学校编码：10384　　分类号_____密级_____
学　　号：19920141152913　　UDC_____

厦门大学

硕 士 学 位 论 文

金属薄板件的残余应力测量和振动时效研究

Research on residual stress measurement and vibration stress relief of sheet metal

林 俊 辉

指导教师姓名：郑建毅　副教授

专 业 名 称：机　械　工　程

论文提交日期：2017 年 04 月

论文答辩时间：2017 年 05 月

学位授予日期：2017 年　　月

答辩委员会主席：_____

评　　阅　　人：_____

2017 年 05 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果，均在文中以适当方式明确标明，并符合法律规范和《厦门大学研究生学术活动规范（试行）》。

另外，该学位论文为（　郑建毅副教授　）课题（组）的研究成果，获得（　郑建毅副教授　）课题（组）经费或实验室的资助，在（　郑建毅副教授　）实验室完成。（请在以上括号内填写课题或课题组负责人或实验室名称，未有此项声明内容的，可以不作特别声明。）

声明人（签名）：林俊辉

2017 年 05月 26日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

（　　）1.经厦门大学保密委员会审查核定的保密学位论文，于　　年　　月　　日解密，解密后适用上述授权。

（ √ ）2.不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：林俊辉

2017年 05月 26日

摘要

小孔法的塑性效应会给高残余应力测量带来误差，为了解决这个问题，论文中对 ASTM E837-13a 标准中的校准系数的塑性修正进行了研究。同时，组建了用于金属薄板件振动时效的电磁激振系统，研究了振动时效消除金属薄板件的残余应力。论文的研究内容围绕以下几个方面展开。

首先，研究了小孔法测量铝合金构件高残余应力的塑性效应修正方法。基于形状改变比能密度理论，对 ASTM E837-13a 标准中的校准系数进行塑性修正；结合双线性弹塑性理论，采用 ANSYS 软件进行有限元仿真标定；使用电子万能试验机进行拉伸加载实验验证，修正前和修正后的高残余应力测量误差的平均值范围是 0~80%和 0~12%；使用 ANSYS 进行二轴应力仿真验证实验。结果表明，在小孔法测应力过程中，先使用 ASTM E837-13a 中的$\bar{a}$和$\bar{b}$算残余应力σ，如果得到的σ值小于 $0.5\sigma_s$，则σ即为所求应力值；否则，使用本研究中的修正方法对$\bar{a}$和$\bar{b}$进行修正，然后使用修正后的$\bar{a}$和$\bar{b}$计算应力。

其次，组建了用于金属薄板件振动时效的电磁激振系统。按要求设计了电磁激振器的总体方案，包括动圈的结构和支撑动圈的 8 块弹簧片；采用 ANSYS 对动圈进行模态分析，通过改变动圈的尺寸、结构和材料，使得动圈的一阶共振频率大于激振器的最大工作频率；运用 ANSYS 对激振装置的磁路进行了有限元仿真，获得磁路工作气隙处的磁感应强度值。

再次，实验研究了振动时效消除 7075 铝合金残余应力的效果。在实验中采用淬火使构件内部产生较大的初始残余应力；根据 ANSYS 有限元模态分析，确定实验构件的夹持方式和激振频率，对构件进行振动时效实验；采用小孔法评估振动时效的效果。经过低频、中频、高频振动时效后，第一主应力值的平均值由 118 MPa 降低至 57 MPa、80 MPa、13 MPa。由此可见，振动时效能有效地减小 7075 铝合金中的残余应力。

最后，实验研究了振动消除铜片的翘曲。使用 ANSYS，对铜片进行模态分析；采用低频 50 Hz、中频 300 Hz、高频 5 kHz 的激振方案，每个铜片的激振时间都是 25 min；用激光传感器进行铜片的翘曲测量，以此来判断振动时效前后铜

片的残余应力变化。实验考察了激振频率对于铜片的振动时效的影响。经过振动时效，工位一、二、三铜片的翘曲减少百分率的平均值分别约是 80%、35%、30%。

关键词：残余应力；小孔法；振动时效

*本文的研究工作得到国家自然科学基金（51305371，51305373），中央高校基本科研业务费专项资金（20720140517）和福建省自然科学基金资助项目（2014J05063）的资助。

Abstract

Plastic effect would lead to measurement error when high residual stress was measured using hole-drilling method (HDM). To solve the problem, the correction of calibration coefficients in the ASTM E837-13a standard was studied in this paper. At the same time, the system of electromagnetic vibration exciter for vibration stress relief (VSR) of metal sheet was formed and the VSR of sheet metal was studied. Research contents of this paper were listed as follows.

Firstly, a method correcting plastic effect was studied when high residual stress of aluminum alloy specimen was measured by HDM. The calibration coefficients in the ASTM E837-13a standard were corrected based on the distortional strain energy density theory; Finite element simulated calibration by ANSYS software considering double linear elastic-plastic theory was carried out; Verification experiment by stepwise tensile loading using electronic universal testing machine was carried out, before and after the correction, the ranges of average value of high residual stress measurement error were 0~80% and 0~12%; Verification experiment by simulated biaxial stress was done using ANSYS. Results showed that in the residual stress measurement by HDM, firstly, $\bar{a}$ and $\bar{b}$ in ASTM E837-13a should be used in calculating residual stress σ, If the σ obtained was smaller than $0.5\sigma_s$, the σ was the true residual stress; Otherwise, $\bar{a}$ and $\bar{b}$ should be corrected following the method in this study, then the corrected $\bar{a}$ and $\bar{b}$ should be used to calculate the true residual stress.

Secondly, the system of electromagnetic vibration exciter for VSR of metal sheet was formed. According to the requirement, overall scheme of electromagnetic vibrator exciter was designed, including structure of movable coil and 8 spring pieces for supporting moving coil; Modal analysis of movable coil was carried out using ANSYS. The movable coil size, structure and material were changed to make the first resonance frequency of the movable coil be greater than the maximum operating frequency of the exciter. Magnetic circuit of the vibrator exciter was simulated using ANSYS and the magnetic flux density in its working air gap was obtained.

Thirdly, the result of VSR of 7075 aluminum alloy was studied. In the experiment, a large residual stress in specimen was generated by quenching; According to ANSYS finite element modal analysis, the clamping conditions and excitation frequency of 7075 aluminum alloy specimen were determined and the VSR experiments to the specimen were carried out; Effect of VSR was evaluated by HDM. After low frequency, medium frequency and high frequency VSR, the average value of the first principal stress were reduced from 118 MPa to 57 MPa, 80 MPa and 13 MPa.

Finally, the vibration warp relief of copper sheet was studied by experimental research. Using ANSYS, modal analysis of copper sheet was carried out; The excitation schemes were used with low frequency 50 Hz, intermediate frequency 300 Hz, high frequency 5 kHz, the excitation time of each scheme were 25 min; The laser sensor was used to measure the warp of copper sheet, so as to determine the residual stress change of copper sheet before and after VSR. The effect of exciting frequency of VSR of copper sheet was investigated by experiments. Via VSR, the average values of warp elimination rate of copper sheet in station one, two and three were about 80%, 35% and 30%, respectively.

Keywords: Residual stress; Hole-drilling method; Vibration stress relief

*This work was supported by the National Natural Science Foundation of China (51305371, 51305373), the Fundamental Research Funds for the Central Universities (20720140517), and the Natural Science Foundation of Fujian Province of China (2014J05063).

目 录

Table of contents