

工艺优化设计

2A16 铝合金锥形件多级充液热成形仿真及优化分析

杨希英¹, 郎利辉¹, 郭禅¹, 王永铭²

(1. 北京航空航天大学, 北京 100191; 2. 首都航天机械公司, 北京 100076)

摘要: **目的** 解决2A16 铝合金锥形件常温充液成形困难、表面质量差的问题。**方法** 介绍了充液热成形工艺,并提出了3种锥形件成形方案,通过专用有限元软件Dynaform对所有方案进行了数值仿真;同时,对一步成形方案进行了试验。**结果** 通过试验验证了有限元模型的正确性。由仿真分析可知,成形缺陷包括悬空区起皱和凹模圆角及底部破裂,一步成形方案不可取,两步成形方案均可以将减薄率控制在13%以下。起皱危险主要发生在零件法兰以下30~55 mm处。**结论** 充液热成形与常温充液成形相比,可以显著提高材料的成形性;两步充液热成形方案可以获得2A16 铝合金锥形件;预成形凸模的形状设计对零件的表面质量影响明显;最终确定用先热冲压筒形件,后充液热成形的工艺方案,来成形2A16 铝合金锥形件。

关键词: 充液热成形; 锥形件; 工艺优化; 铝合金

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Optimization and Simulation Investigation on Muti-step Sheet Warm Hydroforming of 2A16 Aluminum Alloy Conical Part

YANG Xi-ying¹, LANG Li-hui¹, GUO Chan¹, WANG Yong-ming²

(1. Beihang University, Beijing 100191, China; 2. Capital Aerospace Machinery Company, Beijing 100076, China)

ABSTRACT: **Objective** To solve the problems of forming difficulty and poor surface quality for normal hydro-mechanical deep drawing of 2A16 aluminum alloy conical part. **Methods** Sheet warm hydroforming was introduced and three solutions to form the conical part were designed. Numerical simulations were executed to analyze all the solutions using the finite element software Dynaform. Meanwhile, the experiment of one-step warm hydroforming was carried out. **Results** The correctness of the finite element model was verified by the experiments. As known from the analysis of the simulation, the forming defects included wrinkling of noncontact region and fracture at the punch corner and die corner. The scheme of one-step forming was not desirable, while two-step forming schemes could control the thinning rate below 13% and the risk of wrinkling mainly occurred in the noncontact region of 30 to 55 mm below the part flange. **Conclusion** Compared with normal hydro-mechanical deep drawing, warm hydroforming significantly increased the formability of materials. Two-step warm hydroforming could successfully obtain 2A16 aluminum alloy conical part. The designed shape of preforming punch evidently affected the surface quality of the final part. The final solution was determined as first hot stamping the cylindrical part

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作者简介: 杨希英(1985—),男,河北衡水人,博士研究生,主要研究方向为液压成形。

and then forming the conical part by warm hydroforming.

KEY WORDS: warm hydroforming; conical part; process optimization; aluminum alloy

在航空、航天及汽车制造领域,通过使用轻质材料实现结构轻量化已成现代工业发展的趋势^[1]。然而,在常温下,铝合金、镁合金、钛合金等轻质材料的成形性较差,制约了其进一步应用^[2]。板材充液热成形技术兼具常温下板材充液成形和板材温热成形的双重优点,能显著提高材料的成形性能,实现复杂零件的整体成形,保证成形质量、精度以及达到产品轻量化的要求^[3-7]。该技术是将加热到一定温度的流体介质充入到经过预热的模具型腔中,通过加热和冷却系统将模具和流体介质的温度控制在一定范围内,使板材能在温热状态下按照设计的加载路径成形^[8]。

锥形件是一类典型的轴对称零件,在其成形过程中易出现断裂、起皱等缺陷^[9-11]。落压等常规工艺成形铝合金锥形件,具有废品率高、精度低、道次多、效率低等缺陷^[12]。基于以上原因,针对2A16铝合金锥形件充液热成形,文中提出了不同的工艺方案,并分别进行了数值仿真分析,讨论工艺参数对零件成形及质量控制的影响,最终获得了较优化的成形方案。

1 零件概述

1.1 零件几何特征

文中研究的锥形件形状尺寸如图1所示,端部

口径 $\phi 296.5$ mm,底部直径 $\phi 67.3$ mm,高173.6 mm,底部圆角R20 mm,壁厚为1.2 mm,倾斜锥角为 43° ,具有相对高度大、壁厚薄、悬空区易起皱、底部易撕裂等特点,难以采用常规冲压成形。

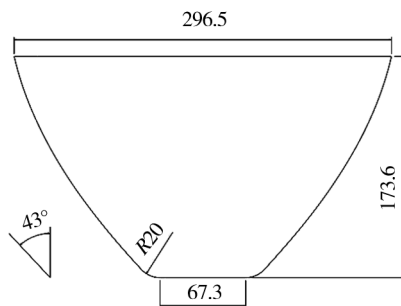


图1 零件形状及尺寸

Fig. 1 The shape and size of the part

1.2 材料参数

该零件所用材料为2A16-0铝合金,板料厚度为1.2 mm。材料力学性能采用单向拉伸测试获得,测试温度取3个特征点:20, 210, 300 $^\circ\text{C}$,应力应变曲线如图2所示。在本文数值仿真过程中,应用210 $^\circ\text{C}$, $v = 1.5$ mm/min 应力应变曲线进行分析^[13]。

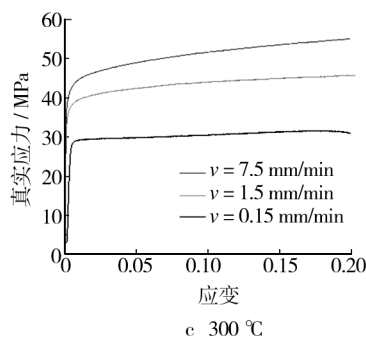
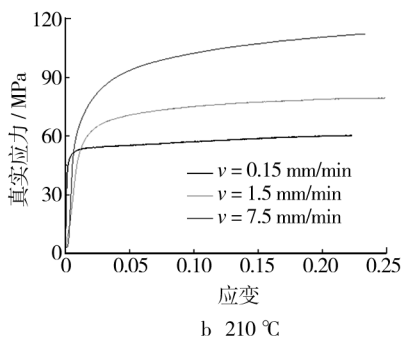
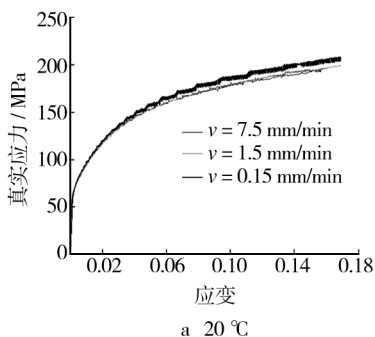


图2 2A16 铝合金应力应变曲线

Fig. 2 Stress-strain curves of 2A16 aluminum alloy

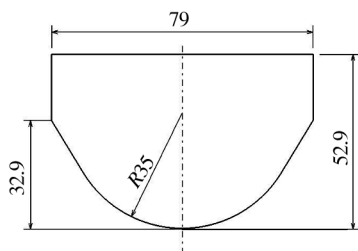
2 工艺分析

2A16 铝合金材料在常温下的成形性较差,导致

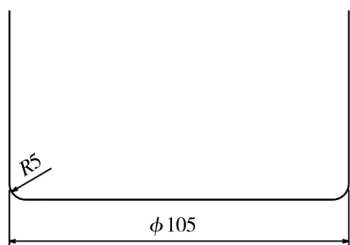
该锥形件采用常温充液成形亦难以成形,故采用充液热成形试制2A16 铝合金锥形件。

根据该典型零件的特征,提出一步成形及两步成形方案。其中两步成形方案包括2种预成形凸模

设计:①预成形凸模采用近终成形的圆弧过渡形状,如图 3a 所示;②预成形凸模为圆筒形,如图 3b 所示。



a 圆弧过渡形状



b 圆筒形

图 3 预成形凸模设计方案

Fig. 3 Design scheme of pre-forming punch

3 数值仿真

选用板料成形 CAE 专用软件 Dynaform 对充液热成形过程进行有限元模拟^[14]。模型中的凸、凹模及压边圈被视为刚性体,采用刚性四边形单元进行网格划分,坯料网格划分采用 4 节点 Belytschko-Tsay 壳单元^[15]。在溢流润滑作用下,坯料与凹模、压边圈的摩擦因数设置为 0.05,与凸模的摩擦因数设置为 0.15。根据单向拉伸试验数据设置材料参数,凸模下行速度设置为 4000 mm/s。利用软件自带求解器 MSTEP 进行坯料反算,并考虑修边余量及后续模拟迭代结果进行完善,最终确定为直径 D140 mm 的圆坯料。

3.1 一步成形

锥形件成形中的缺陷主要包括:前期凸模圆角处的破裂、中期悬空区的起皱及后期凹模圆角处的破裂。在凸模与板料间预留反胀高度并增加反胀阶段,可以降低前期破裂可能,调整后后期液室压力加载路径可以降低中期起皱及后期破裂可能。对锥形

件进行一步成形工艺分析及仿真优化,最终获得零件减薄分布云图如图 4 所示。

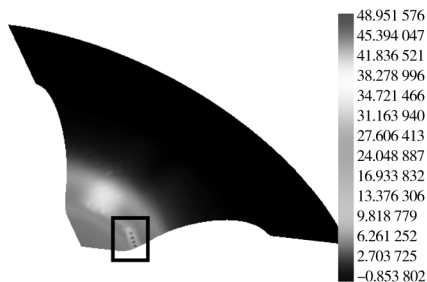
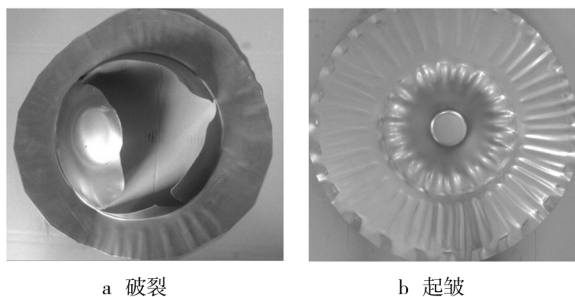


图 4 零件减薄分布云图(%)

Fig. 4 Cloud chart of part thinning distribution

一步成形模拟结果减薄率在 50% 左右,凸模下行 40 ~ 50 mm 处时,零件即产生破裂,无法成形。使用 2A16 铝合金板材进行充液热成形实验,改变压边间隙、反胀压力坯料尺寸均无法成形零件,零件破裂位置与数值模拟结果一致,均为凸模圆角处。图 5 为成形过程中的 2 种常见缺陷。



a 破裂

b 起皱

图 5 一步成形中的常见缺陷

Fig. 5 Common defects in one-step warm hydroforming

3.2 两步成形

3.2.1 第一种方案

预成形压边间隙为 1.3 mm,反胀高度为 25 mm,液室压力加载曲线如图 6 所示。从图 7 可知,在反胀结束后凸模下行初期,板料存在减薄率突变过程。该现象是由于板料未与凸模形成有益摩擦导致。随着凸模下行,板料在液室压力的作用下,贴在凸模表面,可以有效降低继续减薄程度。预成形零件最终减薄率为 10.55%,如图 8 所示。

终成形压边间隙为 1.32 mm,凸模初始位置为与预成形零件底部接触,在凸模下行 5 mm 时,液室压力按照图 9 所示曲线进行加载。零件最大减薄率为 11.33%,云图如图 10 所示。从图 11 可知,虽然

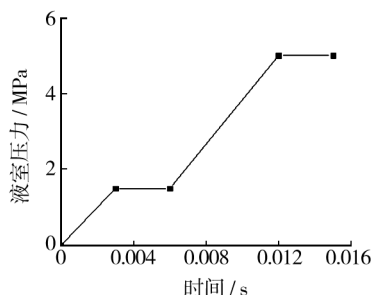


图6 预成形阶段液室压力-时间曲线(方案一)

Fig.6 Pressure loading vs time curve during the preforming process (scheme 1)



图7 预成形阶段减薄率突变云图(方案一)(%)

Fig.7 Cloud chart of thinning rate mutation during preforming (scheme 1)

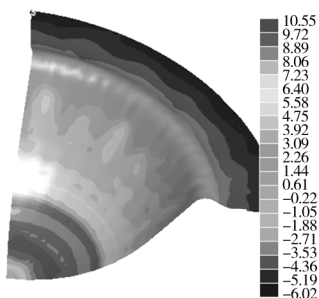


图8 预成形零件减薄率云图(方案一)(%)

Fig.8 Cloud chart of thinning rate of the preformed part (scheme 1)

该成形方案可以保证零件不发生破裂,但在零件法兰以下 30 ~ 55 mm 处的悬空区,零件具有明显的起皱趋势。

3.2.2 第二种方案

预成形为常规热冲压成形,压边间隙设置为 1.25 mm,仿真结果如图 12 所示,最大减薄率为

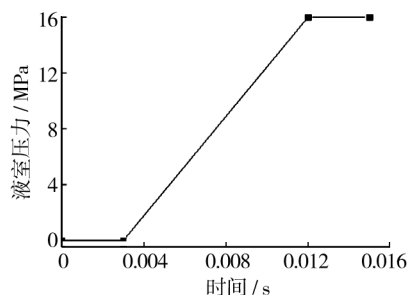


图9 终成形阶段液室压力-时间曲线(方案一)

Fig.9 Pressure loading vs time curve in final forming (scheme 1)

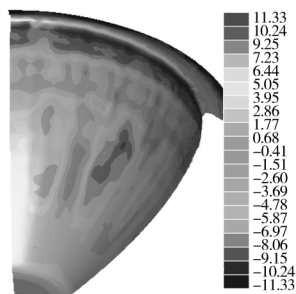


图10 零件减薄率分布云图(方案一)(%)

Fig.10 Cloud chart of thinning rate distribution of the part (scheme 1)

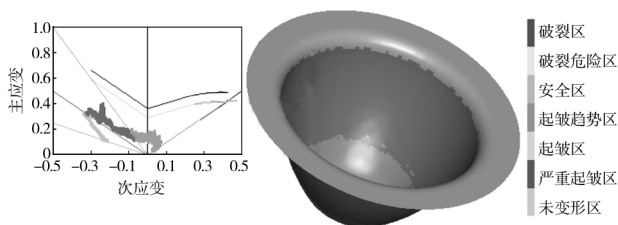


图11 仿真结果 FLD 图(方案一)

Fig.11 The simulation results of FLD (scheme 1)

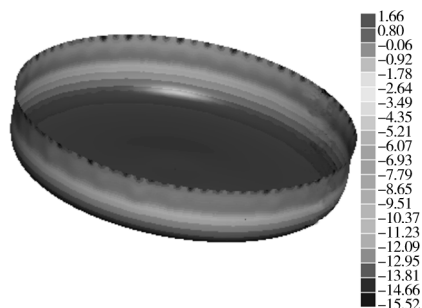


图12 零件减薄率分布云图(方案二)(%)

Fig.12 Cloud chart of thinning rate distribution (scheme 2)

1.66%,可知预成形变形量很小,对整个成形工艺影响不大。

终成形压边间隙为 1.3 mm,反胀高度设置为 15 mm,液室压力加载曲线如图 13 所示。零件最大减薄率为 12.1%,可以保证零件不发生破裂,零件减薄率分布云图如图 14 所示。从仿真结果 FLD 图(图 15)可知,在该成形方案下,成形后零件大部分表面贴膜效果良好,虽然在零件法兰以下 30~50 mm 处的悬空区,同样具有起皱趋势,但并不明显,可以通过后续整形进行消除。

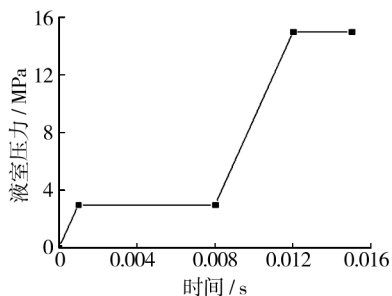


图 13 预成型阶段液室压力-时间曲线(方案二)

Fig. 13 Pressure loading vs time curve during preforming (scheme 2)

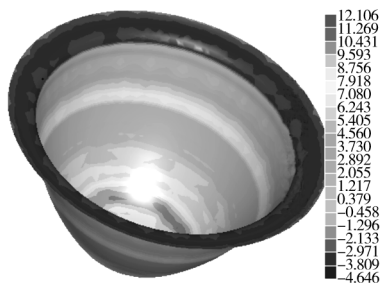


图 14 零件减薄率分布云图(方案二)(%)

Fig. 14 Cloud chart of thinning rate distribution of the part (scheme 2)

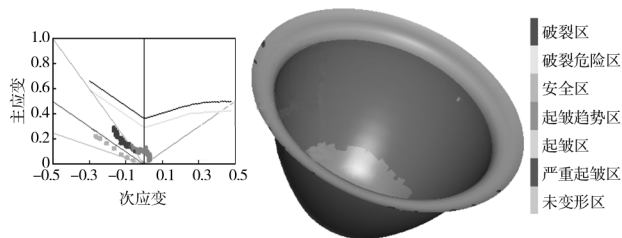


图 15 仿真结果 FLD 图(方案二)

Fig. 15 The simulation results of FLD (scheme 2)

4 结语

1) 对于 2A16 铝合金锥形件,采用一步充液热成形工艺,结合仿真分析和实验验证可知,在凸模行程至 50 mm 处即产生破裂,无法得到最终零件。

2) 对文中两步成形方案,由仿真优化结果可知,2 种方案均可成形出最终零件,但第 1 种方案易在悬空区产生起皱缺陷。为保证零件成形精度及贴膜度,最终确定第 2 种成形方案用于 2A16 铝合金锥形件的成形。

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