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# REVERSE SPRINGBACK: A CURIOUS MANIFESTATION OF THERMOELASTICITY

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**Abstract**—A new and rather unexpected phenomenon has been observed in the shape memory alloy, Cu–Al–Ni: a strip, having previously been plastically deformed, springs spontaneously to an even greater deformation strain when the deforming forces are removed—a reverse, elastic springback, opposite in direction to the expected movement. The effect is produced by cooling through $M_d$ (the temperature at which martensite can first be stress induced) while constraining the material in the deformation geometry. The effect is caused by a transformation momentum: the martensitic transformation, having been oriented in the early stages by the constraining forces, continues to transform in the same biased manner, even after the constraining geometry has been fully achieved and the constraining stress relaxed.

**Résumé**—Un nouveau et inattendu fenomène a été observé dans l'alliage a effets de memoire, Cu–Al–Ni: une tranche, qui avait été préalablement deformee plastiquement, retourne spontanément vers une plus grande deformation quand les forces appliquées sont enlevées—un retour elastique inverse, en direction opposee au mouvement qu'on pourrait s'attendre. On produit cet effet en refroidissant à travers $M_d$ (la temperature à laquelle la martensite peut pour la premiere fois etre produite par des contraintes) pendant qu'on retient le materiel dans la geometrie deformée. L'effet se doit à un élan de transformation: la transformation martensitique, ayant été orientée au commencement par les forces retenantes, continue sa transformation orientée meme après la geometrie retenue avoir été complètement achevée et al contrainte imposée relaxée.

**Zusammenfassung**—Ein neues, unerwartetes Phänomen wurde in der Formgedächtnislegierung CuAlNi beobachtet: ein vorher plastisch verformter Streifen springt nach Entlastung spontan zurück zu einem Radius, der einer grösseren Dehnung als der ursprünglich eingebrachten entspricht—ein umgekehrtes, elastisches Zurückfedern in einer Richtung, die der erwarteten Bewegung entgegengesetzt ist. Der Effekt wird verursacht durch Passieren der $M_d$-Temperatur beim Abkühlen (der Temperatur, bei der die Martensitbildung durch Anlegen einer Spannung induziert werden kann), wobei der Probekörper in seinem ursprünglichen, verformten Zustand festgehalten wird. Der Effekt wird verursacht durch die treibende Kraft der Phasenumwandlung: die Martensitbildung, durch die einwirkende äussere Kraft in eine bevorzugte Orientierung gezwungen, setzt sich in der gleichen Vorzugsorientierung fort, selbst nachdem die erzwungene Geometrie erreicht ist und somit die orientierungsbestimmenden Spannungen dadurch abgebaut sind.

## INTRODUCTION

If one were to plastically bend an initially flat strip to some well-defined curvature, one would naturally expect an elastic springback, or partial straightening, to occur when the bending load is released. But imagine instead a material that spontaneously bends to an even tighter curvature when released—in essence, a "reverse springback". The implication would seemingly be that the original total deformation is partitioned into the usual plastic and elastic parts, but with a plastic contribution greater than the total, and an elastic contribution of a negative sense. Such a situation may be difficult to rationalize, but is nevertheless exactly what is observed in Cu–Al–Ni strips cooled from the austenitic state through $M_d$ while constrained in the deformed geometry.

As will be shown, the reverse springback effect is quite small, but can be arrived at through several different routes. Although the effect is of no apparent practical value, it is undoubtedly of some scientific value in the sense that it demonstrates some interesting new characteristics of thermoelastic transformations. The purpose of this paper is first to present evidence for the effect, and then to propose a qualitative mechanism for its occurrence. As will be seen, the effect can be explained in terms of a transformation momentum argument; that is, by considering that the stress-directed austenite-to-martensite transformation continues transforming in a biased manner even though the stress originally responsible for the transformation biasing is completely removed.

### *The Cu–Al–Ni alloy*

The material used in this study contained, by weight, 14.2% Al and 3.3% Ni. This particular alloy was originally developed for high temperature shape memory applications [1], and was produced by blending, cold compacting, sintering, and hot rolling three pre-alloyed powders of different composition. The powder manufacturing route was chosen to enhance

Table 1. Tensile properties of Cu–Al–Ni powder alloy

| Temperature (°C) | Yield strength (MPa) | Ultimate tensile strength (MPa) | Elongation to failure (%) |
|---|---|---|---|
| 20 | 520 | 900 | 6.0 |
| 200 | 480 | 530 | 7.0 |

the ductility of the alloy, which is rather brittle in the cast condition. The tensile properties of the alloy at both room temperature and at 200°C are shown in Table 1.

The alloy naturally exhibits a powerful one-way shape memory effect and essentially no two-way, or reverse, effect (as is typical of $\beta$-brass memory alloys); a two-way effect can be induced, however, by inhomogeneously precipitating a bainite layer [1]. The transformation temperatures of the alloy are quite sensitive to aluminium content; the transformation temperatures of the alloy used in this particular study were: $A_s = 90$, $A_f = 95$, $M_s = 75$ and $M_f = 70$°C.

The structures of the Cu–Al–Ni alloy system are complex, but have recently been studied in depth [2–4]. Briefly, the austenitic phase, denoted $\beta_1$, has the ordered $DO_3$ structure, and decomposes martensitically on cooling to any one of a number of martensite structures, depending upon the temperature, stress-state, and exact composition of the alloy; all of the martensite structures—$\beta_1'$ (18R), $\beta_1''$ (M18R), $\gamma_1'$ (2H), and $\alpha_1'$ (6R)—can be constructed by different stacking sequences of the $(1\ 1\ 0)\beta_1$ planes.

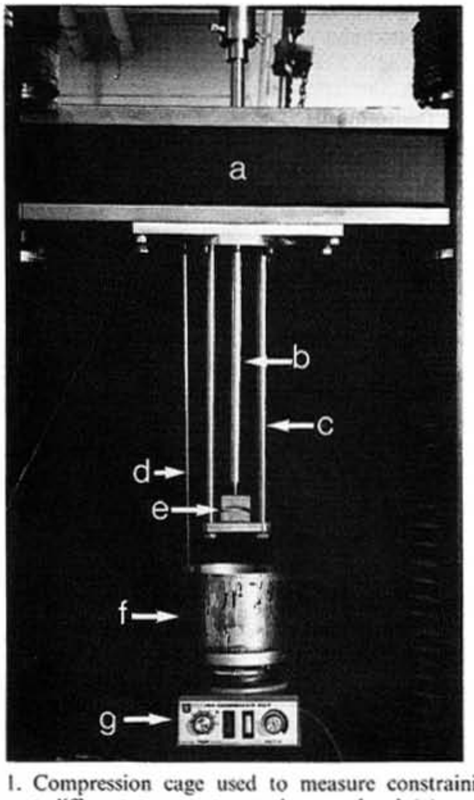


Fig. 1. Compression cage used to measure constraining forces at different temperatures: the crosshead (a), compression rod passing through the crosshead (b), compression cage attached to the crosshead (c), thermocouple (d), bending dies and specimen (e), oil bath (f), and hot plate (g).

## EXPERIMENTAL

Hot rolled strips of 2.5 mm thickness and 2.5 mm width were solution treated at 900°C for 30 min, water quenched, and then deformed between steel dies of various accurately defined curvatures; to correct for the specimen thickness, the concave dies had radii of curvature 2.5 mm larger than the convex. In most cases the pressing loads were applied using a specially designed pair of pliers, similar in construction to vice-grips. With this arrangement, pressing could be done in various media, such as hot oil or molten salt.

A few specimens were deformed in a mechanical screw Instron tensile testing machine. The objective, in these cases, was to deform to some fixed curvature, and then to measure the force necessary to constrain the specimen in that fixed geometry during heating and cooling cycles. The fixturing arrangement used for these tests is shown in Fig. 1. The chief advantages of using such a compression cage are that stresses and strains due to thermal expansion are self-canceling and that the entire cage can be inserted into an oil bath to insure homogeneous and accurate temperature control.

## RESULTS

A "normal" springback was observed when the strips were cold bent and then immediately released from the dies: a springback, for example, from a 40 mm radius of curvature to a 55 mm radius of curvature. The "reverse springback" phenomenon was observed in three major variations, meaning that three quite distinct treatments were found to produce the effect: cold deformation and constrained austenization, hot deformation and constrained cooling, and constrained ageing. They will be described separately and in this order.

### *Cold deformation and constrained austenization*

Figure 2 demonstrates the reverse springback in the form in which it was first discovered. The originally flat strip was bent at room temperature to an inside radius of 40 mm (corresponding to an inside radius strain of 3.03%). After deformation, the dies and specimens were placed in a molten salt bath at 250°C for a few minutes (until the temperature equilibrated) and then cooled again to room temperature (usually by quenching, but the effect was found to be independent of cooling rate). The dies were then opened, the specimen removed, and its curvature measured by comparing with templets of various radii. Of the more than 30 specimens deformed and measured in this fashion, all showed

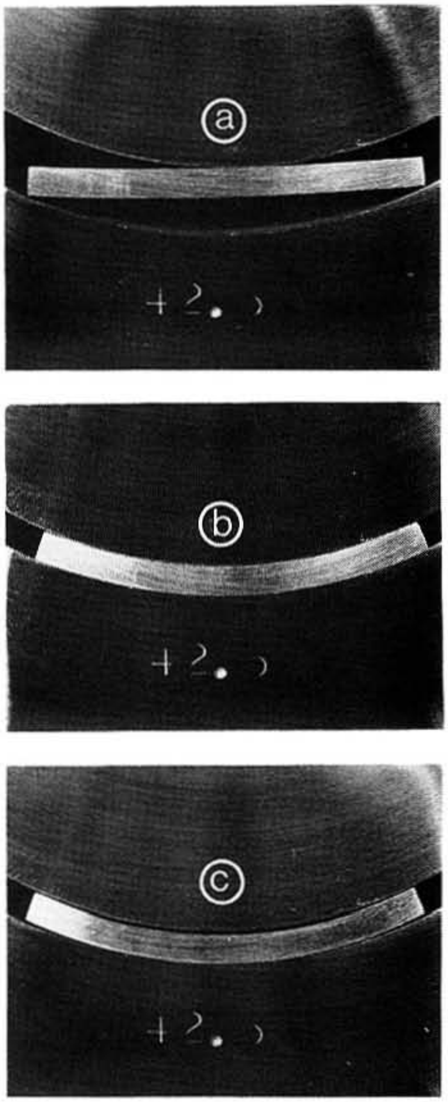


Fig. 2. The reverse springback as it was originally observed: the original flat strip is shown in (a) just prior to bending and constraint, (b) shows the same strip constrained to a 40 mm inside radius of curvature, and (c) shows the strip shape after cooling from 300°C and releasing.

smaller radii of curvature after release than that imposed during the original deformation. In the example shown in Fig. 2, the reverse springback was from an original radius of 40 mm, to a radius of 37 mm; all tests, in fact, carried out in such a manner resulted in the same degree of springback (to within our abilities to measure radii changes). Based on the strains on the inside specimen radii, this correlates to a springback from 3.03 to 3.28%, or a strain difference of 0.25%. Though the effect is small, it is quite unmistakeable in its direction, and very reproducible.

### *Hot deformation and constrained cooling*

A still more direct manifestation of the effect can be observed by hot deforming. In this case, the specimens were gently pinched between the dies—with a force insufficient to cause deformation—and then inserted into a salt bath a 250°C. When the strip and dies were equilibrated to 250°C, the dies were tightly closed and the specimen deformed. Immediately following deformation, the dies and specimens were withdrawn, cooled to room temperatue and measured. The radii of several strips were measured in this manner, and the springback results were identical to those presented above: a reverse springback of roughly 0.25%.

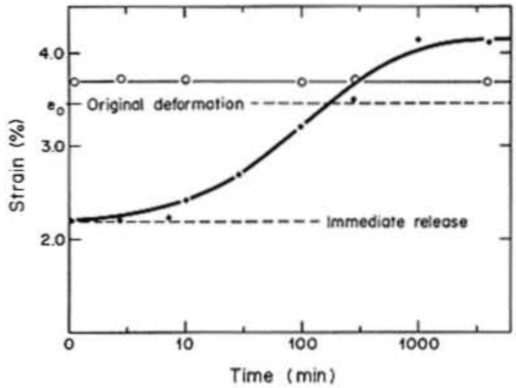


Fig. 3. The curvature of Cu–Al–Ni strips after heating to 250°C, deforming, and then ageing for various times while constraining to $e_0$. The closed symbols correspond to specimens which were hot released and then cooled, and the open symbols are measurements after constrained cooling.

Before proceeding to the last and most dramatic variation of reverse springback, it is appropriate to shortly discuss how variations in the above treatment parameters influence the effect. The radius to which the strip is originally bent seems to be irrelevant to the effect. Any bending strain leaving a measurable permanent strain without excessively cracking the specimen was found to produce the effect, and the magnitude of the effect appears to be constant. The temperature of the austenization or hot pressing is also largely irrelevant as long as the temperature was above 200°C. Temperatures above 400°C were not tested. The time at temperature was also found to be independent of the effect. Holding times as short as 10 s, and as long as 5000 min were tested both at 250° and 300°C with no variation in the observed springback (see open symbols in Fig. 3). The implication is that the only critical operation is the action of cooling through $M_s$ and $M_f$ while constrained; how a specimen arrives in the austenitic state, how long it is kept there, and where in the austenitic phase field the specimen is held, all seem to be irrelevant.

### *Constrained ageing*

In apparent contradiction to the above concluding comment, the last and most dramatic example of the reverse springback phenomenon occurs when the alloy is hot deformed (or cold deformed and austenitized), aged while constrained in the deformed

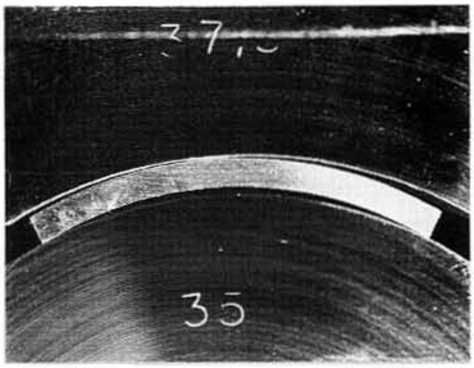


Fig. 4. The most dramatic example of reverse springback, shown after a flat strip was bent to a 35 mm inside radius of curvature, aged for 1000 min at 300° while constrained to this shape, released while hot, and then cooled slowly to room temperature.

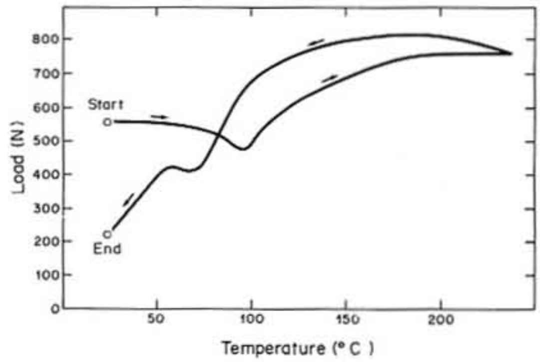


Fig. 5. Force required to constrain an initially flat element to a 60 mm radius of curvature shown as a function of temperature (heating and cooling).

geometry, and then released from the dies while still hot. The strip initially straightens when released, but during subsequent cooling adopts a curvature notable sharper than the original bend. This is exemplified in Fig. 4. In this case, an initially flat strip was heated to 250°C and bent to a curvature of 35 mm (3.45% deformation); the strip and dies were kept closed for 1000 min and then opened while still at 250°C. The strip curvature measured immediately after opening the dies (still at 250°C) was measured approximately as 60 mm (2.04%). After cooling to room temperature, the strip curvature was again measured, and found to be 28.5 mm (4.23%). Thus the strain at the inside radius of the released strip was 0.78% greater than that of the original deformation. Figure 3 compares the final strip curvature with that of the deformation dies. Contrary to the first two variations, constrained ageing is distinctly an isothermal process, meaning that the effect is strongly dependent upon ageing time (see solid symbols in Fig. 3), and temperature.

*Force-temperature measurements*

The existence of reverse springback implies that at some point during the cooling process, the zero-stress shape of the strips must have been exactly that of the die—passing from a lesser curvature in the austenitic phase field to a greater curvature in the martensitic regime. In order to identify this temperature, strips were cold deformed to a 60 mm radius using the compression cage described above, then slowly heated to 250°C (in a heated oil bath) while monitoring the load necessary to constrain the specimen to this curvature radius. After reaching 250°C, the oil bath was slowly cooled—again while monitoring load. It should be noted that the load train was rather long, and that there was quite a bit of elastic strain stored in it. Thus even though the element may inflect, one should not realistically expect to observe a zero load during the element inflection since elastic compressive stresses will always be present in the load train. Moreover, as a result of this large system elasticity, one should not expect quantitatively meaningful force values. One should nevertheless expect to observe an inflection in the load-temperature curve, and the temperature of the inflection should be meaningful.

Four experiments were conducted in the above manner with remarkably similar results; only the temperatures at which the various events and inflections occurred were slightly different. The result of one such experiment is shown in Fig. 5. Upon heating, an initial decrease in the load required to constrain the specimen shape was observed, with the minimum load occurring at the measured $A_s$ temperature (95°C). During continued heating, the force increased rather sharply, and then leveled off, presumably delineating the completion of the martensite-to-austenite transformation. During the cooling cycle, a small increase in load was first observed, followed by a rather steep decrease. The origins of the initial increase are not clear, although all tests exhibited this increase. The decline in constraining force at 125°–150°C presumably corresponds to the alloys's $M_d$ temperature (the temperature on cooling at which it becomes possible to stress induce the martensitic transformation). During

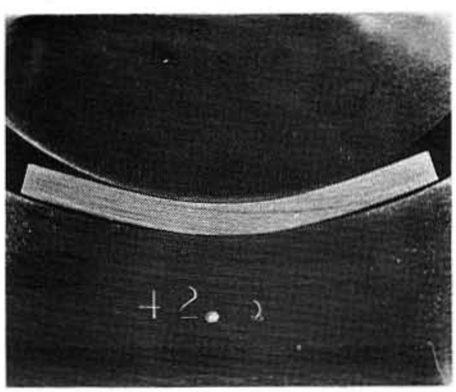

Fig. 6. Reverse springback after bending between unmatched dies—in essence, three-point bending.

further cooling, an upward inflection in the constraining force was observed. This, presumably, was a result of the geometrical inflection of the element. The same force inflection was observed in all four specimens, but at slightly different temperatures. Following the inflection and second force maximum, a second decrease in force was observed, indicating continued stress relaxation. Although continued relaxation is not unexpected, the inflection stress should be the minimum, and it apparently is not. The reason for this is not clear, but one explanation would be the zero-stress shape is not achieved at exactly the same temperature along the length of the element, and a true zero-stress shape never achieved. After cooling to room temperature, the specimens were unloaded, removed, and confirmed to have undergone a negative springback: from 60 mm to approximately 53 mm (0.29%).

## DISCUSSION

By employing a bending mode of deformation and by bending between circular forms, nearly all springback artifacts are avoided: thermal expansion and contraction can be ignored, volumetric effects of possible phase transformations can be ignored, and all the possible complications of three- and four-point bending are avoided. Thus the effect is undoubtedly real, and obviously related to the thermoelastic nature of the material. Furthermore, the effect does not necessitate any isothermal transformation, as evidenced by the fact that the first two variations presented above are time, and to a large extent, temperature independent. (The third variation was shown to have isothermal characteristics.) For the same reasons, it is evident that the effect in the first two cases does not simply consist of a stress relaxation to the die shape, followed by a reverse, or two-way, shape memory effect; a stress relaxation phenomenon would be time and temperature dependent. Moreover, according to current mechanistic understanding, the two-way effect develops from the residual stresses present after deformation [5,6], and these stresses could never encourage movement beyond the original deformation. This final argument against attributing the effect to a conventional two-way memory movement applies in the third, isothermal variation as well.

We will now present a viable proposal for the mechanism of reverse springback as it pertains to the first two variations. It may appear, at first, that the proposals even contradict the observation of the third variation, but as will be discussed later, the mechanism acting in the third variation is very likely identical to the first two—only somewhat better camouflaged.

Confining ourselves then to the first two variations, the action critical to obtaining the effect is evidently the constrained transformation to martensite during constrained cooling. In both variations, the elements are constrained in their deformed geometries while in the austenitic state, and then cooled. As the elements are cooled below $M_d$, only certain variants of martensite begin to form—those which accommodate the constrained shape and relieve the external stress (Fig. 5). The constrained geometry is apparently fully assumed before the $M_f$ is reached, this means that the bending stresses on the elements can be fully relieved without fully transforming the austenitic matrix. (This assumption is, incidently, supported by the observation of perfect one-way shape memory effects at far higher strain levels.) So at the point of complete relaxation, the structure must consist of favorably oriented martensite plates in an austenitic matrix.

As cooling continues towards $M_f$, the transformation continues, but in the absence of any direction from external stresses; so in principle, the new martensite plates should be randomly oriented, producing no further strains or stresses. The observation of a reverse springback, however, indicates that the transformation continues preferentially, transforming with the same directionality developed earlier. The reason for this continued transformation biasing is most likely that the austenite-to-martensite transformation proceeds more readily by growing the plates that already exist than by nucleating new plates, and the extant plates have already developed a distinct orientation. Alternatively, one could argue that the biasing is a result of an autocatalytic nucleation process, in which orientation of subsequent nucleation events are influenced by the strain fields of the plates already present. No matter which influence is dominant, it is clear that *the transformation, once started in a biased manner, proceeds in a biased manner even after the driving force is removed;* the transformation develops a directional momentum, overshooting the original zero-stress level and actually generates a stress of its own. The new stress, opposite to the original in sense, then begins to influence the transformation by encouraging the formation of martensite variants, opposite in orientation to the original. Thus the magnitude of the reverse springback is limited when deforming between closed dies.

The above proposal explains all observations regarding the first two variations presented above: the temperature independence, the time invariance, and the strain invariance. Moreover, the model is in qualitative agreement with the force measurements of Fig. 5. Stress relaxation begins during cooling at 150°C, which would seem to be a reasonable $M_d$ value. The inflection occurs at 70°C, just as the $M_f$ temperature is reached. As further verification, an element was hot deformed between a convex die of radius 27 mm, and a concave die of radius 42.5 mm, the objective being to restrain movement only in one direction and providing free space in which to "springback" to higher deformations. Since the bending was, in essence, a three-point bending, the strip was deformed irregularly along its length, i.e. there was no well defined curvature. Nevertheless, a substantial reverse springback was observed after cooling to room temperature, and although not quantifiable, the springback was qualitatively larger than the fully constrained case (see Fig. 6)—especially when one considers that the deformation and springback are very localized, and produced by a relatively small part of the specimen.

The third and most dramatic variation of reverse springback, constrained ageing and hot release, can be explained by folding the above arguments together with the existence of a bainitic transformation. The presence of stress assisted bainitic types of transformations in thermoelastic systems has now been demonstrated in at least three different alloy systems: Cu–Zn–Al [7, 8], Ti–10V–2Fe–3Al [9], and most importantly, in Cu–Al–Ni [1]. Moreover, strips of Cu–Al–Ni have been aged while constrained in a bent geometry, and bainite has been observed to precipitate preferentially at the two surfaces (where the stresses were highest). The effect of the bainite transformation has been shown to be to relax the stresses preferentially at the surfaces. In Ref. [1], it was shown that this preferential stress relaxation creates a stress imbalance which can be used to induce a two-way, or reverse, memory effect.

In our case, when the strip is released the austenitic center exerts a stress tending to straighten the strip, but is countered by the strip surfaces, which have permanently assumed the constrained geometry. Clearly the longer the strip is aged under constraint, the more dominant is the influence of the bainite relaxation: thus the strip assumes the constrained geometry. More to the point, the bainitic layers apply a constraining force on the untransformed austenite center just as if the external constraint were still there (though clearly the constraint is not as rigid). Even though the external constraint is removed, the martensite transformation is begun in a biased manner, just as in the first two variations, and again the transformation continues beyond the original deformation strain. Further, as in the example of Fig. 6, the transformation is permitted to overshoot the original deformation strain by a much larger amount, since the element is externally free.

Finally, it would be remiss not to point out that the third variation can be explained by another, similar mechanism. The bainitic structure of the $\beta$-brass alloys has been shown to be quite similar to the martensite structure, both being based on stackings of $(1\ 1\ 0)\beta$ planes [7]. It may be that the martensite transformation is influenced by the extant bainite at the strip surfaces, and as the bainite develops with a distinct accommodating orientation, so does the martensite.

## CONCLUSIONS

Evidence has been presented establishing the existence of a reverse springback effect. Although the alloy in which the effect was found was a shape memory alloy, the effect was quite clearly not simply a reverse, or two-way effect. Instead, the observation was attributed to the tendency of the thermoelastic transformation to continue in a directionally biased manner even after the stress originally responsible for the biasing is completely removed—in essence, a transformational momentum. In principle, the effect could be found in any thermoelastic system, depending upon the balance of nucleation and growth kinetics of the particular system: the effect should be found in cases where the nucleation of new martensite plates is relatively difficult.

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