

学校编码: 10384

分类号\_\_\_\_密级\_\_\_\_,

学号: 20720141150135

UDC\_\_\_\_,

厦 门 大 学

硕 士 学 位 论 文

**Cu-Al-Mn-(Cr, V, Ti)形状记忆合金的  
微观组织及性能研究**

**Investigations on the microstructures and properties of  
Cu-Al-Mn-(Cr, V, Ti) shape memory alloys**

张 帆

指导教师姓名: 杨水源 副教授

专业名称: 材料工程

论文提交日期: 2017年5月

论文答辩时间: 2017年5月

学位授予日期: 2017年 月

答辩委员会主席: \_\_\_\_\_

评 阅 人: \_\_\_\_\_

2017年5月

厦门大学博硕士学位论文摘要库

## 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( )课题(组)的研究成果,获得( )课题(组)经费或实验室的资助,在( )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) :

年 月 日

厦门大学博硕士学位论文摘要库

## 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)：

年 月 日

厦门大学博硕士学位论文摘要库

## 摘要

Cu-Al-Mn 基形状记忆合金具有良好的塑性和形状记忆性能，且成本低并易于切削加工，因此具有极其广阔的应用前景。然而，Cu-Al-Mn 基形状记忆合金的临界应力以及疲劳强度都比较低，阻碍了其更多的发展应用。本论文采用合金化方法以 Cu-Al-Mn 合金为基体，分别添加了 Cr、V 和 Ti 元素，制备了 Cu-Al-Mn-Cr、Cu-Al-Mn-V 和 Cu-Al-Mn-Ti 三个体系的合金，并逐步采用金相、EPMA、XRD、DSC、压缩、TMA 等测试方法，对各合金体系的微观组织结构、相变特性、力学性能和形状记忆性能进行了系统的研究。主要结论如下：

(1) Cu-Al-Mn-Cr 系合金具有可逆的马氏体相变，由  $L2_1$  母相、 $A2(\text{Cr})$  析出相以及少量的  $2H(\gamma'_1)$  马氏体组成。尽管合金在变形前都是  $L2_1$  奥氏体母相，但卸载后仍有部分应力诱发的  $2H(\gamma'_1)$  马氏体发生稳定化而留存下来。因此，在本论文中，合金在室温变形的条件下，合金不仅在变形过程中表现出超弹性，也在卸载后加热时具有形状记忆效应。其结果进一步表明，Cu-12.8Al-7.5Mn-2.5Cr (wt.%, 下同) 合金有着良好的超弹性，其应变可达 2.9%，同时具有 1.5% 的形状记忆效应。Cu-12.7Al-6.9Mn-1.8Cr 合金具有更好的超弹性，在预应变为 10% 时超弹性应变可达 5%，并具有 2% 的形状记忆效应。Cu-12.5Al-5.8Mn-4.1Cr 合金的形状记忆效应在预应变为 10% 时可达 2.5%，且仍呈现 2.8% 超弹性应变。

(2) Cu-Al-Mn-V 系合金由  $L2_1$  奥氏体母相、 $\delta(\text{V, Mn})$  析出相和  $2H(\gamma'_1)$  马氏体相组成。合金中的  $\delta(\text{V, Mn})$  相和  $2H(\gamma'_1)$  马氏体相的含量会随着 V 含量的增加而逐步递增。同 Cu-Al-Mn-Cr 合金类似，在室温变形时，由  $L2_1$  奥氏体母相压缩变形会发生应力诱发  $2H(\gamma'_1)$  马氏体稳定化的现象。Cu-Al-Mn-V 合金的超弹性和形状记忆效应可归纳为三类。I 类包括 Cu-12.8Al-9.4Mn-1.8V 和 Cu-13.1Al-8.6Mn-2.1V 两个合金，这类合金的超弹性很好，其超弹性应变可达 5.4% 和 3.9%。II 类包括 Cu-12.9Al-6.8Mn-4.0V 和 Cu-13.4Al-6.3Mn-4.5V 两个合金，这类合金具有良好的形状记忆效应，其形状记忆效应可达 3.5% 和 3.9%。III 类是 Cu-13.4Al-8.7Mn-2.5V 合金，其超弹性与形状记忆效应均介于前两类合金之间。

(3) Cu-Al-Mn-Ti合金的微观组织由 $\text{Cu}_2\text{AlMn}$  ( $L2_1$ 母相)、 $\text{Cu}_2\text{TiAl}$  ( $L2_1$ 结构)以及 $2\text{H}(\gamma'_1)$ 马氏体构成。随着预变形的增加,部分 $\text{Cu}_2\text{AlMn}$ 母相由应力诱发转变成 $2\text{H}(\gamma'_1)$ 马氏体,并在卸载后发生稳定化。Cu-Al-Mn-Ti系合金随着Ti含量增加而呈现出不同的形状记忆性能。合金的超弹性及其应变随着Ti含量的增多而逐渐减小。 $\text{Cu-12.9Al-8.3Mn-0.5Ti}$ 合金具有良好的超弹性,其最大超弹性应变可达4.6%。合金的形状记忆效应则随着Ti含量增加而升高, $\text{Cu-12.3Al-8.6Mn-1.9Ti}$ 和 $\text{Cu-12.8Al-7.7Mn-2.6Ti}$ 合金有着良好的形状记忆效应,其最大值可达2.3%和2.5%。然而,随着进一步增加Ti的含量则会大幅降低合金的形状记忆性能, $\text{Cu-13.7Al-7.4Mn-4.3Ti}$ 合金中仅有1.8%最大超弹性应变和1.1%的最大形状记忆效应。

关键词:

Cu-Al-Mn 合金 微观结构 马氏体相变 形状记忆效应 马氏体稳定化



## Abstract

Cu–Al–Mn-based SMAs have been applied in several practical applications for the advantages of easy fabrication, good shape memory properties and low manufacturing cost. However, the critical stress for stress-inducing martensitic transformation and the fatigue strength of Cu–Al–Mn SMAs are very low, which limit their further practical applications. In this study, three types of Cu–Al–Mn-based SMAs were prepared by alloying Cr, V and Ti, including Cu–Al–Mn–Cr, Cu–Al–Mn–V and Cu–Al–Mn–Ti, respectively. Then their microstructures, martensitic transformation characteristics, mechanical and shape memory behaviors were investigated by means of optical micrograph, XRD, EPMA, DSC, compressive and TMA tests. The details of the results are described as follows:

(1) Cu–Al–Mn–Cr SMAs exhibit a mixed microstructure consisted of dominant  $L2_1$  parent,  $A2(\text{Cr})$  phase and small amounts of  $2H(\gamma'_1)$  martensite, as well as a reversible martensitic transformation. Although the alloys are main  $L2_1$  parent before deformation, partial stress-induced  $2H(\gamma'_1)$  martensite can be stabilized and retained after unloading. Therefore, the same alloy under a certain deformation temperature (room temperature) not only exhibits superelasticity property during deformation, but also the deformed alloy also shows shape memory effect when heated. The results further show that Cu–12.8Al–7.5Mn–2.5Cr alloy has a good superelasticity strain of 2.9% as well as a shape memory effect of 1.5%. Cu–12.7Al–6.9Mn–1.8Cr alloy possesses much the best superelasticity strain close to 5.0% under a pre-deformation of 10% and a shape memory effect of 2.0%. The best shape memory effect up to 2.5% with 10% of pre-deformation and a superelasticity strain of 2.8% are obtained in Cu–12.5Al–5.8Mn–4.1Cr alloy.

(2) Cu–Al–Mn–V SMAs have complex microstructure consisted of  $L2_1$  parent,  $\delta(\text{V, Mn})$  phase and  $2H(\gamma'_1)$  martensite. The amounts of  $\delta(\text{V, Mn})$  phase and  $2H(\gamma'_1)$  martensite increase with the increase of V content. The results further show that the

stabilization of stress-induced  $2H(\gamma'_1)$  martensite from  $L2_1$  parent occurs during deformation. The superelasticity and shape memory effect are summarized to three situations. Situation I includes Cu–12.8Al–9.4Mn–1.8V and Cu–13.1Al–8.6Mn–2.1V, which have excellent superelasticity strains being up to 5.4% and 3.9% respectively. Cu–12.9Al–6.8Mn–4.0V and Cu–13.4Al–6.3Mn–4.5V alloys are situation II, and exhibit good shape memory effects being up to 3.5% and 3.9% respectively. The superelasticity and shape memory effect of Cu–13.4Al–8.7Mn–2.5V alloy that is situation III are between the above two situations.

(3) Cu–Al–Mn–Ti SMAs have a mixed microstructure consisted of dominant  $Cu_2AlMn$  ( $L2_1$  parent),  $Cu_2TiAl$  phase (also  $L2_1$  structure) and  $2H(\gamma'_1)$  martensite. With the increasing of deformation, partial stress-induced  $2H(\gamma'_1)$  martensite from  $Cu_2AlMn$  parent can be stabilized and retained after unloading. The results further show that the superelasticity decreases with the increase of Ti content. Cu–12.9Al–8.3Mn–0.5Ti alloy has a good superelasticity strain of 4.6% and a shape memory effect of 1.5%. While increasing the Ti content, Cu–12.3Al–8.6Mn–1.9Ti and Cu–12.8Al–7.7Mn–2.6Ti alloy possess better shape memory effect up to 2.3% and 2.5%, respectively. However, with the further addition of Ti, the shape memory effects decrease. Cu–13.7Al–7.4Mn–4.3Ti alloy only has a max superelasticity strain of 1.8% as well as the best shape memory effect of 1.1%.

**Keywords:** Cu–Al–Mn; Microstructure; Martensitic transformation; Shape memory effect; Martensite stabilization

# 目录

摘要.....	I
Abstract.....	III
<b>第一章 绪论</b> .....	11
1.1 引言.....	11
1.2 形状记忆合金简介.....	12
1.2.1 马氏体相变.....	12
1.2.2 形状记忆效应.....	14
1.2.3 超弹性.....	15
1.3 Cu-Al-Mn 基形状记忆合金.....	16
1.4 选题意义和研究内容.....	19
1.4.1 选题意义.....	19
1.4.2 研究内容.....	20
参考文献.....	21
<b>第二章 样品制备及实验方法</b> .....	26
2.1 样品制备.....	26
2.1.1 铸态样品制备.....	26
2.1.2 样品的热处理.....	27
2.1.3 测试样品制备.....	29
2.2 实验方法.....	28
2.2.1 显微组织观察.....	28
2.2.2 合金成分分析.....	28
2.2.3 晶体结构分析.....	28
2.2.4 相变特性测试.....	28
2.2.5 超弹性与形状记忆效应.....	29

### 第三章 Cu-Al-Mn-Cr 系合金的微观组织结构、相变特性、力学及形状记忆性能 ..... 32

3.1 引言 .....	32
3.2 合金的微观组织结构 .....	33
3.2.1 微观组织结构.....	33
3.2.2 合金成分分析.....	34
3.2.3 晶体结构分析.....	35
3.3 合金的相变特性 .....	36
3.4 合金的力学及形状记忆特性 .....	37
3.4.1 力学性能.....	37
3.4.2 形状记忆特性.....	38
3.5 应力诱发马氏体稳定化 .....	42
3.6 本章小结 .....	44
参考文献 .....	45

### 第四章 Cu-Al-Mn-V 系合金的微观组织结构、相变特性、力学及形状记忆性能 ..... 47

4.1 引言 .....	47
4.2 合金的微观组织结构 .....	48
4.2.1 微观组织结构.....	48
4.2.2 合金成分分析.....	49
4.2.3 晶体结构分析.....	51
4.3 合金的相变特性 .....	53
4.4 合金的力学及形状记忆特性 .....	55
4.4.1 力学性能.....	55
4.4.2 形状记忆特性.....	56
4.5 应力诱发马氏体稳定化 .....	61
4.6 本章小结 .....	63
参考文献 .....	65

<b>第五章 Cu-Al-Mn-Ti 系合金的微观组织结构、相变特性、力学及形状记忆性能</b> .....	67
<b>5.1 引言</b> .....	67
<b>5.2 合金的微观组织结构</b> .....	68
5.2.1 微观组织结构.....	68
5.2.2 合金成分分析.....	69
5.2.3 晶体结构分析.....	70
<b>5.3 合金的相变特性</b> .....	71
<b>5.4 合金的力学及形状记忆特性</b> .....	73
5.4.1 力学性能.....	73
5.4.2 形状记忆特性.....	74
<b>5.5 应力诱发马氏体稳定化</b> .....	78
<b>5.6 本章小结</b> .....	80
参考文献 .....	81
<b>第六章 总结</b> .....	82
<b>致谢</b> .....	83
<b>攻读硕士学位期间科研成果</b> .....	错误! 未定义书签。
<b>攻读硕士学位期间所获奖励</b> .....	85

# CONTENTS

<b>Abstract( Chinese)</b> .....	I
<b>Abstract</b> .....	III
<b>CHAPTER 1 Introduction</b> .....	11
<b>1.1 Introduction</b> .....	11
<b>1.2 Introduction of shape memory alloys</b> .....	12
1.2.1 Martensitic transformation.....	12
1.2.2 Shape memory effect .....	14
1.2.3 Superelasticity.....	15
<b>1.3 Cu–Al–Mn-based shape memory alloys</b> .....	16
<b>1.4 Basis, purpose and major contents</b> .....	19
1.4.1 Basis and purpose .....	19
1.4.2 Major contents .....	20
<b>Reference</b> .....	21
<b>CHAPTER 2 Preparation of specimen and experimental procedure</b>	26
<b>2.1 Preparation of specimen</b> .....	26
2.1.1 Preparation of as-cast alloys .....	26
2.1.2 Heat treatment procedures .....	27
2.2.3 Preparation of investigative specimen .....	27
<b>2.2 Experimental procedure</b> .....	28
2.2.1 Observation of microstructure .....	28
2.2.2 Measurement of composition.....	28
2.2.3 Analysis of crystal structure.....	28
2.2.4 Measurement of martensitic transformation .....	29
2.2.5 Superelasticity and shape memory effect .....	29

## **CHAPTER 3 Microstructures, transformation behaviors, mechanical**

<b>and shape memory properties of Cu–Al–Mn–Cr alloys</b> .....	32
<b>3.1 Introduction</b> .....	32
<b>3.2 Microstructure</b> .....	33
3.2.1 Microstructure .....	33
3.2.2 Composition .....	34
3.2.3 Crystal structure .....	35
<b>3.3 Transformation behaviors</b> .....	36
<b>3.4 Mechanical and shape memory characteristics</b> .....	37
3.4.1 Mechanical properties .....	37
3.4.2 Shape memory properties .....	38
<b>3.5 Stabilization of stress-induced martensite</b> .....	42
<b>3.6 Conclusion</b> .....	44
<b>Reference</b> .....	45

## **CHAPTER 4 Microstructures, transformation behaviors, mechanical**

<b>and shape memory properties of Cu–Al–Mn–V alloys</b> .....	47
<b>4.1 Introduction</b> .....	47
<b>4.2 Microstructure</b> .....	48
4.2.1 Microstructure .....	48
4.2.2 Composition .....	49
4.2.3 Crystal structure .....	51
<b>4.3 Transformation behaviors</b> .....	53
<b>4.4 Mechanical and shape memory characteristics</b> .....	55
4.4.1 Mechanical properties .....	55
4.4.2 Shape memory properties .....	56
<b>4.5 Stabilization of stress-induced martensite</b> .....	61
<b>4.6 Conclusion</b> .....	63
<b>Reference</b> .....	65

<b>CHAPTER 5 Microstructures, transformation behaviors, mechanical and shape memory properties of Cu–Al–Mn–Ti alloys</b> .....	67
<b>5.1 Introduction</b> .....	67
<b>5.2 Microstructure</b> .....	68
5.2.1 Microstructure .....	68
5.2.2 Composition .....	69
5.2.3 Crystal structure .....	70
<b>5.3 Transformation behaviors</b> .....	71
<b>5.4 Mechanical and shape memory characteristics</b> .....	73
5.4.1 Mechanical properties .....	73
5.4.2 Shape memory properties .....	74
<b>5.5 Stabilization of stress-induced martensite</b> .....	78
<b>5.6 Conclusion</b> .....	80
<b>Reference</b> .....	81
<b>CHAPTER 6 Summary</b> .....	82
<b>Acknowledgements</b> .....	83
<b>Publications</b> .....	84
<b>Awards</b> .....	85



Degree papers are in the "[Xiamen University Electronic Theses and Dissertations Database](#)". Full texts are available in the following ways:

1. If your library is a CALIS member libraries, please log on <http://etd.calis.edu.cn/> and submit requests online, or consult the interlibrary loan department in your library.
2. For users of non-CALIS member libraries, please mail to [etd@xmu.edu.cn](mailto:etd@xmu.edu.cn) for delivery details.

厦门大学博硕士论文摘要库