# 贝氏体与贝氏体钢

## ——纪念康沫狂先生九十华诞论文集

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科学出版社
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## 内 容 简 介

本书汇集了康沫狂教授及其培养的博士生在国内外发表的有关学术论文85篇，集中反映了康沫狂教授60多年教学和科研的成果。全书分为6个部分，分别为贝氏体相变动力学（含预贝氏体相变）及组织形貌学、贝氏体晶体学（含铁素体的过饱和度测定）、贝氏体（含马氏体）相变热力学、贝氏体相变机制、贝氏体（含一些奥氏体、马氏体）的性能、贝氏体钢和新型准贝氏体钢及其特性。

本书可供金属材料及热处理专业的有关研究人员、高校教师、研究生及高年级学生阅读参考。

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祝贺《贝氏体相变机制及贝氏体钢》出版

—纪念康沫狂教授九十華誕—

康沫狂教授上世纪四十年代初和我都是國立西北工學院的學生，虽然不是同班，宿舍却連在一起，在那流亡在異乡的日子里，朝夕相处，知之甚深：康先生樸實好學，為人正直。康先生原讀机械專業，没想到畢業以后，我们走到一起來了，都从事了材料的研究與开發。

几十年來，我遇到過他的不少學生，對他都是一片讚揚声。康先生長期从事贝氏体相变研究，提出了以實驗為基础的一套理論模型；开发出极具特色的贝氏体及准贝氏体合金鋼。為成果推廣，他具有坚韌不拔的执着精神，堪為我科技工作者的楷模。

同龄人 师昌绪

二〇〇九年七月一日

# 热烈祝贺康沫狂教授九十大寿

首先鞠躬祝贺尊敬的康沫狂教授九十大寿！

我是康沫狂教授的第一届金属材料及热处理专业本科生，1961 年毕业，如今已年过古稀。但每当回忆我的学术生涯时，眼前首先浮现出来的便是康老师。我不仅是最早跟随恩师从事高强度钢研究的学生，而且是老师把我领进了这个学术领域并成为同行。我为有健在的老师而在心理上感到年轻，在学术上感到有所依靠。

康沫狂教授是我国著名的金属材料与热处理科学家、教育家，60 多年的教学和科研建树，已在我国金属材料与热处理高等教育和科学技术发展中“发酵”出了巨大的效应，惠及了他的弟子、学生和国内外同行。值此庆祝康沫狂教授九十大寿之际，颂扬老师的功德，表达我对老师溢于言表的感恩和尊崇心境。

**奠基开拓，功彪学界。**1956 年进入西北工学院（现为西北工业大学）初，我和同学们最感新鲜和骄傲的一件事就是相传我们专业教研室有位康教授。他筹建了西北工学院“金属学与热处理及车间设备”专业，在他苦心经营、呕心沥血、不懈开拓下，很快铸成了“四大金刚”、“四小金刚”为主体的教师队伍，并购置数量可观的有关实验设备，成为现在西北工业大学实力最强的专业之一，也名冠全国高校。几十年来，本科、硕士、博士毕业学子的勤奋、忠恳和事业有成受到普遍赞扬！

**勤于实践，学识问鼎。**中国有句古训叫“业精于勤”，这句话好似专为康教授而写。大学教授在人们的观念中当然是理论家，而康教授留给我最为突出、最为深刻的印象和特点，是他敢于直面科学实验，直面生产现场，直面构件故障。他是我少见的在实验室为学生解难，到工厂为生产解难，到现场为使用解难的教授。不难想见，如果没有深厚的理论功底和绝技，怕难有这种胆量，即使有胆量，怕也难有这种能力。我最敬佩康老师孜孜不倦地探索、实践，毕生精力奉献于合金贝氏体相变方面的研究。在贝氏体相变理论上独树一帜，揭示了其物理本质，建立了新模型，定义了新组织，受到国内外有关同行学者的认可；在贝氏体相变应用上，研制成的高强度和良好热工艺性贝氏体钢，用做飞机关键构件，该钢至今仍在多种型号的飞机上使用；随后又开发出性能更好的新型准贝氏体钢，为国家级科研成果重点推广项目，已用于石油、矿山、交通、兵器等方面，因此康老师获国家发明二等奖和其他多种奖项，雄冠同行。

**诲人不倦，桃李天下。**康沫狂教授在西北工业大学创建了我国当时航空院校金属材料与热处理第一个博士点，他和同事们共建了我国材料科学和工程一级学科第一批国家重点专业。他以强烈的科学使命感、民族使命感和赤子之心，几十年来，殚精竭虑培养学生，其中他亲手培育的博士生达数十人，桃李满天下。如今他的诸多弟子、学生在高等院校、科研院所、工厂企业乃至国家机关都已是栋梁之才，是材料与热处理专业界领军人物和中坚力量。他们取得的科学技术和各种成就都伴同康老师这颗巨星一起放

射着灿烂的光芒！

**德高望重，师表楷模。**康沫狂教授学思敏感、敢为人先、执著追求、学识渊博、坚毅创新、造诣高超、教书育人、为人师表，如今还壮心不已，关心他的弟子、学生的成长，他是真正的“老师”。康老师之平易近人给学生留下极为深刻的记忆。我们这些年过古稀的老学生走到一起，必谈的话题自然是对大学学习、生活的眷恋和美好回忆。其中，记忆最清晰的老师是康教授，最赞叹的老师是康教授，最怀感激之情的老师还是康教授。每遇有人问我学的什么专业时，我总是心怀骄傲地告诉人家说：“我是西工大康沫狂教授的学生！”

双手合十祈愿尊敬的康沫狂教授福寿绵长！

赵振业

中国工程院院士

二〇〇九年六月十九日

# 康沫狂教授简介

康沫狂，1920 年 1 月生，汉族，河南省新野县上庄乡邓庄村人。曾就学于南阳初中、开封高中，于 1941 年被保送至国立西北工学院机械系上学，毕业后又入空军高级机械研究班学校学习，1946 年留校任教。1949 年调中央工校任讲师。1950 年调西北工学院任讲师、副教授。1957 年西北工学院与西安航空学院合并为西北工业大学，留任副教授、教授、金属材料及热处理教研主任、校学术委员会委员、碳/碳复合材料研究所顾问等职。1984 年被国务院学位委员会评为博士生导师。曾兼任重庆大学和太原工业大学教授，航空部第一、二、三届学术委员会委员，航空学会第二、三届理事兼材料工程专业委员会副主任委员，全国高校机械类热加工专业教材编审委员会委员，中国船舶工业总公司第十二研究所顾问，陕西省金属学会理事，教育部设在西安交通大学的金属强度开放实验室学术委员会委员，《金属热处理学报》、《航空材料学报》和《金属热加工工艺》等期刊编委等职；现任美国 TMS 高级会员和《金属热处理》高级顾问。1991 年被国务院批准享受政府特殊津贴。1992 年航空航天部授于“有突出贡献专家”称号。陕西省科协授于“陕西科技精英”称号。

在科研领域里，他在贝氏体相变理论方面，用实验证实了溶质原子扩散控制下过饱和的贝氏体切变机制，在低碳低合金钢中发现了不同于贝氏体的粒状组织，在揭示贝氏体碳化物析出源的基础上提出了（无碳化物）准贝氏体概念。在马氏体相变方面，发现了回火马氏体二类脆性本质，明确了奥氏体稳定化和稳定性的规律，建立了低碳马氏体表观点阵常数和碳含量间的新关系方程，以及贝氏体切变相变的热力学。以上种种均获得国内外有关同行的认可。在贝氏体组织应用方面，根据贝氏体相变理论，首先于 20 世纪 60 年代，与同事合作研制成功具有优异热加工性能的高强度贝氏体钢（18Mn2CrMoBA），用于飞机某部件上，代替原苏联钢种 30CrMnSiA，且使生产效率提高近百倍，该钢现仍在使用。20 世纪末，又成功研制出新型高强、高韧、可焊、耐磨的系列准贝氏体钢，既具有原贝氏体钢优异的热加工性能，又超过原贝氏体和回火马氏体钢的综合力学性能，故被列入国家科委“九五”《国家级科技成果重点推广项目》，并在矿山、石油、铁路等工业部门得到应用。在国内外期刊和会议上发表论文“In-situ observation of bainite growth during isothermal holding”（*Acta Materialia*，2006，54，2124）等 350 余篇，出版教材《钢及其热处理》等 2 部和专著《钢中贝氏体》等 3 部。其中不少为国外著名（SCI，EI）索引录用，被国内外同行论著引用约 600 余篇次。获全国科学大会奖（1978 年）和国家发明二等奖（1985 年）及省部级科技进步奖等 16 项。为表彰他的科学研究成就，“何梁何利基金”评委会授予他 1999 年“科学与技术进步奖”，中国热处理学会授于他“周志宏奖励基金”第一届“科学成就奖”（1999 年）。

在65年的教学生涯中，他亲自培养博士生40余人，硕士生20余人，本科生千余人，桃李遍天下。他的诸多弟子和学生已成为院士、博士导师、教授、研究院院长、工厂厂长、总工程师及国内外著名学者，在高等学校、科研院所、工厂企业乃至国家机关都已是栋梁之才，材料界诸多领域的领军人物和中坚力量。

# 目　　录

# 一、贝氏体相变动力学(含预贝氏体相变)及组织形貌学

# On the Prebainitic Phenomenon in Some Alloys

M.K. KANG, Y.Q. YANG, Q.M. WEI, Q.M. YANG, and X.K. MENG

The prebainitic phenomenon in several copper alloys and ferrous alloys was investigated by means of internal friction measurement and composition analysis. The internal friction peaks of zinc or carbon atoms diffusion in $\beta$ brasses or in austenite of ferrous alloys, respectively, were related to the zinc or carbon-depleted region formation within the bainitic incubation period observed by composition analysis. The possibility of bainite shear nucleation in solute atoms' depleted regions, formed by diffusing of solute atoms to a certain level, was pointed out.

## I. INTRODUCTION

THE prebainitic phenomenon is one of the important subjects of bainitic transformation which has been greatly debated. In the 1930s, Kurjumov[1] pointed out that carbon-depleted austenite can form during the incubation period of steels holding at medium temperature and then the austenite transforms into ferrite. In the 1940s, a similar view was suggested by Klier and Lyman.[2] The existence of the carbon-depleted region in austenite was confirmed indirectly by the X-ray method by Entin[3] in the 1960s and with the method of ultrasonics[4] and high-temperature X-ray diffraction[5] in the 1970s. However, Aaronson *et al.*[6] thought it impossible to decompose the austenite into carbon-depleted and rich regions, *i.e.*, spinodal decomposition, according to their thermodynamic calculation. Hsu *et al.*[7] showed indirectly by means of internal friction that it is a soft mode nucleation process of bainite in the incubation period. Garwood[8] and Takezawa and Sato[9] proposed that the bainite in $\beta$ brasses can form in the zinc-depleted region by shear. Feng *et al.*[10] pointed out that many defects exist in austenite and that, by Monte-Carlo simulation, the carbon-depleted region appears in austenite during the incubation period and then bainite forms by shear in that region. Although the prebainitic phenomenon is an important aspect of understanding the mechanism of bainite formation, the description of solute atoms' behavior in the bainitic transformation, the direct measurement of the composition change during bainitic incubation period, and direct observation of the nucleation site are scarce at present. Thus, it is necessary to study these phenomena in detail.

M.K. KANG, Professor, and X.K. MENG, Ph.D., are with the Department of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an, 710072, People's Republic of China. Y.Q. YANG, Q.M. WEI, and Q.M. YANG, formerly Ph.D. Candidates with Northwestern Polytechnical University, are Postdoctoral Researchers, Nanjing University, Nanjing, 21008, Beijing University of Science and Technology, Beijing, 10085, and Zhejiang University, Hangzhou, 310027, respectively, People's Republic of China.

This article is based on a presentation made at the Pacific Rim Conference on the "Roles of Shear and Diffusion in the Formation of Plate-Shaped Transformation Products," held December 18–22, 1992, in Kona, Hawaii, under the auspices of ASM INTERNATIONAL's Phase Transformations Committee.

## II. EXPERIMENT

The tested $\beta$ brasses were prepared by melting high-purity Cu and Zn or Cu, Zn, and Al in a graphite crucible, respectively, and casting into ingots with diameters of 80 mm, followed by homogenizing at 1073 K for 48 hours and forging into rods of 20-mm and 10-mm diameter, respectively. The composition is Cu-42.85Zn (weight percent) and Cu-26.84Zn-4.22Al (weight percent). The specimens for internal friction measurement with a dimension of 1 × 1 × 60 mm and for metallography were cut from the rods. These specimens were betanized in a molten salt bath at 1063 K for 2 minutes and then quenched into water to obtain ordered $\beta'$ or a nitrite-nitrate salt bath holding at 523 K for 20 minutes (Cu-Zn) or for 4 minutes (Cu-Zn-Al) within the incubation period and, hence, also obtaining $\beta'$. No bainite was observed by using an optical microscope or a transmission electron microscope (TEM).

The composition of tested steels is shown in Table I. In addition to commercial 9CrSi, the steels were molten in a vacuum arc furnace and cast into ingots. After homogenizing the steel at 1423 K for 72 hours and then forging it into rods, specimen 2 # and 4 # for internal friction measurement were made from the rods and heat-treated in vacuum-packed quartz tubes at 1423 K for 10 hours and then quenched into water. The microstructure of so-treated specimens is austenite at room temperature. Some of the specimens austenitized in a salt bath at 1423 K for 20 minutes were then quenched in water to obtain an austenitic structure or held at 573 K for 25 minutes, at which the bainite incubation period is as long as 4 hours. No decomposition product in austempering was found using an optical microscope or a TEM. The specimens of 9CrSi for composition analysis were homogenized at 1423 K for 84 hours, followed by austenizing in a salt bath at 1223 K for 20 minutes, and were then quenched in water; the microstructure is a mixture of martensite and austenite. Other specimens were austempered at 553 K for 400 seconds, at which the bainitic incubation period is 1000 seconds,[11] and then quenched in water; this microstructure is also a mixture of martensite and austenite.

Internal friction measurements were carried out in an inverted torsion pendulum controlled by computer. The frequency range is 0.57 to 2.0 Hz. The carbon content

**Table I. Chemical Composition of Tested Steels (Weight Percent)**

| Alloy | C | Mn | Si | Cr |
|---|---|---|---|---|
| 2# | 1.96 | 3.69 | 0.37 | — |
| 4# | 1.75 | 3.69 | 0.37 | — |
| 5# | 1.24 | 3.06 | — | — |
| 9CrSi | 0.89 | 0.043 | 1.47 | 1.15 |

in steels was measured by a PHILIPS* 595 scanning Auger Micro-Probe, and the composition change in $\beta$ brasses was measured by a Hitachi H-800 TEM under transmission-scanning mode (STEM) and an EDAX* PV9100 energy dispersion spectrometer.

*PHILIPS and EDAX are trademarks of Philips Electronics Instruments Corp., Mahwah, NJ.

## III. RESULTS AND ANALYSIS

### A. *The Experimental Results of Internal Friction*

Figures 1 and 2 are the experimental results of internal friction for Cu-Zn and Cu-Zn-Al, respectively. Internal friction peaks appear near 473 K. They are of relaxation type, because the peak temperature increases as the frequency increases and it is independent of heating rate. The same results were obtained for specimens 2 # and 4 # of steels, as shown in Figures 3 and 4. The peak temperature ($T$) and associated frequency ($f$) are shown in Table II.

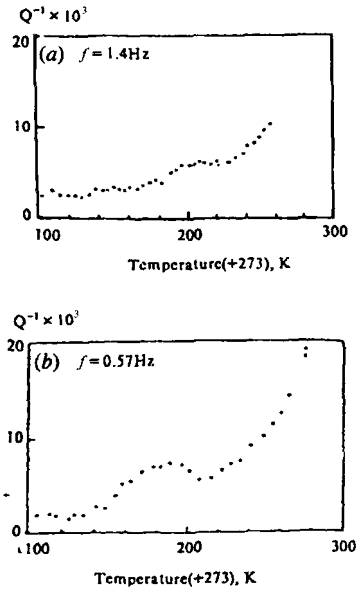


Fig. 1—The internal friction of Cu-Zn alloy.

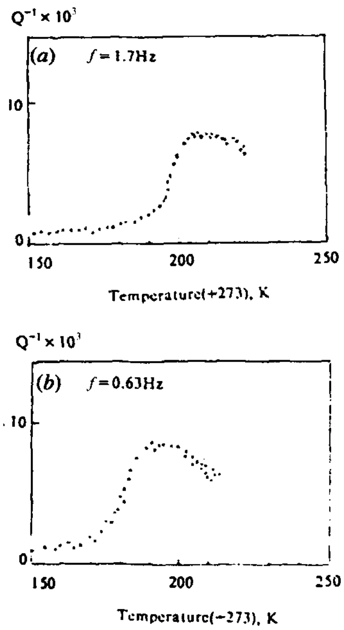


Fig. 2—The internal friction of Cu-Zn-Al alloy.

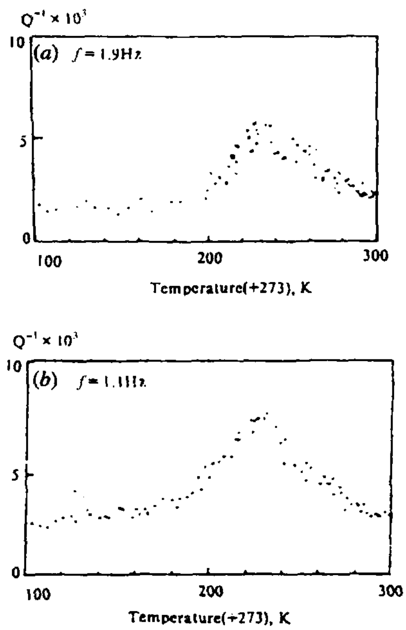


Fig. 3—The internal friction of steel 2#.

*B. The Calculation of Activation Energy*

The activation energy, $Q$, is calculated with the equation[12]

$$Q = \frac{RT_1T_2}{(T_2 - T_1)} \ln\left(\frac{f_2}{f_1}\right) \qquad [1]$$

where $R$ is the universal gas constant, $f_1$ and $f_2$ are the frequencies, and $T_1$ and $T_2$ are peak temperatures. The activation energy of Cu-Zn alloy is 115.27 KJ/mol and that of Cu-Zn-Al alloy is 115.87 KJ/mol, which are similar to the diffusion activation energy of zinc atoms in ordered $\beta$ brass.[13] It is evident that the internal friction peaks are induced by the diffusion of zinc atoms in ordered $\beta$ brasses. That the activation energy of specimens 2 # and 4 # of steels is 117.21 KJ/mol, similar to the diffusion activation energy of carbon atoms in austenite,[14] shows that the internal friction peak is induced by the diffusion of carbon in austenite.[15]

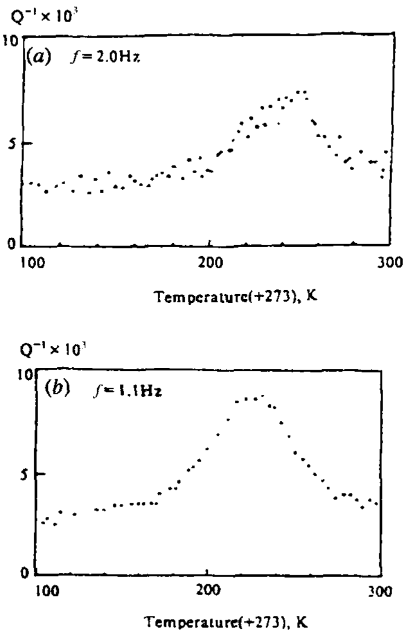


Fig. 4—The internal friction of steel 4#.

**Table II. Peak Temperature ($T$) of Internal Friction and Frequency ($f$) of Some Tested Alloys**

| Alloy | $T$ (K) | $f$ (Hz) |
|---|---|---|
| Cu-Zn | 479 | 1.4 |
| | 465 | 0.57 |
| Cu-Zn-Al | 478 | 1.70 |
| | 463 | 0.63 |
| 2# | 508 | 1.9 |
| | 499 | 1.1 |
| 4# | 509 | 2.0 |
| | 497 | 1.1 |

The width of the internal friction peaks mentioned earlier is larger than that of the Debye relaxation peak, and the shape of the peaks is not symmetric. This kind of internal friction peak is similar to that caused by segregation or precipitation of solute atoms.[16]

C. *Composition Measurement Results*

In order to show directly the composition change within the incubation period of bainite, the composition measurements and comparisons of austempered specimens with those of quenched specimens were conducted.

Figures 5 and 6 show the solute distribution of quenched and austempered specimens in Cu-Zn and Cu-Zn-Al alloys, respectively. Obviously, solute atoms distribute homogeneously in quenched specimens (Figures 5(a) and 6(a)), but there exist solute atoms in the depleted and rich regions in austempered specimens within the incubation period, as shown in Figures 5(b) and 6(b). The carbon atomic-depleted and rich regions are also formed in austenite in steels within the bainitic incubation period. The distribution curves of carbon atoms in quenched and austempered specimens are shown in Figures 7 and 8. The results indicate that there is (1) a very small fluctuation of the carbon content in quenched specimens and (2) a large fluctuation of the carbon content in austempered specimens because of the formation of the carbon-depleted region and rich region.

The results mentioned earlier show that the phenomena of solute atom depletion and richness appear because

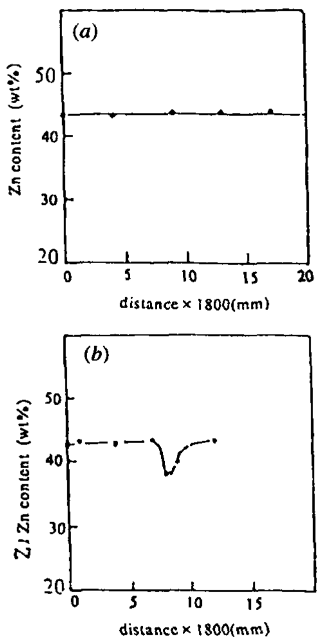


Fig. 5—The distribution of Zn content in Cu-Zn alloy: (*a*) quenched and (*b*) austempered at 523 K for 20 min.