THE AEROSPACE APPLICATIONS OF NICKEL-TITANIUM AS A SUPERELASTIC MATERIAL

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Abstract—*Nickel-titanium, commonly referred to as Nitinol, is a shape-memory alloy with superelastic properties that make it useful in certain environments and applications. These properties include shape-memory, flexibility, and durability. Titanium, a primary material, is a material that reacts with carbon and oxygen when molten and is not easy to work with. Consequently, there are two commercially viable methods for producing Nitinol that account for titanium's reactivity: vacuum induction melting and vacuum arc re-melting.*

One difficulty that engineers have encountered in the field of space exploration is creating solutions to problems that are long-term. Longevity is important because repairs to a mechanical system are often impossible post-deployment. Rovers are a well-known instance of this problem. The wheels are an important part of the rover because they are required for getting around on the planet, but they often sustain heavy damage inflicted by treacherous terrain. One way to avoid using mechanical systems is to take advantage of material systems. Therefore, space exploration is an area where Nitinol has a great deal of potential. Nitinol is being considered as the main component of a flexible spring tire that will carry future rovers across the surface of Mars. This is one of the most practical applications of Nitinol because it perfectly fits the criteria of the required material, which guarantees an improvement in the long-term viability of the design. This increased longevity means that there will be less of a need for replacement, which means that this solution is more sustainable than previous ones. However, these Goldilocks conditions are infrequent; it turns out that Nitinol is often more expensive than practical for everyday problems and certain functions that its material properties can perform are outperformed by mechanical systems.

Key Words - Material Engineering, Nickel-Titanium Applications, Nitinol Applications, Rover Tires, Shape Memory Alloy, Superelasticity

INTRODUCING NITINOL AS A VIABLE MATERIAL FOR SPACE APPLICATION

When nickel and titanium are mixed in a composite alloy, the resultant material is classified as a shape-memory alloy. The alloy is called Nitinol, named from its two key ingredients (nickel and titanium), and from its place of discovery at the Naval Ordnance Laboratory in White Oak, Maryland [1]. Nitinol has superelastic properties that manifest in increased flexibility and durability, as well as the shape-memory properties, which allow the material to change shape during a heat treatment processes. All these properties can be adjusted by adding other materials and making a more complicated alloy. Alloy manipulation occurs during the production stage, where the alloy is combined from its constituents into a homogenous ingot by either vacuum induction melting or vacuum arc re-melting. Nitinol's superelastic properties stood out to engineers at NASA who are considering using Nitinol as the primary material in their latest wheel design for the rovers that are to explore the unforgiving terrain of Mars: the spring tire. The expectation is that this new wheel, which features a Nitinol spring mesh as its exterior, will lead to more discoveries on planets like Mars and fewer terrain-related failures.

The increased durability of the rovers will increase the lifetime of rovers. This in turn will decrease the number of required rocket launches. Also, as the colonization of other planets becomes more ubiquitous, along with the use of transport vehicles, there will be a greater need to limit the amount something needs repaired. The use of Nitinol in rover wheels is something that can keep these kinds of repairs down because it is a better materials goods quicker, and progress technology at a quicker rate.

MATERIAL CAPABILITIES

Overview

Nitinol fits into a class of material called "shape-memory alloy" whose members exhibit the properties of superelasticity and shape-memory. Elasticity is the ability of a material to return to its original form after a compression or tension force is released. As an extension of that, superelasticity is a term to describe the extreme degree of elasticity these materials demonstrate. Past the point of maximum elasticity is plastic deformation, which describes what happens whenever a compression or tension force deforms a material to the point of permanence. Shape-memory is the ability of a material to return from a plastic state to a previously programmed shape. These two qualities allow for Nitinol to be extremely flexible and durable, which make it qualified to interact with the rough surface of Mars.

Shape Memory by Heat Treating

Shape-memory abilities are perhaps the most impressive property Nitinol has. Nitinol is ductile, meaning that it can be drawn into wires. These wires can then be "programmed" to remember a shape by heating the material to a certain temperature, known as the threshold temperature. The shape can then be changed to something entirely different, but the Nitinol will return to the original shape once the threshold temperature is applied. There are two kinds of shape-memory: one-way and two-way. The process of programming both one-way and two-way Nitinol falls into a broader category of molecular manipulation called heat treating.

Heat treating is the general term to describe the altering of the physical properties of a material. It involves heating a material to a certain value and then allowing it to cool at different speeds. Quenching and tempering are common types of heat treating. Forged ferrous metals like steel are both quenched and tempered. The quench is done by removing the hot metal from the forge and submerging it in liquid to rapidly cool it. In steel, this facilitates the production of hard martensite, which hardens the material to an extreme; the resulting material is brittle and can shatter when struck. Tempering is the process of heating metal in the forge and letting it cool slowly. If done after a quench, the metal becomes less brittle and more flexible and will no longer shatter.

When Nitinol is heated to its critical temperature, its molecules set themselves in a position that they return to the next time the material is heated. This is because Nitinol moves through two phases when its temperature increases. It begins in the martensitic phase, during which the Nitinol is relatively soft, easy to shape, and is plastic (this the opposite of steel's hard martensitic phase, where the steel becomes hard and brittle). Then at the threshold temperature it changes to the austenitic phase. This can be described as a solid-state phase change [2]. This is like other solid to liquid phase changes, except the material remains a solid because it is very tightly packed before and after the transition. The material becomes much harder in the austenitic phase. Nitinol's shape-memory comes from its trend of getting harder as it gets hotter. When a Nitinol wire bends in the martensitic phase, the molecules rearrange to compensate for the new shape. This bending is plastic deformation, which in non-shape-memory alloys such as steel is permanent unless the material is recast or re-forged. But in Nitinol and other shape-memory alloys, heat can be applied, the material will enter the austenitic phase, and the molecules will establish their austenitic phase positions. If the shape is maintained while the wire cools, these positions will be "remembered" and locked. After the wire cools and returns to the martensitic phase it can be reshaped into anything. Finally, when being raised to the threshold temperature again the molecules will make the material rigid and return to their remembered positions in the programmed shape.

The process of two-way shape-memory differs from one-way shape-memory in the cooling step. When at room-temperature, a two-way shape-memory alloy will be in a certain shape, which will change to a different shape as its temperature increases past the threshold value. Then as it cools, it will return to its original shape instead of maintaining the new shape. Two-way shape memory allows the material to switch back and forth between two shapes when the temperature is past the threshold temperature. This characteristic is very sensitive though, for if the material is heated too much, it will lose its two-way shape memory.

Heat treatment is what determines whether or not Nitinol has two-way shape memory or one-way shape memory. It all depends on if Nitinol is molded to a certain shape at a higher and lower temperature. For example, a Nitinol wire can be bent and then placed in cold water to remember the bent shape, and then removed from the cold water. Then at room temperature it can be unbent. After this, the Nitinol will possess two-way shape memory as it was programmed at the temperature of the cold water and at room temperature.

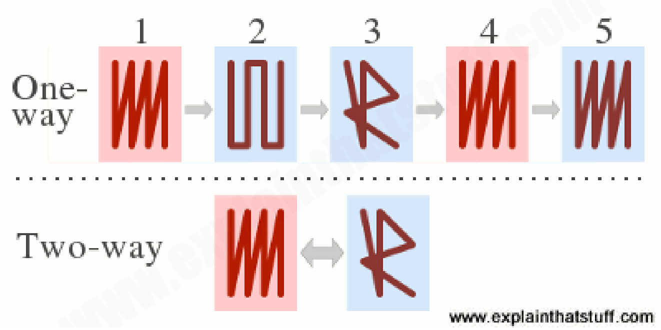

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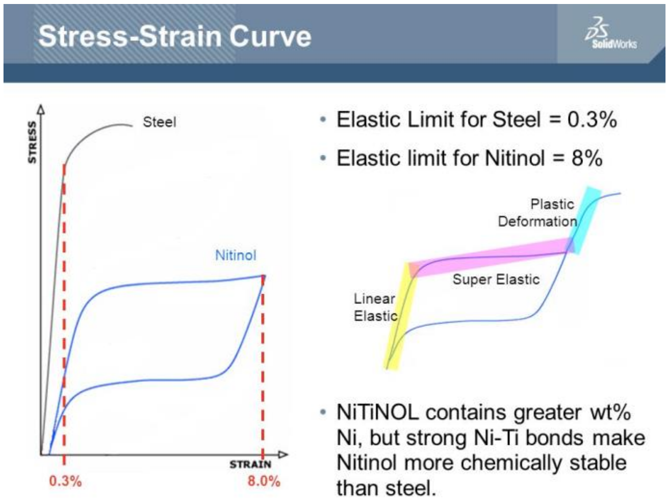
FIGURE 1 [2]

Figure 1 demonstrates the differences between one-way and two-way shape memory. The top half demonstrates that one-way shape memory is not a symmetrical characteristic. A piece of wire can be randomly bent, but when heated it will always return to its single remembered shape. Stage 1 in the image is the remembered shape of the wire, and in stages 2 and 3 the wire is bent randomly. In stage 4 the randomly bent wire is heated up past its threshold temperature and so then it returns to the remembered shape in stage 1. Once it is in its remembered state, it will stay in its remembered state unless bent as shown in stage 5. The bottom half of Figure 1 demonstrates two-way shape memory. It shows that the wire will flip back and forth between two remembered positions, which are controlled by either heating or cooling the wire past the threshold temperature.

Flexibility

As a shape memory alloy, Nitinol is extremely flexible and, according to NASA researchers, can "undergo significant reversible strain (up to 10%), enabling the tire to withstand an order of magnitude more deformation than other non-pneumatic tires before undergoing permanent deformation." Such other alloys include spring steel- a type of steel which has a carbon content between 0.5% and 1% and is of medium to high hardness [3]. Spring steel is capable of deforming about .3%-.5% before plastic deformation, which means that Nitinol outperforms spring steel when it comes to withstanding and recovering from stress [4]. This is visually demonstrated in Figure 1 below, in which the black line is steel and the two blue lines are Nitinol. For steel, the linear increase of stress versus strain shows the range of elastic deformation of steel. The graph begins to curve at .3%, which shows that the steel has begun to plastically deform. It continues to plastically deform until it breaks. Nitinol demonstrates a similar linear increase of the stress versus strain, but it does not experience as much stress as steel at higher strains. Following the linear increase, Nitinol also appears to show plastic deformation, which is thought to be the case because as the strain is increasing, the stress is near constant. At the elastic limit of 8% the strain on nitinol is slowly removed, but the material returns to its original shape. This means that the portion of the graph that was thought to represent plastic deformation was actually representing super elasticity. The only time that Nitinol would actually plastically deform would be once the 8% elastic limit is reached, but the material can return to its original shape if it is heated past its threshold temperature.


Stress-Strain Curve

- Elastic Limit for Steel = 0.3%
- Elastic limit for Nitinol = 8%
- NiTiNOL contains greater wt% Ni, but strong Ni-Ti bonds make Nitinol more chemically stable than steel.

FIGURE 2 [5]

The phases Nitinol goes through define the flexibility of the material at any point. The martensitic phase makes the material superelastic. It becomes plastic after a strain of about 8%, and then relies on the shape memory to return to its original shape. The other phase is the austenitic phase. In this phase the material is extremely difficult to deform. This second phase is the source of the shape memory ability as previously explained. These two solid crystalline states combined are responsible for both the shape memory and superelasticity of Nitinol.

Durability

Durability is an important quality for any material to have, but it does not always mean the same thing for every material because material durability is implicitly dependent on how well the material performs its function, which can vary significantly. A comparison of Nitinol and steel applications is useful in explaining this; steel is good for bridge-building because it is strong and rigid to a useful extent, but it was found to be not durable in its applications in the tires that will be discussed in later sections. On the other hand, Nitinol would make a poor bridge because it is flexible, which is why it performs well as a tire. As the wheel traverses over rocks and other sharp objects, it is able to deform greatly rather than sustain permanent damage [6]. Ultimately, this allows the wheel to last longer, which is crucial in an environment where repairs of damaged components are virtually impossible. Additionally, this lack of a need for repairs will reduce the amount of Nitinol waste and will limit the amount of resources used. The manufacturing of the material contributes greatly to the durability of Nitinol because work hardening can reduce deformation stress. Work hardening also increases strength and gives it two-way shape memory abilities [1]. The manufacturing process is an important step in the production of Nitinol because it provides an opportunity to adjust the properties of the material by way of composition. This is another one of the main characteristics of Nitinol.

PRODUCTION

Vacuum Induction Melting

Before the incredible properties of Nitinol can be utilized, it has to be properly manufactured first. The most common method of making a Nitinol ingot is by a process called vacuum induction melting (VIM) in a crucible made from graphite. This method exposes titanium to contamination, so there are countermeasures taken to ensure that this does not happen. The first kind of contamination is called carbon contamination. Graphite is a macrostructure of carbon molecules and is used in crucibles because of its high melting point, which is much higher than that of both Nitinol and other metals. When a titanium ingot is at extremely high temperatures and comes in contact with graphite, molecules of titanium carbide (TiC) are formed with titanium atoms on the surface of the ingot and carbon atoms on the inside surface of the crucible. Titanium carbide is a molecule that, when in abundance, can compromise the structural integrity and material capabilities of Nitinol. When the presence of TiC gets above 1800 ppm, the workability of the alloy becomes poor and the alloy itself becomes brittle, which is something not desirable when working with Nitinol [6].

Another form of contamination is oxygen contamination. Oxygen contamination is a common phenomenon in metallurgy. Oxidized molecules can ruin a weld or a billet in a forge, much in the same way TiC ruins Nitinol. When working a piece of metal in a forge, the material is "fluxed", which establishes an oxygen barrier. Good fluxing materials become highly reducing at high temperatures, which prevents the formation of metal oxides [6].

There exist methods to prevent both types of contamination, but they are not perfect. To prevent carbon contamination, the walls of the graphite crucible are lined with nickel to provide a physical barrier between the titanium, which is inserted in the center, and the graphite. Then a vacuum is made in a chamber around the crucible to create a near-oxygen-free environment, which prevents oxidation. The space is then flooded with argon gas to cover the crucible and prevent any remaining oxygen from coming in contact with the molten titanium. Argon is denser than oxygen, so the bottom of the chamber will be filled mostly with argon with a layer of the remaining oxygen resting on top. Then an electric current is induced through the use of electromagnets to create a heating element. This is done until the nickel and titanium become homogeneous, and then the molten alloy is cast.

Melt Number	Element	Charge (wt.%)	Ingot	
			wt.%	at. %
1	Ni	53.00	56.32	51.00
	Ti	47.00	43.00	47.72
	Fe	-	0.50	0.48
	C	-	0.18	0.80
2	Ni	53.00	53.65	48.34
	Ti	47.00	46.00	50.81
	Fe	-	0.20	0.19
	C	-	0.15	0.66
3	Ni	53.50	54.33	49.15
	Ti	46.50	45.40	50.35
	Fe	-	0.20	0.19
	C	-	0.07	0.31

FIGURE 3 [6]

Figure 3 outlines the composition of ingots after VIM melting and casting, where "wt.%" is percentage by weight and "at. %" is percentage by atom count. "Chemical composition of the ingots was determined by XRF, ICP spectroscopy and gravimetric methods. Carbon analysis was carried out using a CS2000 LECO make carbon–sulphur gas analyzer. Oxygen was analyzed using a TC436 LECO nitrogen–oxygen gas analyzer" [6]. The carbon contamination was 1800 ppm in the first ingot, 1500 ppm in the second ingot, and 700 ppm in the third ingot. All three ingots had oxygen contamination levels of around 400 pm [6]. As indicated by the dashed lines in the "Charge" column, none of these ingots began with carbon included in the mixture, yet carbon was in the final product. The carbon detected is the carbon that reacted with titanium in the TiC. The trend through subsequent casts is that both the weight and atomic percent values decrease, which is attributed to the caking of TiC on the sidewalls of the crucible. In order for carbon in the graphite to interact with the titanium, it must first diffuse through the layers of TiC deposit, so as the layers increase the interaction becomes less frequent. Essentially, the ingots became purer as the same graphite crucible was used more. Eventually, the point is reached where the layer of TiC is of uniform thickness and the loss of titanium due to carbon contamination can be predicted. VIM reaches its maximum output efficiency at this point. This ability to predict the loss allows for the manufacturing of more precise compositions of Nickel and Titanium.

Vacuum Arc Re-melting

The other method of making Nitinol is with a technique called vacuum arc re-melting (VAR). This process begins by welding nickel and titanium together in a combined billet, which is eventually used as an expendable electrode. The furnace VAR takes place in is a complex construction which features a moveable furnace head and a fixed melt basin. The head protrudes from a sled, whose movements are controlled by a servo and a computer. The basin is made of a hollow steel jacket with a hollow copper tube inside and sits beneath the furnace head. It is open on one end and stands vertically. The nickel-titanium electrode acts as a cathode and the copper base acts as an anode, which allows for the striking of a high-current arc between the electrode and the copper. The arc creates extremely high temperatures and facilitates the melting of the nickel-titanium electrode into the copper melting space below. To prevent the copper from melting in the high temperatures, water is circulated between the copper layer and the steel layer. As the copper crucible below begins to form a steadily rising pool, the servo retracts the furnace head and maintains a constant distance between the head and the surface of the pool so as to maintain a constant length in the arc [7]. Because the entire billet is never melted at the same time, acceptable levels of homogeneity are not achieved after the first time through the process, so this process is repeated as many as four times or until acceptable homogeneity is achieved [8].

A Comparison

Vacuum induction melting and vacuum arc re-melting are the two most ubiquitous production methods of Nitinol. Comparison of these two methods boils down to cost, how difficult it is to produce Nitinol, and quality of the resulting ingot. VIM is less expensive than VAR, and the least expensive in general, which is likely why it is the more widely used production method of the two. It does not require expensive machinery; the only specialized instrument is the vacuum chamber, and there are no mechanically controlled parts. VIM is also quicker than VAR. Producing Nitinol with this method can require as few as thirty minutes from start to finish, beginning with the preparation process and loading the crucible and ending at casting. This process can be done in a facility as high-end as a lab, or as low end as a garage. Ingot size is limited by the size of the graphite crucible, which is relatively inexpensive and can come in fairly large sizes. VIM is decidedly the better option for producing workable Nitinol on a budget. But if cost is not an issue or if quality is important, then VAR will provide more reliably pure product and should therefore be the method of production. VAR carbon contamination tends to reach a maximum of no higher than 200 ppm, while VIM carbon contamination is not usually lower than 600 ppm [6]. As explained previously, the melting process needs to be run several times in order to obtain ideal homogeneity, which means the VAR process takes longer than VIM. But the decrease in carbon contamination leads to higher quality alloy, which will contain more desirable properties. It will be less brittle, more flexible, and can be worked much more easily.

Other forms of nitinol production do exist, such as non-consumable arc melting, electron beam melting, and plasma melting. Non-consumable arc melting is similar to VAR, except that the cathode is not consumed in the melting process. The process, takes a lot longer, and creates a smaller amount of the alloy, making it very expensive. Electron beam melting is similar to 3D printing in that it is additive; metal powder is melted layer by layer, which builds an ingot. This is done by an electron beam and can be done to an exact geometry, but this process takes a lot of time. Plasma melting is similar to VIM, except it uses plasma instead of electricity. All of the above-mentioned production methods are not very taxing to the environment as they all take a minimal amount of resources to perform. None of these methods are commercially viable because they are too expensive as they take a lot of time or require expensive machinery. These are methods that NASA may have to use if they are interested in creating a Nitinol alloy of higher purity. They will likely need it to be as pure as possible because of how high the cost of failure is, which means they will probably use either VAR or electron melting as they have the highest purity.

Ultimately, Nitinol production is extremely difficult because titanium is difficult to work with, and the production process selected will be based on the desired characteristics of the manufacturer.

Alloy Composition

Alloy composition is an important thing to keep track of when working with Nitinol because the material transformation temperatures are extremely sensitive to compositional changes. A 1% change in nickel content can change the martensite start temperature by 100 K. Additionally, this modification increases the yield strength of the austenitic phase.

Figure 2 demonstrates the effects of such changes on the martensite start temperature. This makes Nitinol applicable to a variety of environments, and its applicability is heightened when one looks at the other compositional changes that can be done to change the properties of Nitinol. Furthermore, the addition of iron and chromium can reduce the transformation temperatures even more. The addition of copper can lower the stress required to deform the martensitic phase and decrease hysteresis, or the delay in the physical transformation despite the conditions for change being met. These modifications are usually seen as desired changes, but there do exist some undesired compositional manipulations. As discussed earlier, it is very difficult to manufacture Nitinol to be purely nickel and titanium because there is both carbon and oxygen contaminations. These compromise the integrity of Nitinol, decreasing the workability and strength of the material. Among the other properties, the ease of manipulability of Nitinol makes it very versatile for many applications and environments, extending to applications on other planets.

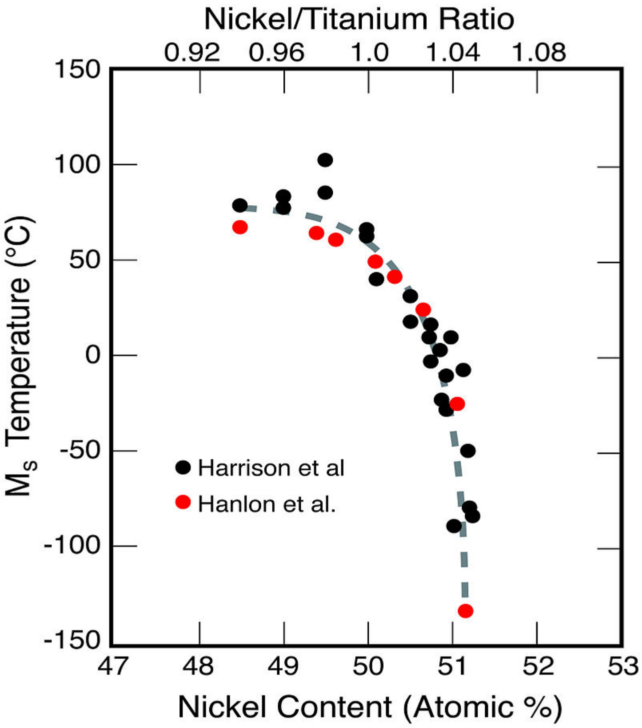


FIGURE 4 [9]

NITINOL TIRES

A History of Rover Tires and Introduction of a Problem

In the 1960s and '70s, before Nitinol tires or even the Spring Tire model were conceived, there were three designs that NASA and other space agencies experimented with. The Russian *Lunokhod* lunar rover used rim wire mesh with protruding ridges for grip, stabilized by what were essentially bicycle spokes [10]. The Modularized Equipment Transporter (MET) Rover was a two-wheeled cart featuring rubber tires that were inflated with nitrogen. They were designed to make it easier to pull the cart through the soft and forgiving lunar soil. The NASA Lunar Roving Vehicle used mesh tires with inner frames to compensate for inner deflection. None of these models were very durable and they would plastically deform.

Finally, the Spring Tire was designed in the early 2000s. The original Spring Tire was a construct of springs made from spring steel woven together into a flexible mesh sheet, which was arranged around a central axis in the shape of a tire. This tire design was better than previous designs because it was made of a more durable material and generated good traction on sand and rocks, but the spring steel tire was still susceptible to deformation because of the hollow nature of the structure. These wheels would handle well on the moon, but the entire surface of Mars is treacherous terrain and a wheel that is permanently deformed is not useful. Damping capabilities, which are not provided by the tire, are essential for maintaining the performance of instruments and other components that cannot be repaired easily after deployment. *Curiosity* used a rocker-bogie wheel system, shown in Figure 4, which mechanically helps provide the soft ride that NASA was looking for. The attached wheels are the bogie and the single wheel is the rocker. Each set of these systems is attached in the middle to the other side via a differential. This system allows the rover to maintain a relatively constant weight on each wheel. It also provides stability and minimizes rover tilt. but this system limits the rover to only being able to drive over rocks as tall as 31 inches. This system also limited the travel speed to an average of 30 meters an hour, which is incredibly slow [10]. In 2013 when the wheels on *Curiosity* began to experience significant wheel damage, engineers were concerned that the rover would not be able to travel far enough to complete its mission. Engineers began to examine the Spring Tire as a potential solution to the unforgiving Martian terrain and began to work on improving the prototype Spring Tire models for future rovers.

FIGURE 3 [10]

Figure 3 is an image of the spring tire. The design is bare-bones and almost entirely spring mesh. The deflection of the tire on the rock is but a fraction of the total possible deflection of the whole structure. The rear wheel is the current wheel on rovers.

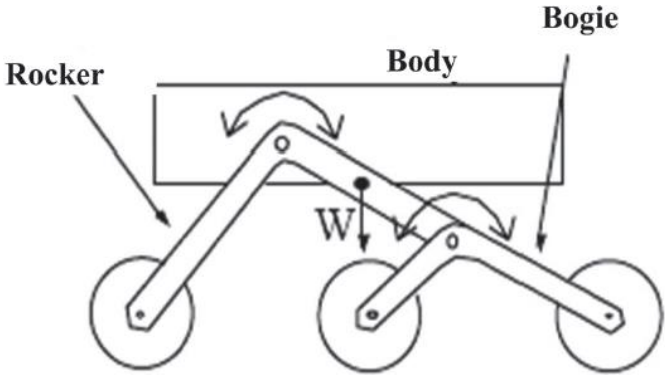


FIGURE 4 [11]

Nitinol Spring Tires

Nitinol's ability to overcome plastic deformation made the use of Nitinol a significant improvement over the use of spring steel in tire models. With the same construction, the Nitinol tires could deform up to thirty times more than what could be achieved with steel without having permanent deformation occur. According to Santo Padula, a Materials Scientist who was an integral part in the development of the Nitinol Spring Tire, the tire could "deform all the way down to the axle and [still] return to shape". [12] Even if the wheel did have to ability to plastically deform, the wheel can be heated past the transformation temperature and the shape memory ability will kick in. The extreme deformation is valuable because the surface of the tire can deform to match the contours of the surface it is on, create a powerful grip on the ground, then return to the original round tire shape as the wheel turns. With the increased flexibility, the wheel is able to grip the terrain better than an ordinary wheel as it is able to conform to the exact geometry of the terrain. Additionally, the flexible potential of Nitinol can be changed by adjusting the shape and composition of the material. This allows the wheels to deflect a greater amount, resulting in more traction on various terrains. Ultimately, this means that there are more design options with differing levels of Nitinol dependence and mechanical system dependence. Other changes include limiting the energy transferred to the vehicle and increasing load carrying potential. As a direct result of this flexibility and increased grip, the speeds of the vehicle can be increased, and the load carrying potential is greater [12]. Definite values for the top speed and load carrying potential are currently not available because more testing needs to be done before they can be determined.

WHY IS THIS IMPORTANT

The idea to use Nitinol wheels on future Mars rovers is one that still requires a lot of research and time until it is seen in application. Traditionally aluminum wheels have been acceptable at traversing the surface of Mars because of how lightweight and strong the material is. So there is still a lot of testing that needs to be done before the traditional aluminum wheels are retired. From the research that has been performed, it can be concluded that Nitinol wheels currently outperform the traditional wheel. The application of Nitinol wheels will affect the future of planetary exploration, and the human race. Ultimately, outer space research has led innovators to the development of countless technologies that are now used widely by the public. The continuation of this research is required in order to further the technological capabilities of the modern world. Nitinol will help accelerate this process, and will lead to new discoveries, making it a viable engineering innovation.

This technology is not only applicable to Mars rovers, it can actually be applicable to many aspects of everyday life. Glasses can be made out of a nitinol alloy, enabling them to be extremely flexible and not break when bent. Airplanes can have more efficient wing designs as the winglets on the ends can easily be manipulated to change the drag on the wing. Nitinol wire can even be used in orthodontics as orthodontic wire so that the wires do not need to be adjusted as often. These are all ways the technology can be implemented today, but there are probably many more undiscovered capabilities of Nitinol technology.

SUSTAINABILITY

Whenever creating a new product or solution, engineers have to consider the sustainability of that innovation. The questions of sustainability need to be asked. When answering that question for the case of Nitinol the overall answer is that Nitinol is sustainable. A contributing factor to this is the durability of Nitinol. This is because the increased durability of Nitinol reduces the amount of waste due to rocket launches and repairs needed to supply or fix rovers. This is because there will be a lower demand for the replacement of old rovers and the wheels on them. Additionally, the increased durability will lower the amount of waste on Mars due to old and damaged wheels. Any actual waste due to Nitinol can be re-melted and then reformed into replacement Nitinol wheels. The only problem with this is that expensive systems are required to do this and so either expensive machinery would need shipping to Mars or the Nitinol would need to be shipped back to Earth. This is not as great of a concern as Nitinol is actually quite environmentally friendly. Nitinol has been used inside of humans as stents and to function as bone casts. Another factor that contributes to the sustainability of this technology is the flexibility of Nitinol. As colonies are established on Mars there will be a need to have a central landing location for food and other necessities, and this means that these goods will need transported. With current rovers that move at a rate of 30 meters per hour, this would take an extremely long time. This could lead to the possibility of colonies not receiving shipments in times and thus have to come up with a way to solve that problem. Since Nitinol wheels will be able to increase the speed of the rovers, this will not be as much of a problem because the rovers will be able to move quicker, getting the goods to their destinations on time. This increased rate of movement also allows colonies to be established further away, possibly allowing for different research opportunities at different locations. These increased research opportunities will facilitate the development of new technologies and will be beneficial in the long term. Overall the sustainability of Nitinol when applied to rover wheels is very high. The features of Nitinol that make this application sustainable are the high durability, flexibility, research opportunities, and increased range. The problem when considering the sustainability of Nitinol is the cost, and overall the benefits outweigh the high initial cost of Nitinol wheels on rovers.

CONCLUSION

Nitinol is a fantastically unique material that has the ability to do things that other materials are simply incapable of. Sometimes it seems like a supermaterial. But if it is this amazing, why can you not find it everywhere? Frankly, Nitinol is expensive, it can be impractical, and there are sometimes better alternatives. For example, research was done investigating whether or not shape-memory alloys would perform well as winglets on airplane wings. As it turns out, it is very difficult to control the temperature of a material that is flying several hundred miles per hour on a planet that has seasons. It can be done but with difficulty. Maintaining a shape with a mechanical system made far more sense than by doing it with material properties. Another example is that Nitinol can be used very effectively as an orthodontic wire, but it is not practical when much less expensive materials can be used almost as effectively. And while the Nitinol spring wheel will likely perform well on Mars, on Earth they would be expensive, have poor traction on flat asphalt where most driving is done, and be expensive to repair. This would make Nitinol not sustainable on Earth applications, but when considering the applications on Mars the material is very sustainable.

In short, Nitinol is useful, but it has a niche, and outside that niche it is not always practical or better than competing materials. At this point in time Nitinol rover wheels should be considered as they are very sustainable and will lead to advancements in society. Ultimately, in the case of rover wheels for Mars missions, there are no other designs that are challenging the re-invented wheel.

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ACKNOWLEDGEMENTS

As authors, we would like the thank the University of Pittsburgh for giving us the opportunity and resources to research the topic of Nitinol. Additionally, we would like to thank Tevis Jacobs for inspiring us to write about Nitinol.