

PAPER • OPEN ACCESS

Relationship between strain stored by compressive deformation and crystallographic orientation in a pure aluminum

To cite this article: Y Takayama *et al* 2015 *IOP Conf. Ser.: Mater. Sci. Eng.* **82** 012029

View the [article online](#) for updates and enhancements.

You may also like

- [Change in intragranular misorientation during stress relaxation in Al-Cu-Mg-Mn alloy subjected to continuous cyclic bending](#)
Takumi Hoshino, Kouki Miura, Yoshimasa Takayama et al.
- [Characteristics of terahertz waves from laser-created plasma with an external electric field](#)
T. Fukuda, T. P. Otsuka, T. Kobayashi et al.
- [Spin injection effect in thin Bi2212 single crystal](#)
Kenichiro Murata, Kazuto Otaka, Kazuhiro Yamaki et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Relationship between strain stored by compressive deformation and crystallographic orientation in a pure aluminum

Y Takayama¹, T Yoshimura² and H Watanabe¹

¹Department of Mechanical and Intelligent Engineering, Graduate School of Engineering, Utsunomiya University, Utsunomiya 321-8585, Japan

²Graduate Student, Utsunomiya University, Utsunomiya 321-8585, Japan
E-mail: takayama@cc.utsunomiya-u.ac.jp

Abstract. In order to investigate relationship between stored strain and crystallographic orientation, 99.99% purity aluminum cubes were compressed with uniaxial or with plane strain state up to a nominal strain of 30%. The aluminum cubes were examined on the same surface before and after compression by SEM/EBSD technique. Stored strain was estimated by Kernel Average Misorientation (KAM) derived from the EBSD analysis, and Taylor factor (TF) was measured before the compressive deformation. The analysis revealed that KAM value or the stored strain decreases until a certain value of TF and then increases with increment of TF.

1. Introduction

Recrystallization textures developed during annealing are governed by the energy stored in deformation state. It is well known that the stored energy depends on crystallographic orientation [1]. Alternatively, this is the reason why the recrystallization texture forms. Several attempts have been made to evaluate the stored energy by calorimetric [2, 3] and diffraction techniques [4-12]. The latter technique is divided into two types. One is the basic method [4-8] in which X-ray line broadening is measured to obtain the stored energy in grains having specific orientations, for example (100) plane parallel to the rolling plane in the sample. Another is the extended method [9-12] which was used to determine the stored energy for a much wider space described by the orientation distribution function. Using the extended method, Kallend and Huang, Gerber *et.al* [9, 12], Rajmohan *et.al* [10] and Rajmohan and Szpunar [11] carried out the measurement of the stored energy in copper, interstitial free steel and can body aluminum alloy after rolling. They also investigated the relation between the stored energy and the Taylor factor (TF) [13] which shows the total slip system activity expected during the deformation of a grain of specific orientation. Although the stored energy increases with an increase in Taylor factor, the obtained results indicated some exceptions and a lot of scatter. It was understood that these exceptions and the scatter were attributed to the rotation of the grain orientation to the final one and the inhomogeneity of the deformation. Takayama and Szpunar [14] performed the evaluation of the stored energy from the kernel average misorientation (KAM) on electron backscatter diffraction analysis in scanning electron microscopy (SEM/EBSD) to investigate the relation between the stored energy and Taylor factor in an Al-Mg-Mn alloy sheet worked by the continuous cyclic bending (CCB). Their analysis revealed that the stored energy is high for the high TF region, whereas a significant increase of the stored energy with the decrease of the Taylor factor appears in the vicinity of the minimum TF value of 2.



This paper presents the relationship between the stored energy and Taylor factor in aluminum subjected to compression with uniaxial or with plane strain state by using SEM/EBSD analysis.

2. Experimental procedure

A hot-rolled plate of 4N purity aluminum (99.99% Al) with a 12mm thickness was prepared through a process of DC casting, forging, annealing and hot-rolling at 673K. Cubic specimens with all edges of 10mm were made from the plate as each edge is respectively parallel to rolling direction (RD), transverse direction (TD) or normal direction (ND).

Specimens were compressed in uniaxial or plane strain compression (PSC) until a strain of about 20% or 30% at ambient temperature with measurement of load and displacement. The two kinds of PSCs, ND-RD and ND-TD were conducted as compression in ND and elongation in RD and TD, respectively. The Teflon sheet was inserted for lubrication between the specimen and the upper and lower dies. Analyzed surface was mechanically and electrochemically polished before compression.

SEM/EBSD analysis was carried out on the same area of $1000\mu\text{m} \times 1000\mu\text{m}$ with a step size of 5 or 10 μm before and after compression.

3. Results and discussion

3.1. Load-displacement curves

Figure 1 displays load-displacement curves during compression at ambient temperature. The compressive load becomes higher in order of uniaxial, ND-RD and ND-TD as shown in the figure. PSC shows the higher flow stress and is subjected to larger strain energy because it is accompanied with higher constraint of deformation compared with uniaxial compression. Thus, ND-TD PSC is larger in strain energy than ND-RD.

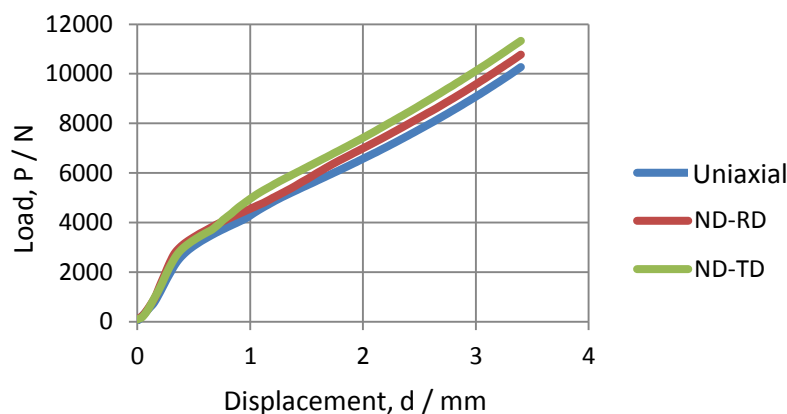


Fig. 1 Load-displacement curves during uniaxial and plane strain compression test.

3.2 Change in microstructure after compression

Changes in microstructure before and after uniaxial compression in ND until a strain of 20% and 30% are shown by inverse pole figure (IPF) maps in Fig. 2. For both specimens black-rectangular area in the map before compression corresponds to the analyzed area after compression. Comparison between the maps before and after compression reveals change in grain orientation and local deformation in grain interior. Grain rotation angles with compression were measured as 5.5 and 10.7 degrees in average for 20% and 30% compressed specimens, respectively. Moreover, a part of grains are found to approach a stable orientation ND//<101> in compression. An obvious grain subdivision in which a grain is divided into plural ones is observed in 30% compressed specimen.

Figure 3 shows IPF maps before and after PSC until a strain of 20% and 30% and kernel average misorientation (KAM) maps corresponding to stored strain of deformed materials. Remarkable changes in grain orientation or color over the IPF maps are observed in the PSCed specimens compared with uniaxially compressed ones. In the figures <111>//ND

oriented (blue) grains change into $\langle 101 \rangle // \text{ND}$ oriented (green) while $\langle 001 \rangle // \text{ND}$ oriented (red) grains approach to $\langle 101 \rangle // \text{ND}$ via $\langle 103 \rangle // \text{ND}$ (orange) and $\langle 102 \rangle // \text{ND}$ (yellow). In ND-RD30 specimen a drastic grain subdivision, in which a $\langle 111 \rangle // \text{ND}$ grain was divided into three differently oriented grains with large change in orientation. As a result of orientation analysis, the grain subdivision likely occurred with active slips on different slip planes $(1\bar{1}\bar{1})$, $(\bar{1}\bar{1}1)$ and $(\bar{1}1\bar{1})$ for the $[111] // \text{ND}$ grain.

The KAM maps at the bottom of the figure indicate that stored strain concentrates near the grain boundaries in all of compressed specimens. It should be noted that grains with less strain exist. Near $\langle 001 \rangle // \text{ND}$ grains tend to gain less strain. This is probably related to orientations and misorientations of individual grain and neighboring ones. Mean KAMs were calculated to be 1.14, 1.33, 1.13 and 1.78 for ND30, ND-RD30, ND-TD20 and ND-TD30, respectively. This result is consistent with order of the applied load during compression test.

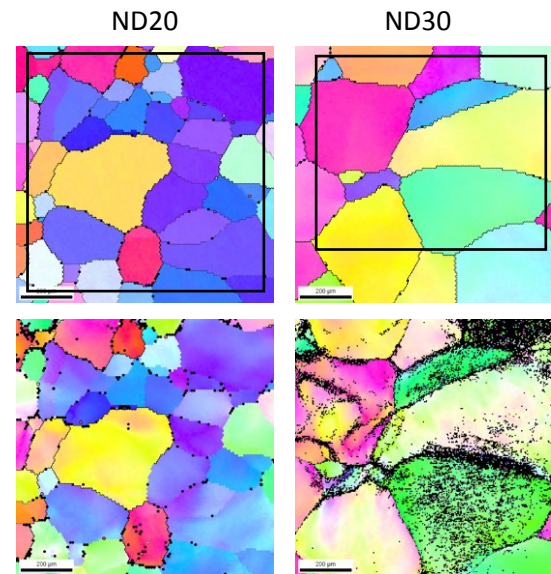


Fig. 2 Microstructures before and after uniaxial compression up to 20 and 30%. Top and bottom maps are before and after compression, respectively.

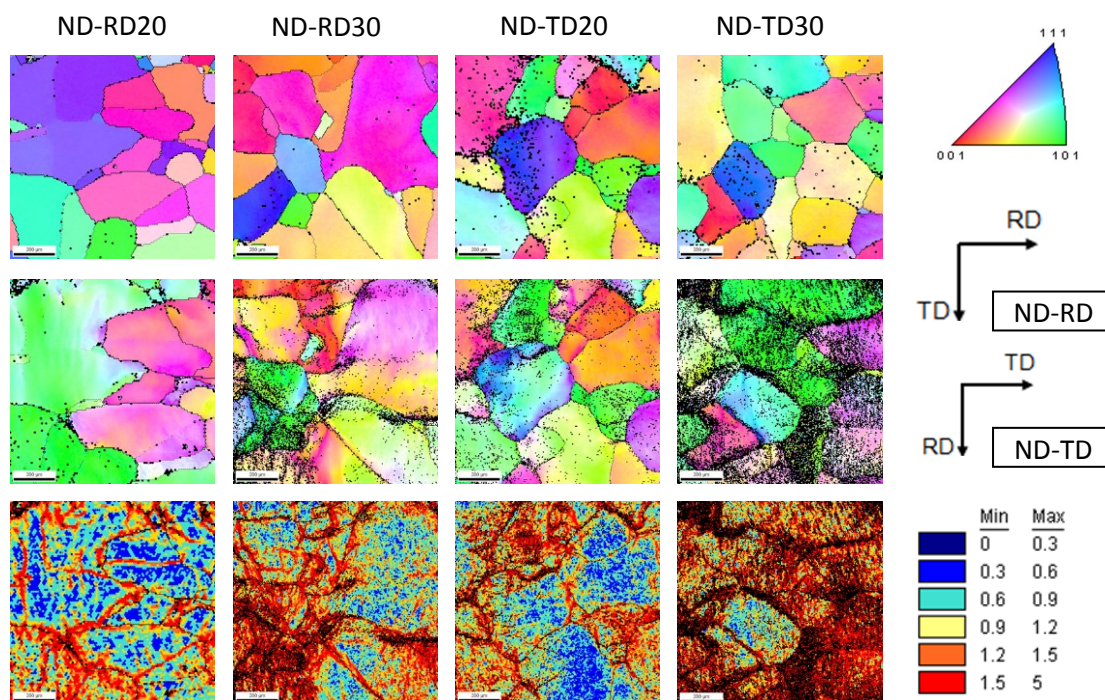


Fig. 3 Microstructures before and after PSC up to 20 and 30%. Top and middle maps are before and after compression, respectively. Bottom maps are kernel average misorientation (KAM) ones after PSC.

3.3 Relationship between KAM and Taylor factor

According to Taylor model [13], orientation before deformation should govern summation of shear strain. KAM after compression was investigated relating to TF before compression.

Figure 4 shows relationship between mean KAM after compression and Taylor factor before compression for the compressed specimens. Mean KAM was calculated for the specimens subjected to uniaxial compression and PSC up to the same strain level of 20% and 30%. TOTAL refers to mean KAM value for both strain level in each range of TF. As shown in the figure, KAM value decreases until a certain value of TF and then increases with increment of TF. TF for minimum KAM is a lower value of 2.75 at a strain level of 30% while it is 3.75 at 20%. TF dependence of KAM obtained here is good agreement with the previous result in Al-Mg-Mn alloy subjected to continuous cyclic bending [14].

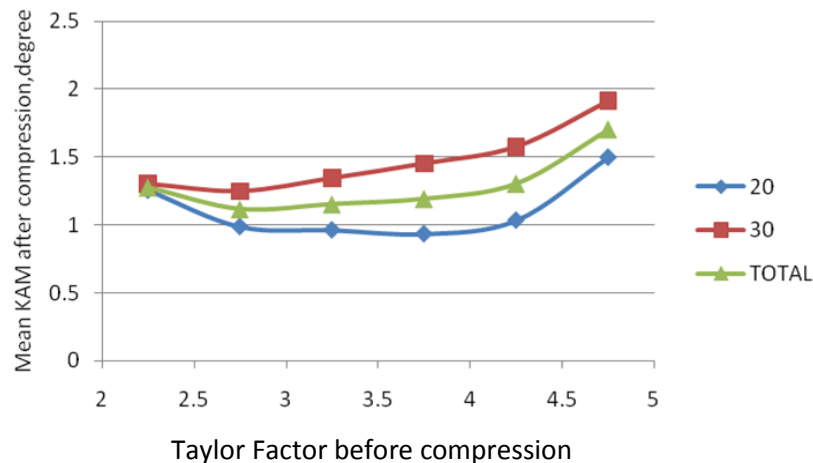


Fig. 4 Relationship between mean KAM after compression and Taylor factor before compression for specimens with the same strain level.

Summary

In order to investigate relationship between stored strain and crystallographic orientation, 99.99% purity aluminum cubes were compressed with uniaxial or with plane strain state up to a nominal strain of 30%. The aluminum cubes were examined on the same surface before and after compression by SEM/EBSD technique. After uniaxial compression a part of grains approached a stable orientation ND//<101>. Remarkable changes in grain orientation from <111>//ND or <001>//ND into ND//<101> were observed in the PSCed specimens compared with uniaxially compressed ones. Stored strain was estimated by Kernel Average Misorientation (KAM) derived from the EBSD data, and Taylor factor (TF) was measured before the compressive deformation. The analysis revealed that KAM value or the stored strain decreases until a certain value of TF and then increases with increment of TF.

References

- [1] W.B. Hutchinson: *Int. Metals Rev.*, 29(1984), 25-42.
- [2] B.L. Averbach, M.B. Bever, M.F. Comerford & J.S. Leach: *Acta Metall.*, 4 (1956), 477-484.
- [3] H.U. Astron: *Acta Metall.*, 3 (1955), 508-509.
- [4] M. Matsuo, S. Hayami and S. Nagashima: *Adv. X-ray Anal.*, 14 (1971), 214-230.
- [5] H. Takechi, H. Katoh and S. Nagashima: *Trans. Metall. AIME*, 242 (1968), 56-65.
- [6] R.L. Every and M. Hartherly: *Texture*, 1 (1974), 183-194.
- [7] G. Mohamed and B. Bacroix: *Acta Mater.* 48 (2000) 3295-3302.
- [8] G. Guiglionda, A. Borbely, J.H. Driver: *Acta Mater.*, 52 (2004) 3413-3423.
- [9] J.S. Kalland and Y.C. Huang: *Metal Sci.*, 18 (1984), 381-385.
- [10] N. Rajmohan, Y. Hayakawa, J.A. Szpunar & J.H. Root: *Acta Mater.*, 45(1997), 2485-2494.
- [11] N. Rajmohan and J.A. Szpunar: *Mater. Sci. Tech.*, 15 (1999), 1259-1265.
- [12] Ph. Gerber, J. Tarasiuk, Th. Chauveau and B. Bacroix: *Acta Mater.*, 51 (2003), 6359-6371.
- [13] G.I. Taylor: *J. Inst. Met.*, 62 (1938), 307-324.
- [14] Y. Takayama and J.A. Szpunar: *Mater. Trans.*, 45 (2004), 2316-2325.