Materials Physics and Mechanics 47 (2021) 59-64 Received: December 4, 2020

JUMPING AT STRAIN RECOVERY IN SHAPE MEMORY Cu-Al-Ni SINGLE CRYSTALS

V.I. Nikolaev*, R.B. Timashov, S.A. Pulnev, L.I. Guzilova, P.N. Butenko, S.I. Stepanov

Ioffe Institute, Polytechnicheskaya 26, St. Petersburg, 194021, Russian Federation

*e-mail: nikolaev.v@mail.ioffe.ru

Abstract. Shape memory Cu-Al-Ni single crystals of two alloy compositions Cu 82.5 wt.% - Al 13.5 wt.% - Ni 4.0 wt.% and Cu 81.98 wt.% - Al 14.02 wt.% - Ni 4.0 wt.% have been studied in view of their ability to undergo spontaneous jumping during reverse martensitic transformation. Crystals of both alloys were compressively deformed up to a full shape memory strain (8%) at room temperature. It was found that specimens of the first alloy with martensite structure jumped higher and demonstrated better reproducibility in cyclic tests. The height of the jump strongly depended on thermal pre-treatment and was unaffected by the strain rate during pre-strain by compression and the heating rate at shape recovery.

Keywords: shape memory, shape memory effect, SM, shape memory alloys, SMA, single crystals, strain recovery, jumping

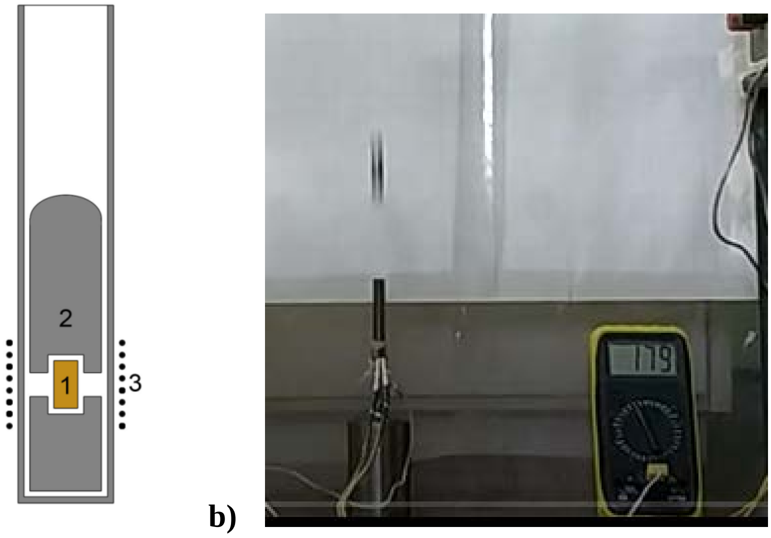
1. Introduction

The effect of spontaneous jumping in shape memory alloys (SMA) crystals looks very attractive for high-speed robotic applications. This strong effect has been observed for the first time by us in shape memory $Ni_{49}Fe_{18}Ga_{27}Co_6$ single crystals [1]. Compressively pre-strained crystals of this alloy spontaneously jump upon heating. The estimated initial velocity of the crystal can reach 22 m/s. Later this effect was discovered in some other SMA crystals [2,3]. All these crystals restore the original shape almost instantly in a very narrow temperature range (burst-like recovery) [4].

From the point of view of technical applications, SMA crystals can be employed in actuators. For efficient operation in devices, the crystal must demonstrate good reproducibility of its motion. However, the cycling operation of "jumping" crystals has not been studied in much detail. There are only a few publications considering the cyclic performance of SMA single crystals [5-6].

In this paper, we study SMA single crystals of two different compositions and initial structures. The first alloy was composed of Cu 82.5 wt.% - Al 13.5 wt.% - Ni 4.0 wt.% (Alloy 1) and had the martensitic structure with M_s = 335K. The second alloy was composed of Cu 81.98 wt.% - Al 14.02 wt.% - Ni 4.0 wt.% (Alloy 2) and had the austenitic structure with M_s = 253K. Both alloys are well-known SMA crystals and have been widely investigated from the point of view of their structural, calorimetric, and thermo-mechanical properties [7-9]. This study is focused on the improvement of the jumping effect in Cu-Al-Ni single crystals. The influence of the initial heat treatment, pre-strain rate under compression loading, and heating rate upon strain recovery on the jump height was investigated.

http://dx.doi.org/10.18149/MPM.4712021_6



a) b)

Fig. 1. Schematic diagram of the experimental setup: (1) specimen, (2) additional load, (3) heater (a); photo of the experimental setup with a temperature controller at the moment of a jump

2. Materials and Methods

Cu-Al-Ni single crystals of both alloys (Alloy 1 and Alloy 2) were grown from the melt by the Stepanov technique [10]. The crystals were orientated along [001] direction. As-grown crystals were of high structural quality and had precisely defined shapes and smooth side surfaces. The crystals used in this study were of cylindrical shape with a diameter of D = 5 mm. The specimens about 10 mm in length were cut out of the crystals by spark erosion. Afterwards, the specimens were annealed at various temperatures in the range of 1120-1263 K for 15 min and quenched in water at room temperature. All specimens were compressively pre-strained to a full shape memory strain along [001] which was over 8%. The deformation was performed at room temperature by Instron 1342 testing machine at various strain rates ranging from 5×10^{-4} s^{-1} to 1 s^{-1}. The pre-strained crystals had an oriented martensitic structure with β' (18R) and γ'(2H) martensitic phases [8].

Then the specimens were placed in the experimental setup shown in Fig. 1a and heated above the transformation temperature A_s. In most cases, this resulted in the burst-like shape recovery accompanied by jumping of the sample. The shape memory recovery process was registered by a high speed (120fps) video camera. Additional weight of 30g was placed on top of the specimen (Fig.1b). To compare, the own weight of the SMA crystal was only about 1.5g. The extra weight was used to limit the velocity and the height of the jump of the sample so it can be captured by the video camera. The initial specimen velocity was calculated from the video recording.

3. Results and discussion

Figure 2 shows stress-strain (σ–ε) curves at uniaxial compression for Alloy 1 (solid line) and Alloy 2 (dashed line) crystals after quenching in water from 1233 K to room temperature. Both curves have a similar shape, they are relatively smooth and do not exhibit any abrupt stress drops similar to those that were previously observed in Alloy 1 crystals quenched at 1120 K and pre-strained at a temperature above 300 K [8]. No changes were found in these curves after shape memory cycling (over 60 cycles of the load to full SM and heating for strain recovery).

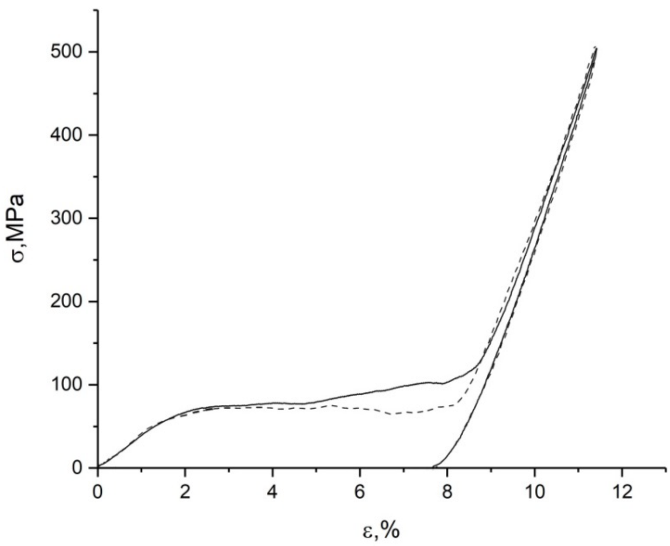
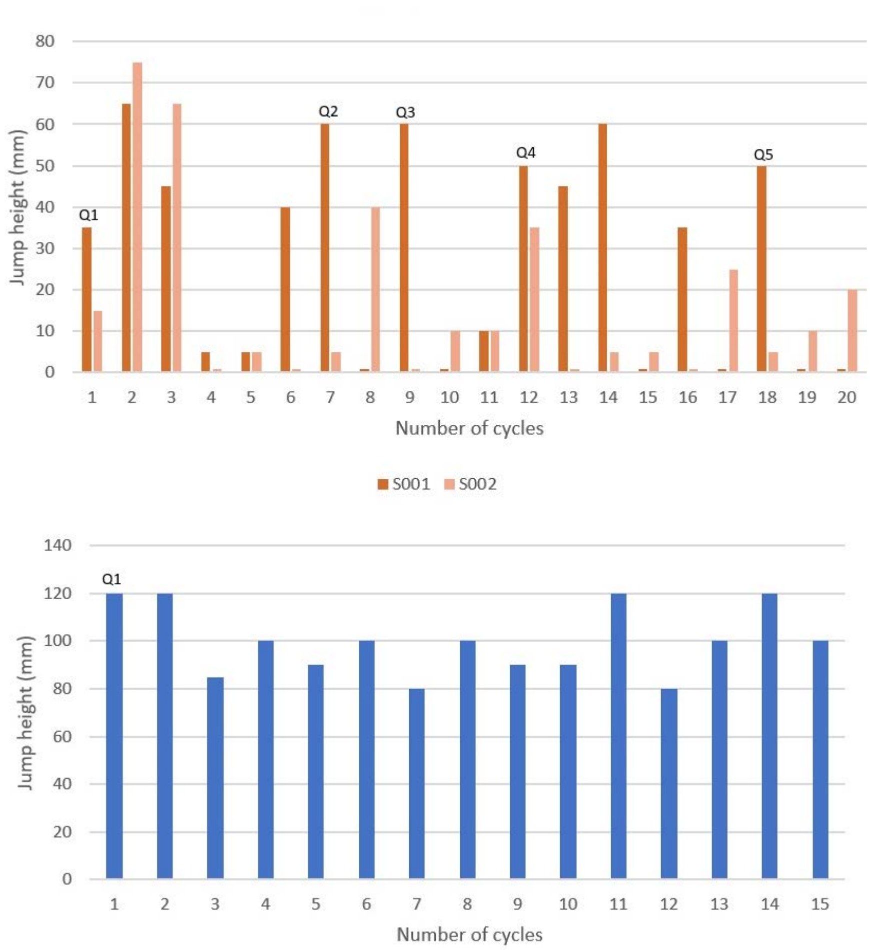


Fig. 2. Stress-strain curves for Alloy 1 (solid line) and Alloy 2 (dashed line) SMA crystals under uniaxial compression along [100] at 293 K



a)

b)

Fig. 3. The height of the jump during cyclic testing; (a) for austenitic Alloy 2 single crystals (sample S001 and sample S002) and (b) for martensitic Alloy 1 single crystal. All crystals were water quenched from 1223 K to room temperature and deformed to the full shape memory strain of about 8%

In order to initiate the shape recovery process, the specimens were heated under the same conditions using the setup shown in Fig. 1. Jumping was observed both for austenitic Alloy 2 (two different samples: S001 and S002) (see Fig. 3a) and martensitic Alloy 1 crystals (see Fig. 3b). However, the height of the jump was 1.5-2 times higher for the martensitic alloy. In addition, as reported in our previous paper [9], the austenitic Alloy 2 exhibited poorer reproducibility during cycle testing. The jumping ability of these crystals degraded after each cycle.

The jumping ability of Alloy 2 crystals can be improved by additional quenching after every 2-7 cycles. These samples are denoted as Q1-Q5 in Fig. 3; the number after Q corresponds to the number of quenches. One can see, that Alloy 2 crystals with additional quenching repeatedly exhibited higher jumps, although the results were unstable. In contrast to that, Alloy 1 crystals exhibited much steadier performance. After single quenching before the first cycle, these crystals exhibited a steady jumping effect with initial velocity up to 30 m/s

For that reason, all further experiments were conducted using the martensitic alloy crystals (Alloy 1). The effects of quenching temperature, strain rate, and heating rate were investigated. It was found that the jumping effect strongly depends on the quenching temperature. For the crystals quenched at 1120 K we observed only a slight motion of the specimen. It should be mentioned that Picornell et al. [7] did observe spontaneous jumping under the same set of experimental conditions. In fact, this was the first mention of jumping SMA crystals in literature, although no data on jumping characteristics were provided. In contrast, we observed jumping only for specimens quenched at temperatures above 1173K (Fig. 4).

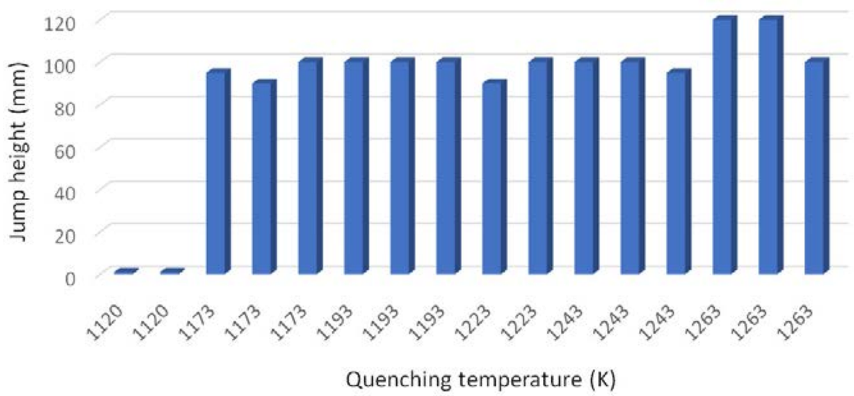


Fig. 4. The height of the jump versus quenching temperature for Alloy 1 single crystals

We investigated the influence of pre-strain deformation rate on the jumping and found that there is no effect in the range of 5×10^{-4} – 1 s^{-1} (Fig. 5). That is a very interesting observation because it shows that pre-straining can be performed very rapidly e.g. by impact deformation.

The martensitic specimens were heated at various heating rates ranging from 0.07K/s to 0.95 K/s. It was found that the jumping effect was insensitive to the heating rate. This result can be also considered as an advantage for applications in fast actuators.

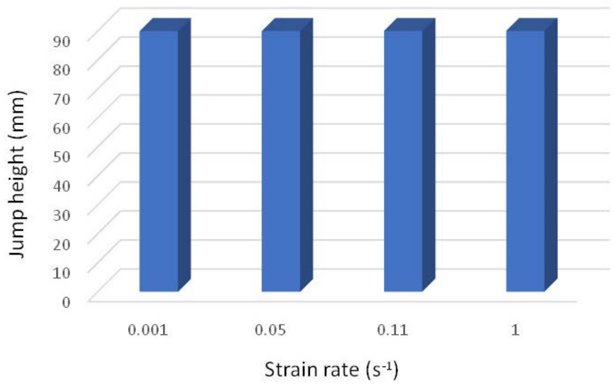


Fig. 5. The height of the jump versus loading rate for Alloy 1 single crystals

4. Summary

Jumping effect in Cu-Al-Ni SMA single crystals with initial martensitic and austenitic structures has been studied. It has been demonstrated that Cu 82.5 wt.% - Al 13.5 wt.% - Ni 4.0 wt.% alloy with initial martensitic structure outperforms Cu 81.98 wt.% - Al 14.02 wt.% - Ni 4.0 wt.% alloy with the initial austenitic structure in terms of magnitude and reproducibility of the jumping effect. The jumping effect strongly depends on quenching temperature and is insensitive to pre-strain rate and heating rate at strain recovery.

Acknowledgments. *The work is supported by Russian Science Foundation, Russia [grant number 16-19-00129]*.

Declaration of Competing Interest. *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

References

[1] Nikolaev VI, Yakushev PN, Malygin GA, Pul'nev SA. Burst character of thermoelastic shape memory deformation in ferromagnetic Ni-Fe-Ga-Co alloy. *Technical Physics Letters.* 2010;36: 914-917.

[2] Nikolaev VI, Yakushev PN, Malygin GA, Averkin AI, Chikiryaka AV, Pulnev SA. The burst character of thermoelastic shape-memory deformation in crystals of Cu-Al-Ni alloys. *Technical Physics Letters*. 2014;40: 123-125.

[3] Yang S, Omori T, Wang C, Liu Y, Nagasako M, Ruan J, Kainuma R, Ishida K, Liu X. A jumping shape memory alloy under heat. *Scientific Reports*. 2016;6: 21754.

[4] Zhao D, Xiao F, Nie Z, Cong D, Sun W, Liu J. Burst-like superelasticity and elastocaloric effect in [011] oriented $Ni_{50}Fe_{19}Ga_{27}Co_4$ single crystals. *Scripta Materialia*. 2018;149: 6-10.

[5] Picornell C, Pons J, Paulsen A, Frenzel J, Kaminskii V, Sapozhnikov K, Van Humbeeck J, Kustov S. Burst-like reverse martensitic transformation during heating, cooling and under isothermal conditions in stabilized Ni-Ti-Nb. *Scripta Materialia.* 2020;180: 23-28.

[6] Panchenko EY, Timofeeva EE, Chumlyakov YI, Osipovich KS, Tagiltsev AI, Gerstein G, Maier HJ. Compressive shape memory actuation response of stress-induced martensite aged $Ni_{51}Fe_{18}Ga_{27}Co_4$ single crystals. *Materials Science & Engineering A.* 2019;746: 448-455.

[7] Picornell C, Pons J, Cesari E. Stabilisation of martensite by applying compressive stress in Cu-Al-Ni single crystals. *Acta mater.* 2001;49(20): 4221-4230.

[8] Picornell C, Pons J, Cesari E. Stress–temperature relationship in Cu–Al–Ni single crystals in compression mode. *Materials Science and Engineering: A*. 2004;378(1-2): 222-226.

[9] Guzilova LI, Nikolaev VI, Yakushev PN, Stepanov SI, Timashov RB, Chikiryaka AV, Pulnev SA. Burst-like shape memory recovery and calometric effect in Cu-Al-Ni alloy single crystals at cyclic test. *Materials Physics and Mechanics*. 2020;46(1): 42-49.
[10] Antonov PI, Kurlov VN. A review of developments in shaped crystal growth of sapphire by the Stepanov and related techniques. *Progress in Crystal Growth and Characterization of Materials*. 2002;44(2): 63-123.