple structures with finer shapes can be found as compared to virgin material (Figure 3b). This propensity for greater ductile fracture on the micro-scale might point towards a previously developed theory for explaining higher formability in incremental forming

[9], which was based on the rationale that during forming, localized necking occurs in the deformed region of the material but it does not grow completely to fracture before the tool moves on to deform a new region of the material. The increased microscopic ductile fracture surfaces seen after fatigue tests might be a remnant from this phenomenon during the deformation of the sheet in ADSIF.

3. Conclusions and future work

In conclusion, based on the obtained data and analysis, the ADSIF process does not produce adverse effects on the fatigue life under cyclic tension, of parts formed on AA2024-T3 sheet material. On the other hand preliminary results seem to suggest that ADSIF formed parts may have greater fatigue life under cyclic tension as compared to the virgin material. Moreover, the fracture surface of ADSIF deformed AA2024-T3 material has evidence of more dimple structures than for the virgin material, which may be a remnant from some strain localization caused during the forming process.

In future work, more experiments will be carried out to establish the general applicability of these results. The complete *S-N* curves for AA2024-T3 will be constructed. Furthermore, the scope of the materials used will be expanded to other metals such as stainless steel, bake hardened steel and titanium alloy. The effect of the ADSIF process parameters, such as incremental depth on the fatigue life of the part will also be examined. Measurements of the depth of the dimple structures seen in the SEM micrographs will be carried out, because the depth of dimples can be considered as a measure of ductility of the formed part.

Acknowledgment

The authors would like to acknowledge the National Science Foundation, USA and Chinese Scholarship Council for their support.

References

[1] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J, Allwood J. Asymmetric single point incremental forming of sheet metal. CIRP Ann – Manuf Technol 2005;54(2):88–114.

[2] Allwood JM, Shouler DR. Paddle forming: a novel class of sheet metal forming processes. Ann CIRP 2007;56(1):257–60.

[3] Wang Y, Wu W, Huang Y, Reddy NV, Cao J. Experimental and numerical analysis of double sided incremental forming. In: Proceedings of the 2009 international manufacturing science and engineering conference; 2009. p. 613–8.

[4] Huang Y, Wang YJ, Cao J, Li M. Prediction of forming limit in single point incremental forming with the ductile fracture criterion. In: Proceedings of the 2007 international manufacturing science and engineering conference, MSEC 2007 Paper No. 31129.

[5] Malhotra R, Cao J, Ren F, Kiridena V, Xia ZC, Reddy NV. Improvement of geometric accuracy in incremental forming by using a squeezing toolpath strategy with two forming tools. J Manuf Sci Eng 2011;133:061019-1.

[6] Agrawal A, Ziegert J, Smith S, Woody B, Cao J. Study of dimensional repeatability and fatigue life for deformation machining bending mode. J Manuf Sci Eng 2012;134:061009-1.

[7] Malhotra R, Cao J, Beltran M, Xu D, Magargee J, Kiridena V, et al. Accumulative-DSIF strategy for enhancing process capabilities in incremental forming. CIRP Ann – Manuf Technol 2012;61:251–4.

[8] ASTM E468-90, Standard practice for presentation of constant amplitude fatigue test results for metallic materials, annual book of ASTM standards, vol. 03.01.

[9] Malhotra R, Xue L, Belytschko T, Cao J. Mechanics of fracture in single point incremental forming. J Mater Process Technol 2012;212(1):1573–90.