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Ensuring the proper end-of-life dismantling of spacecraft/ Satellites using CuAlNi memory alloys:

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ABSTRACT

According to the American association: Union of Concerned Scientists (UCS), 2,666 active satellites dedicated to earth observation were orbiting around our planet in March 2020. Among the active satellites listed by the UCS, the operational lifespan varies from 1 to 20 years. The time until atmospheric re-entry depends on the altitude of the spacecraft and can vary from 6 months (low orbit) to several years (geostationary satellites).

The rise of debris formation in orbit is increasingly jeopardizing the sustainable operation of spacecrafts and asks for policy measures to ensure spacecraft demise after their end of life. A satellite that is insufficiently disintegrated after atmospheric re-entry can cause impact damage on Earth.

The study presented here focuses on the possibility to break a satellite into smaller fragments during atmospheric re-entry from LEO orbit. Considering the mission life and time needed to de-orbit the satellite, the overall timeframe of at least 30 years is assumed for a functional device. Depending on size of the satellite, between four to several dozen separation devices are considered necessary on a single satellite for efficient fragmentation.

Current technologies either use the programmed explosion of pyrotechnic charges, which exhibit sensitivity to chemical changes, or employ technologies based on the use of low melting point alloys, these last are sensitive to creep and fail at functioning at high temperature. These systems are not reliable after a long period in space. We suggest introducing separation devices based on shape memory alloy (SMA) actuators that present the following advantages:

- Temperature control
- Ability to function further away from the melting point, which makes it a reliable device
- Less sensitivity to creep

These shape memory alloys are capable of inducing a significant reversible deformation or a recovery force upon thermal trigger, thanks to the martensitic transformation induced by a thermomechanical loading, and can be designed as passive* separation device during re-entry. The properties of these SMAs have been used for the development of innovative applications in various fields such as civil engineering, automotive, aeronautics, aerospace

CONTEXT

Shape memory alloys (SMAs) are materials whose reputation has continued to grow in recent decades, especially since their classification among the smart materials. SMAs owe their properties to a well-known phase transformation of metallurgists which is martensitic transformation. The Shape Memory Effect (SME) appears as a shear causing a change in structure without any displacement relative of atoms. This transformation, generated in the material, can under the effect of temperature variation (or stress) lead to memorized shapes of the material at high or low temperature.

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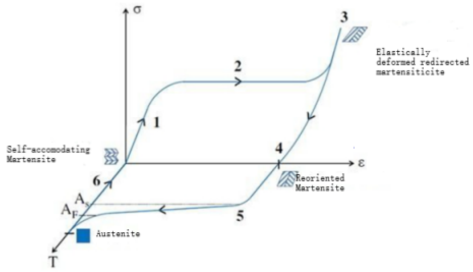


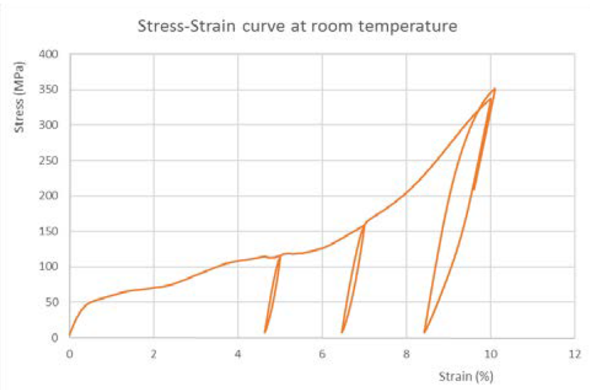
Figure 1: Schematic representation of the memory effect

Ni-Ti alloys are widely used in aerospace applications. These alloys have a maximum qualified functional temperature of 80 ° C, i.e. a margin of 30 ° C, with respect to the maximum transformation point.

More recently, Cu-Al-Ni alloys have already been selected for aerospace applications and offer possibilities at transformation points up to 250°C. These alloys are also under qualification for low-lifetime applications.

By definition, these materials are out of equilibrium; their properties continue to evolve after their formation as they try to reach approach equilibrium, i.e., they exhibit an inherent challenge for long-term stability.

The manufacturing process of single crystal alloy is patented for Nimesis, it has several qualities that are advantageous for space use: As stated before, its activation temperature is higher (-200 to +250°C) than traditional Ni-Ti (0 to 100 ° C). This is higher than commonly encountered in space, and thus gives the guarantee of not being activated in an undesirable manner (while avoiding thermal control problems).



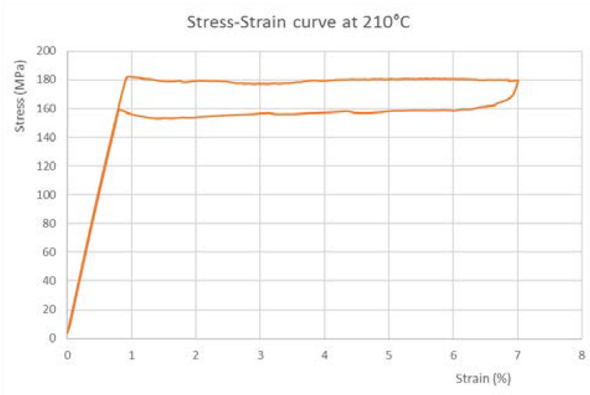


Figure 2: Tensile tests of Cu-Al-Ni single crystal samples at room temperature (martensitic state) (a) and at 210°C (austenitic state) (b)

In addition, Cu-Al-Ni generates more displacement than Ni-Ti alloys, greatly reducing the mass and size of actuators at equal performance compared to competing products, and are therefore particularly suitable for nanosatellites and Cubesats, including competitive costs of the alloy.

PURPOSE OF THE STUDY

Cu-Al-Ni alloys, distinguished by their reasonable cost, and their reliability, have a handicap regarding their sensitivity to thermal aging. The combined action of stress with temperature can lead to the complete deterioration of the shape memory effect. These effects are notably detected on the points of direct and inverse martensitic transformation, or even the complete inhibition of the transformation following the thermomechanical cycles.

Aging of SMAs results from the combined action of temperature and stress; it corresponds to an often-irreversible evolution of the properties of the material, and its study requires complex, multi-physical and multi-scale approaches.

Difficulties related to the experimental characterization of aging phenomena (type of test, type of conditioning, type of specimen), the determination of acceleration conditions of these tests and the "measurement" of the

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lifespans of the SMAs are what gives the research in this field a greater potential, and a higher contribution to the space field.

The Cu-Al-Ni alloy has a β phase, stable at high temperature, capable to transform, by quenching, into martensite. Among the copper base alloys, it is the most stable thermally.

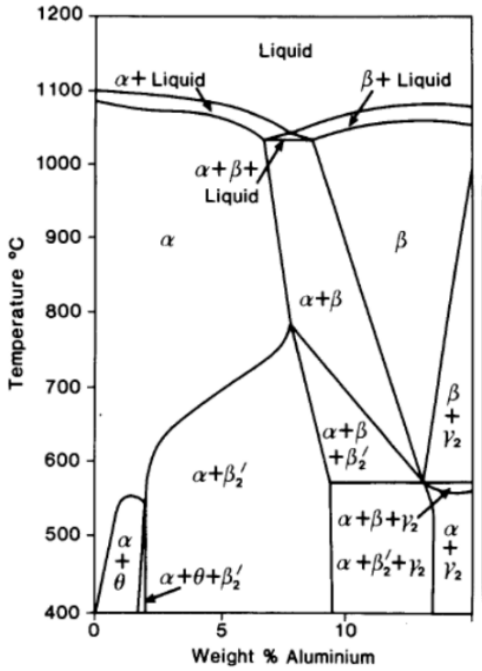

Figure3: Vertical section of Cu-Al-Ni system at 3wt

Original: in: W.O. Alexander, J. Inst. Met., 1938, 63, 163

The main interest of these alloys from a technological point of view is their possible use at temperatures close to 250 ° C, which gives them an advantage over Ni-Ti alloys whose maximum working temperature is limited to 100 ° C. The main problem to be solved, is to ensure the reliability of Cu-Al-Ni alloys at high temperature, that is to determine the limit of stability of the austenitic and martensite metastable phases, in order to avoid the precipitation of stable phases. The main goal will be to accelerate the aging by building an equivalence model of time and temperature.

For these alloys, the stability limit of the quenched austenitic phase was established by Recarte when studying the kinetics of precipitation during isothermal aging at different temperatures between 400 ° and 482 ° C by dilatometry.

Due to the necessary aging time to obtain isothermal kinetics at lower temperatures such as 300 ° C, the results obtained in dilatometry were analyzed using the Johnson-Mhel-equation Avrami, for which the microstructural parameters that control precipitation and ordering have been determined.

While the aging of the austenitic phase has been widely studied in the literature, the same does not apply to the mechanisms that lead to the stabilisation of the martensitic phase.

Martensitic transformation leads to the appearance of interfaces between the two phases: austenite and martensite, but also between the martensite variants appearing in the sample.

The stabilisation of martensite refers to all the phenomenas that lead to irregularities during the reverse martensitic transformation.

It essentially manifests itself by the increase in the temperature of the reverse transformation towards high temperatures and a decrease in the quantity of martensite transformed during the reverse transformation, and sometimes even by the fact that the reverse transformation is more or less completely inhibited with a loss of the shape memory effect. This phenomenon has been studied by several authors with different characterization techniques: resistivity measurement, acoustic emission, friction interior, differential calorimetry, electron microscopy and X-ray diffraction.

Scarbrook and al. Benchiheub, who have studied the effect of thermal cycling under stress in simultaneous measurements of electrical resistivity and strain based on the temperature.

For low stresses (30 MPa) good reversibility of the inverse transformation is observed while a pronounced reversion difficulty appears for

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greater stresses (80 MPa), with an offset of the reverse transformation points towards high temperatures.

This stabilisation generally results from the trapping of the interfaces between the variants of martensite by quenching vacancies, and a structural evolution of the martensitic phase.

To limit this stabilization phenomenon, it is recommended to carry out a stepped hardening or income after quenching. In fact, after the thermal processing of homogenization, quenching causes the appearance of supersaturated deficiencies. Immediately after quenching, it eliminates these deficiencies and provides a cleanup that delays stabilization.

OUR SOLUTION

It appears in the literature that aging in the martensitic phase under constant stress has hardly been studied and, only for a short period of time. Understanding it is the key to ensuring the control of very long-term properties. Furthermore, the cost of the chosen alloy for this project, and its multiple purposes whether for small or large constellations makes it an even more adequate selection.

Our latest development, an actuator called MURPHY reacts to the increase of heat, suitable to the temperature within the atmospheric re-entry.

We offer to use such components to deorbit and demise a satellite or launcher in a passive way. This dedicated range of passive actuators is proposed for the dismantlement of satellites structures. These last are designed to sustain 30 years on orbit, and upon thermal initiation during re-entry, triggering the fragmentation of spacecrafts into smaller parts, easier to disintegrate. It will be implemented as a passive system that will be activated just as the temperature increases: the temperature is adjustable to meet the needs of the industry and to target a specific altitude of dismantlement. So that the system will only be activated with an atmospheric re-entry.

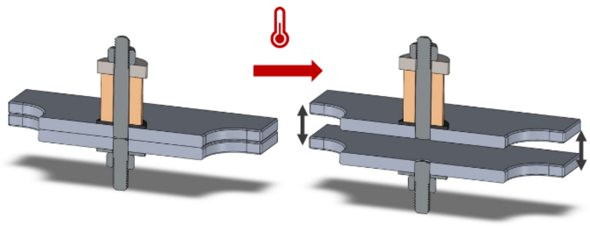

Figure 4: concept of a Murphy actuator for the dismantlement of a structure

TECHNICAL DATA OF MURPHY

Fastener size	M2	M3	M4	M5	M6	M8	M10	M12
External diameter (m)	5,1	7,8	10,3	13,1	15,6	21	26,5	32,1
Internal diameter (mm)	2,3	3,3	4,4	5,4	6,5	8,5	10,8	13,2
Length (mm)	10,0	11,0	13,8	16,9	20,9	26,9	33,4	40,6
Maximum preload (N)	1265	3165	5482	8973	12659	23237	37002	53954
Fracture load (N)	1874	4689	8122	13294	18754	34425	54817	79932

SUMMARY AND OUTLOOK

Shape memory alloys (SMAs) are materials for which the reputation and confidence has continued to grow in recent decades, especially since their classification among the smart materials. SMAs owe their properties to a well-known phase transformation of metallurgists which is martensitic transformation. The latter appears as a shear causing a change in structure without any displacement relative of atoms. This transformation, generated in the material, can under the effect of temperature variation (or stress) lead to memorized shapes of the material at high or low temperature.

NIMESIS TECHNOLOGY has gained a great expertise in this technology allowing it to meet the needs of the space industry in terms of reliability, performance, and market-costs.

In fact, the paradigm shift that the space industry is experiencing is turning the needs towards disruptive technologies. The developments that Nimesis is undergoing represent a line towards this quest.

Bringing together the multiple functions of SMAs (not limited to the list above), as well

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the optimization allowed by additive manufacturing to the space sector will maximize the opportunity to create advanced and efficient products and processes, offering by that an innovative line of functionalities.

Dismantling spacecraft is one of the functionalities that shape memory alloys can provide. The strategy that MURPHY will provide is to be executed at the end of the life of the satellite, depending on the speed and the angle of re-entry, the temperature of the satellite will be set according to the altitude, so that the activation can be adjusted to match this last. Its function will be to separate the structural elements.

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