

MF9211 ADVANCED MATERIALS TECHNOLOGY

UNIT IV

MODERN METALLIC MATERIALS

SYLLABUS.

Dual phase steels, High strength low alloy (HSLA) steel, Transformation induced plasticity (TRIP) Steel, Maraging steel, Nitrogen steel – Intermetallics, Ni and Ti aluminides – smart materials, shape memory alloys – Metallic glass and nano crystalline materials.

High-strength low-alloy steel

High-strength low-alloy steel (HSLA) is a type of [alloy steel](#) that provides better mechanical properties or greater resistance to corrosion than [carbon steel](#). HSLA steels vary from other steels in that they are not made to meet a specific chemical composition but rather to specific mechanical properties. They have a carbon content between 0.05–0.25% to retain formability and [weldability](#). Other alloying elements include up to 2.0% manganese and small quantities of [copper](#), [nickel](#), [niobium](#), [nitrogen](#), [vanadium](#), [chromium](#), [molybdenum](#), [titanium](#), [calcium](#), [rare earth elements](#), or [zirconium](#).^{[1][2]} Copper, titanium, vanadium, and niobium are added for strengthening purposes.^[2] These elements are intended to alter the [microstructure](#) of carbon steels, which is usually a [ferrite-pearlite](#) aggregate, to produce a very fine dispersion of alloy [carbides](#) in an almost pure ferrite matrix. This eliminates the toughness-reducing effect of a pearlitic volume fraction yet maintains and increases the material's strength by refining the grain size, which in the case of ferrite increases [yield strength](#) by 50% for every halving of the mean grain diameter. [Precipitation strengthening](#) plays a minor role, too. Their yield strengths can be anywhere between 250–590 megapascals (36,000–86,000 psi). Because of their higher strength and toughness HSLA steels usually require 25 to 30% more power to form, as compared to carbon steels.^[2]

Copper, silicon, nickel, chromium, and phosphorus are added to increase corrosion resistance. Zirconium, calcium, and rare earth elements are added for sulfide-inclusion shape control which increases formability. These are needed because most HSLA steels have directionally sensitive properties. Formability and impact strength can vary significantly when tested longitudinally and transversely to the grain. Bends that are parallel to the longitudinal grain are more likely to crack around the outer edge because it experiences tensile loads. This directional characteristic is substantially reduced in HSLA steels that have been treated for sulfide shape control.^[2]

They are used in cars, trucks, cranes, bridges, roller coasters and other structures that are designed to handle large amounts of [stress](#) or need a good strength-to-weight ratio.^[2] HSLA steels are usually 20 to 30% lighter than a carbon steel with the same strength.^{[3][4]}

HSLA steels are also more resistant to [rust](#) than most carbon steels because of their lack of pearlite – the fine layers of ferrite (almost pure iron) and cementite in pearlite. ^[citation needed] HSLA steels usually have densities of around 7800 kg/m³. ^[5]

Classifications

- **Weathering steels:** steels which have better corrosion resistance. A common example is COR-TEN.
- **Control-rolled steels:** hot rolled steels which have a highly deformed austenite structure that will transform to a very fine equiaxed ferrite structure upon cooling.
- **Pearlite-reduced steels:** low carbon content steels which lead to little or no pearlite, but rather a very fine grain ferrite matrix. It is strengthened by precipitation hardening.
- **Acicular ferrite steels:** These steels are characterized by a very fine high strength acicular ferrite structure, a very low carbon content, and good [hardenability](#).
- **Dual-phase steels:** These steels have a ferrite microstructure that contain small, uniformly distributed sections of martensite. This microstructure gives the steels a low yield strength, high rate of work hardening, and good formability. ^[1]
- **Microalloyed steels:** steels which contain very small additions of niobium, vanadium, and/or titanium to obtain a refined grain size and/or precipitation hardening.

A common type of micro-alloyed steel is improved-formability HSLA. It has a yield strength up to 80,000 psi (550 MPa) but only costs 24% more than [A36 steel](#) (36,000 psi (250 MPa)). One of the disadvantages of this steel is that it is 30 to 40% less [ductile](#). In the U.S., these steels are dictated by the [ASTM](#) standards A1008/A1008M and A1011/A1011M for sheet metal and A656/A656M for plates. These steels were developed for the automotive industry to reduce weight without losing strength. Examples of uses include door-intrusion beams, chassis members, reinforcing and mounting brackets, steering and suspension parts, bumpers, and wheels. ^{[2][6]}

Transformation Induced Plasticity "TRIP" Steel

Introduction

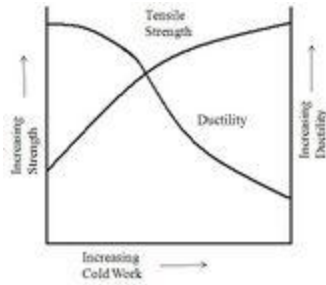


Fig 1: Effect of cold work on the strength and ductility of a typical metal

Transformation Induced Plasticity (TRIP) steel, is a type of steel alloy which exhibits excellent strength and ductility. Transformation induced plasticity refers to the transformation of retained [austenite^W](#) to [martensite^W](#) during plastic deformation. This property allows TRIP steels to have a high formability, while retaining excellent strength. In the processing of metals, there is generally a compromise that must be made between strength and ductility.^[1] This is demonstrated by the graph in Figure 1, which shows the compromise between strength and ductility during cold work. The advantage of TRIP steels is that they have much higher ductility than other steels with similar strength.^[2] The ductility and strength of TRIP steels make them an excellent candidate for automotive applications. Indeed, structural components can be made thinner because TRIP steels have the ductility necessary to withstand high deformation processes such as stamping, as well as the strength and energy absorption characteristics to meet safety regulations.

Underlying materials science principles

TRIP Steel Composition

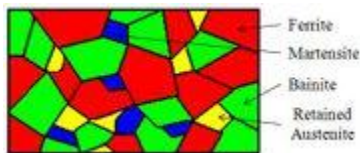


Fig 2: Diagram of the grain structure for a typical TRIP steel

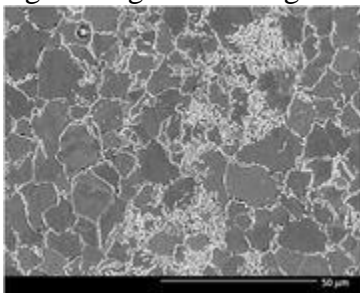


Fig 3: SEM micrograph showing the typical grain structure of a TRIP steel^[3]

Trip steels are hypoeutectoid iron carbon alloys which typically contain 0.1 – 0.4 % carbon by weight. TRIP steels also contain alloying elements which prevent the precipitation of the high carbon [cementite^W](#) phase which is present in typical steels at room temperature. This raises the carbon concentration of the austenite phase, which becomes stable at room temperature. Silicon and Aluminium are the two most common elements used to stabilize the austenite phase at room temperature.^[4] Other alloying elements such as titanium, niobium, vanadium...ect. can also be added to improve the strength of the alloy.

Processing method

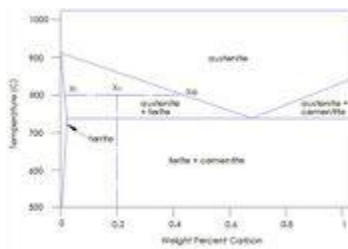


Fig 4: Iron carbon phase diagram showing the intercritical annealing process



Fig 5: Diagram showing the carbon concentration in the bainitic ferrite phase and the austenite phase

In order to produce a strong and ductile TRIP steel, an intercritical annealing process is used to obtain the correct phase distribution.^[5] During intercritical annealing, the steel is brought to a temperature above the [eutectoid^W](#), where the material is composed of a solid austenite phase and a solid ferrite phase. The austenite phase is a high temperature solid phase which only exists in equilibrium at temperatures above 727 degrees Celsius.^[6] The material is then isothermally cooled at a temperature of approximately 400 degrees Celsius,^[4] in order to allow the austenite to form a bainitic ferrite phase. During the eutectoid transformation, excess carbon is produced by the formation of the low carbon ferrite phase. In a typical steel alloy, the excess carbon would form a high carbon cementite phase. However, the silicon and aluminium prevent the formation of cementite. In consequence, the excess carbon diffuses to the remaining austenite phase. In order to obtain the correct microstructure, it is important that the isothermal transformation be completed at a temperature where the formation of bainitic ferrite is slow enough to allow the carbon to diffuse to the austenite. The carbon enriched austenite phase eventually reaches a high enough carbon content that it is stable at room temperature.^[7] The result of the intercritical annealing process is a material composed primarily of ferrite, and [bainite^W](#) formed from the austenite phase during intercritical annealing, as well as dispersed retained austenite, and martensite phases. The grain microstructure can be seen in Figure 2 which shows a schematic of the phases, and Figure 3 which shows a micrograph taken with a [scanning electron microscope^W](#). Figure 4 depicts the intercritical annealing process on the iron phase diagram. Figure 5

demonstrates the carbon concentration of the ferrite and austenite phases during the intercritical annealing process.

The “TRIP” effect

The transformation induced plasticity phenomenon occurs when the retained austenite transforms to martensite during plastic deformation.^[1] The transformation of retained austenite produces a high carbon martensite phase which is very brittle. However, the retained austenite is very finely dispersed in the ferrite phase. This fine dispersion allows TRIP steels to retain their strength. The transformation of austenite into martensite is almost instantaneous and completely diffusionless.^[6] In TRIP steels, plastic deformation forms martensite nucleation sites in microscopic areas seeing large deformations.^[8] These nucleation sites trigger the formation of the martensite phase. The nucleation areas are known as shear bands, where [crystallographic defects](#)^W such as twins or stacking fault bundles are located.

Material Properties of TRIP Steels

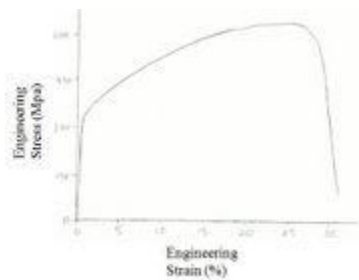


Fig 6: Typical engineering stress-strain curve for TRIP steels

A typical engineering stress-strain curve for TRIP steels is shown in Figure 6. As can be seen, TRIP steels have a large amount of work hardening. The high work hardening can be attributed to the TRIP effect, as well as the fact that TRIP steels are primarily composed of soft ferrite and hard bainite. This "dual phase" nature allows for local deformation of the ferrite phase while maintaining a high tensile strength. Indeed, their [tensile strength](#)^W is typically twice the value of their [yield strength](#)^W.^[2] This means that TRIP steels also exhibit very stable work hardening, where the onset of necking occurs at relatively high elongation values (over 25%). This makes TRIP steels ideal for forming operations such as stamping or bending. Forming operations are often limited by the loss of strength of the component due to wall thinning, or rupture because the material reached its forming limit. TRIP steels are ideal for such operations because they have a high formability limit and have stable yield point elongation which increases the structural integrity of formed components.

Improving the performance of TRIP steels

Improving the galvanized surface finish of TRIP steels

[Hot-dip galvanizing^W](#) is a widely used surface treatment for steels. During the process, molten zinc bonds with the iron to form a layer which protects against corrosion. Original TRIP steels only contained silicon as the alloying element used to suppress the formation of the cementite phase. The content of silicon in these alloys was approximately 1.5 % by weight. This relatively high silicon content formed silicon oxide at the surface of the steel prior to the galvanizing process. ^[9] This oxide severely degraded the properties of the galvanized surface coating. ^[4] Newer TRIP steels have partially or completely replaced silicon with aluminium as an alloying component. The aluminium plays the same role as the silicon, but does not have negative effects on the surface finish during galvanizing. Therefore, the silicon content can be reduced while maintaining the TRIP properties of the steel.

High strength micro-alloying of TRIP steels

Basic TRIP steels have a tensile strength of approximately 600 MPa. However, by varying the alloy content, TRIP steels can have tensile strengths above 800 MPa. This was first accomplished by raising the carbon content of the alloy to approximately 0.4 % by weight. ^[1] However, this high carbon content leads to poor weldability. As well, the retained austenite becomes more stable due to the increased carbon content, which diminishes the formability of the TRIP steel. Instead of increasing the carbon content, alloying elements such as titanium, niobium, and vanadium can be used to give TRIP steels added tensile strength. ^[1] These alloying elements increase the strength of the steel through [precipitation hardening^W](#), while having a minimal effect on weldability and formability.

Improving fuel efficiency of automobiles

TRIP steels are an ideal choice for structural materials in automobiles. They have the ductility and stable work hardening necessary to withstand high deformation processes such as stamping. As well, their high tensile strength makes them ideal for highly stressed components. Finally, they have excellent energy absorption properties because of their ductility and strength, which can improve vehicle safety during a crash. Because of these beneficial properties, TRIP steels could be used in smaller quantities to replace current steel components. This is known as "down-gauging", where thinner sheets of steel are used to form components.

Weight reduction estimate

Approximately 55 percent of the mass of an average passenger car is made of steel. ^[10] It has been shown that the volume of a mild steel formed sheet can be reduced by 20 percent by using TRIP steel, while maintaining the same stiffness. ^[11] Therefore, it can be assumed that the use of TRIP steel could reduce the mass of steel on a vehicle by 20 percent, and the total vehicle mass by 11 percent.

Effect of weight reduction on fuel efficiency

The percentage of consumed fuel that goes directly into recovering inertial losses from braking is 5.8 percent. ^[12] The weight savings from using TRIP steel would reduce the amount of inertial losses by 11 percent, because kinetic energy is directly proportional to mass. This means that using TRIP steels could lead to a reduction in total fuel consumption of 0.64 percent.

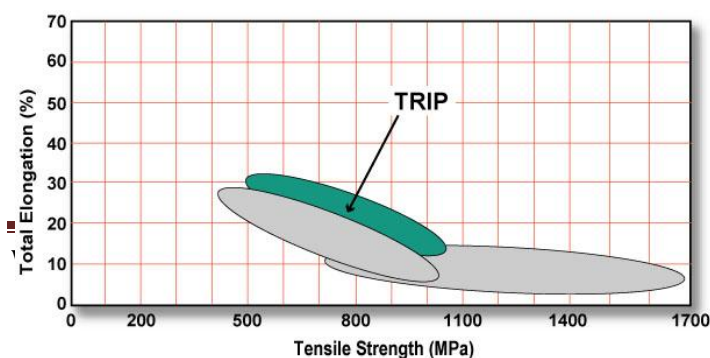
Magnitude of effect on a global scale

If we assume that an average passenger vehicle consumes 10L/100km (23.5 mpg), and that an average car travels 20 000 km (12500 miles) in one year, the weight savings translate to an annual fuel consumption reduction of 12.8 liters (3.33 gallons). In 2007, there were 136 billion passenger cars in the United States. ^[13] This means that using TRIP steels in vehicle fabrication has the potential to reduce fuel consumption by 1.74 billion liters (460 million gallons). This represents a carbon dioxide emissions reduction of 4.18 billion kg (1.9 billion lbs), which is a reduction of 0.07% of the total United States carbon dioxide emissions. ^[14]

Economics of TRIP steels

Steel is commonly used because of its strength, formability and low cost relative to other metals. Metals such as titanium, magnesium, and aluminum have a higher strength to weight ratio and could offer significant weight savings in automobile components. However, they are much more expensive due to their lower abundance, higher production costs, and higher machining costs. As well, worldwide supply of these metals is fairly limited. These factors prevent these metals from being commonly used in low end production cars, which the majority of the population drives. TRIP steels do not face any of these difficulties, because they are a low alloy steel. Implementing the intercritical annealing step in steel processing should not prove to be difficult. This means that TRIP steels could be produced for the same price as other high strength steels. The most important barrier TRIP steels have faced in their market integration is the poor galvanizing surface finish. The galvanizing process is used on a large number of automotive components, because it is easy, inexpensive, and effective. With the recent discovery of aluminium as a replacement for silicon, TRIP steels no longer face past difficulties with galvanizing. TRIP steels can now be effectively protected from corrosion in an economically viable way, which means we may be seeing commercial production of TRIP steel products in the near future.

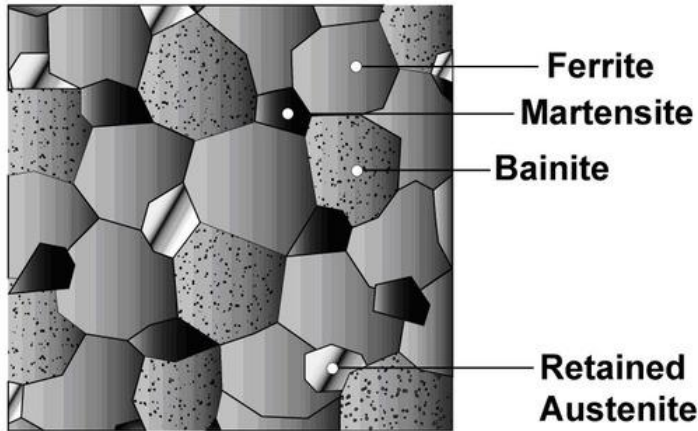
Transformation-Induced Plasticity (TRIP) Steel



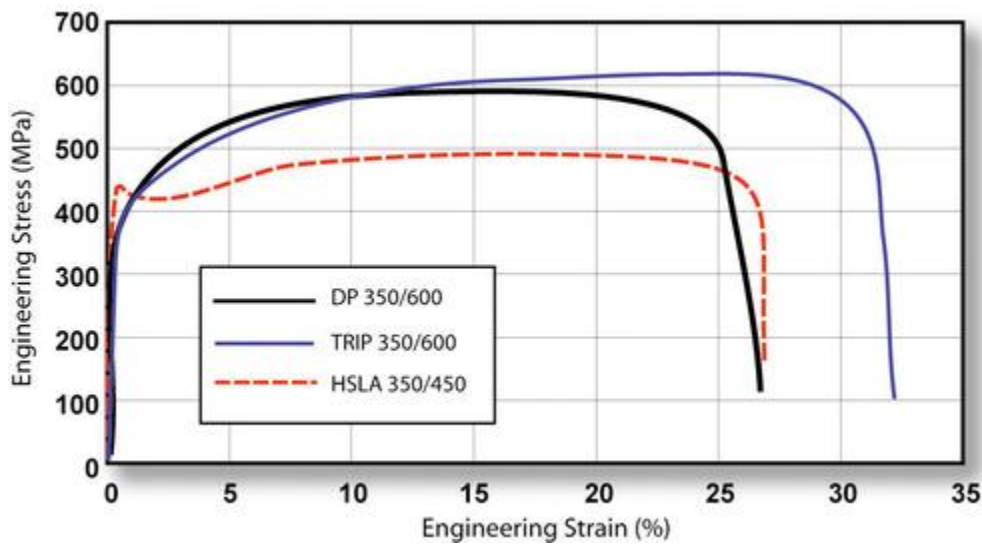
The microstructure of TRIP steels is retained austenite embedded in a primary matrix of ferrite. In addition to a minimum of five volume percent of retained austenite, hard phases such as

martensite and bainite are present in varying amounts. TRIP steels typically require the use of an isothermal hold at an intermediate temperature, which produces some bainite. The higher silicon and carbon content of TRIP steels also result in significant volume fractions of retained austenite in the final microstructure. Figure 1-4 shows a schematic of TRIP steel microstructure.

TRIP



During deformation, the dispersion of hard second phases in soft ferrite creates a high work hardening rate, as observed in the DP steels. However, in TRIP steels the retained austenite also progressively transforms to martensite with increasing strain, thereby increasing the work hardening rate at higher strain levels. This is illustrated in Figure 1-5, where the engineering stress-strain behaviour of HSLA, DP and TRIP steels of approximately similar yield strengths are compared. The TRIP steel has a lower initial work hardening rate than the DP steel, but the hardening rate persists at higher strains where work hardening of the DP begins to diminish. Additional engineering and true stress-strain curves for TRIP steel grades are located in [AHSS Application Guidelines Image Gallery](#), Figure 2-9C.



The work hardening rates of TRIP steels are substantially higher than for conventional HSS, providing significant stretch forming. This is particularly useful when designers take advantage of the high work hardening rate (and increased bake hardening effect) to design a part utilizing the as-formed mechanical properties. The high work hardening rate persists to higher strains in TRIP steels, providing a slight advantage over DP in the most severe stretch forming applications.

TRIP steels use higher quantities of carbon than DP steels to obtain sufficient carbon content for stabilizing the retained austenite phase to below ambient temperature. Higher contents of silicon and/or aluminium accelerate the ferrite/bainite formation. Thus, these elements assist in maintaining the necessary carbon content within the retained austenite. Suppressing the carbide precipitation during bainitic transformation appears to be crucial for TRIP steels. Silicon and aluminium are used to avoid carbide precipitation in the bainite region.

The strain level at which retained austenite begins to transform to martensite is controlled by adjusting the carbon content. At lower carbon levels, the retained austenite begins to transform almost immediately upon deformation, increasing the work hardening rate and formability during the stamping process. At higher carbon contents, the retained austenite is more stable and begins to transform only at strain levels beyond those produced during forming. At these carbon levels, the retained austenite persists into the final part. It transforms to martensite during subsequent deformation, such as a crash event.

TRIP steels therefore can be engineered or tailored to provide excellent formability for manufacturing complex AHSS parts or exhibit high work hardening during crash deformation for excellent crash energy absorption. The additional alloying requirements of TRIP steels degrade their resistance spot-welding behaviour. This can be addressed somewhat by modification of the welding cycles used (for example, pulsating welding or dilution welding).

Maraging steel

Maraging steels (a [portmanteau](#) of "[martensitic](#)" and "aging") are [steels](#) ([iron alloys](#)) which are known for possessing superior strength and toughness without losing [malleability](#), although they cannot hold a good cutting edge. *Aging* refers to the extended heat-treatment process. These steels are a special class of low-[carbon](#) ultra-high-strength steels which derive their strength not from carbon, but from precipitation of inter-metallic compounds. The principal alloying element is 15 to 25 wt.% [nickel](#).^[1] Secondary alloying elements are added to produce [intermetallic precipitates](#), which include [cobalt](#), [molybdenum](#), and [titanium](#).^[1] Original development was carried out on 20 and 25 wt.% Ni steels to which small additions of Al, Ti, and Nb were made.

The common, non-stainless grades contain 17–19 wt.% nickel, 8–12 wt.% cobalt, 3–5 wt.% molybdenum, and 0.2–1.6 wt.% titanium. Addition of chromium produces stainless grades

resistant to corrosion. This also indirectly increases [hardenability](#) as they require less nickel: high-chromium, high-nickel steels are generally [austenitic](#) and unable to transform to [martensite](#) when heat treated, while lower-nickel steels can transform to martensite. Alternative variants of Ni-reduced maraging steels are based on alloys of Fe and Mn plus minor additions of Al, Ni, and Ti where compositions between Fe-9wt.% Mn to Fe-15wt.% Mn have been used. The Mn has a similar effect as Ni, i.e. it stabilizes the austenite phase. Hence, depending on their Mn content, Fe-Mn maraging steels can be fully martensitic after quenching them from the high temperature austenite phase or they can contain retained austenite. The latter effect enables the design of maraging-TRIP steels where TRIP stands for Transformation-Induced-Plasticity.^[2]

Properties

Due to the low carbon content maraging steels have good [machinability](#). Prior to aging, they may also be cold rolled to as much as 80–90% without cracking. Maraging steels offer good [weldability](#), but must be aged afterward to restore the properties of [heat affected zone](#).^[1]

When [heat-treated](#) the alloy has very little dimensional change, so it is often machined to its final dimensions. Due to the high alloy content maraging steels have a high hardenability. Since ductile FeNi martensites are formed upon cooling, cracks are non-existent or negligible. The steels can be [nitrided](#) to increase case hardness, and polished to a fine surface finish.

Non-stainless varieties of maraging steel are moderately [corrosion](#)-resistant, and resist [stress corrosion](#) and [hydrogen embrittlement](#). Corrosion-resistance can be increased by [cadmium plating](#) or [phosphating](#).

Heat treatment cycle

The steel is first [annealed](#) at approximately 820 °C (1,510 °F) for 15–30 minutes for thin sections and for 1 hour per 25 mm thickness for heavy sections, to ensure formation of a fully [austenitized](#) structure. This is followed by [air cooling](#) to room temperature to form a soft, heavily-dislocated iron-nickel lath (untwinned) martensite. Subsequent aging ([precipitation hardening](#)) of the more common alloys for approximately 3 hours at a temperature of 480 to 500 °C produces a fine [dispersion](#) of Ni₃(X,Y) intermetallic phases along dislocations left by martensitic transformation, where X and Y are [solute](#) elements added for such precipitation. Overaging leads to a reduction in stability of the primary, metastable, coherent precipitates, leading to their dissolution and replacement with semi-coherent [Laves phases](#) such as Fe₂Ni/Fe₂Mo. Further excessive heat-treatment brings about the decomposition of the martensite and reversion to austenite.

Newer compositions of maraging steels have revealed other intermetallic stoichiometries and crystallographic relationships with the parent martensite, including rhombohedral and massive complex Ni₅₀(X,Y,Z)₅₀ (Ni₅₀M₅₀ in simplified notation).

Uses

Maraging steel's strength and malleability in the pre-aged stage allows it to be formed into thinner rocket and missile skins than other steels, reducing weight for a given strength.^[3] Maraging steels have very stable properties, and, even after overaging due to excessive temperature, only soften slightly. These alloys retain their properties at mildly elevated [operating temperatures](#) and have maximum service temperatures of over 400 °C (752 °F).^[citation needed] They are suitable for engine components, such as crankshafts and gears, and the firing pins of automatic weapons that cycle from hot to cool repeatedly while under substantial load. Their uniform expansion and easy machinability before aging make maraging steel useful in high-wear components of [assembly lines](#) and [dies](#). Other ultra-high-strength steels, such as [AerMet](#) alloys, are not as machinable because of their carbide content.

In the sport of [fencing](#), blades used in competitions run under the auspices of the [Fédération Internationale d'Escrime](#) are usually made with maraging steel. Maraging blades are superior for [foil](#) and [épée](#) because crack propagation in maraging steel is 10 times slower than in carbon steel, resulting in less blade breakage and fewer injuries.^{[4][5]} Stainless maraging steel is used in [bicycle](#) frames and [golf](#) club heads. It is also used in surgical components and hypodermic syringes, but is not suitable for scalpel blades because the lack of carbon prevents it from holding a good cutting edge.

Maraging steel production, import, and export by certain states, such as the United States,^[6] is closely monitored by international authorities because it is particularly suited for use in [gas centrifuges](#) for [uranium enrichment](#); lack of maraging steel significantly hampers this process. Older centrifuges used aluminum tubes; modern ones, carbon fiber composite.

Physical properties

- [Density](#): 8.1 g/cm³ (0.29 lb/in³)
- [Specific heat](#), mean for 0–100 °C (32–212 °F): 813 J/(kg·K) (0.108 Btu/(lb·°F))
- [Melting point](#): 2575 °F, 1413 °C
- [Thermal conductivity](#): 25.5 W·m/(m²·K)
- Mean coefficient of thermal expansion: 11.3×10⁻⁶
- [Yield tensile strength](#): typically 1030–2420 MPa (150,000–350,000 psi)^[7]
- Ultimate [tensile strength](#): typically 1600–2500 MPa (230,000–360,000 psi). Grades exist up to 3500 MPa (500,000 psi)
- Elongation at break: up to 15%
- K_{IC} fracture toughness: up to 175 MPa·m^{1/2}
- [Young's modulus](#): 210 GPa^[8]
- [Shear modulus](#): 77 GPa
- [Bulk modulus](#): 140 GPa
- [Hardness](#) (aged): 50 HRC (grade 250); 54 HRC (grade 300); 58 HRC (grade 350)^[citation needed]

Maraging Steels

Maraging steels are carbon free iron-nickel alloys with additions of cobalt, molybdenum, titanium and aluminium. The term maraging is derived from the strengthening mechanism, which is transforming the alloy to martensite with subsequent age hardening.

Table 1 summarizes the alloy content of the 18% nickel – cobalt - molybdenum family as developed by Inco in the late 1950s.

Air cooling the alloy to room temperature from 820°C creates a soft iron nickel martensite, which contains molybdenum and cobalt in supersaturated solid solution. Tempering at 480 to 500°C results in strong hardening due to the precipitation of a number of intermetallic phases, including, nickel-molybdenum, iron-molybdenum and iron-nickel varieties.

Maraging Steels

Type	Yield Strength (0,2% proof stress) (MPa)	% Alloy content				
		Ni	Co	Mo	Ti	Al
18Ni1400	1400	18	8.5	3	0.2	0.1
18Ni1700	1700	18	8	5	0.4	0.1
18Ni1900	1900	18	9	5	0.6	0.1
18Ni2400	2400	17.5	12.5	3.75	1.8	0.15
17Ni1600 (cast)	1600	17	10	4.6	0.3	0.05

Table 1: Summary of the alloy content of the 18% nickel – cobalt - molybdenum family

With yield strength between 1400 and 2400 MPa maraging steels belong to the category of ultra-high-strength materials. The high strength is combined with excellent toughness properties and weldability.

Typical applications areas include:

- aerospace, e.g. undercarriage parts and wing fittings,
- tooling & machinery , e.g. extrusion press rams and mandrels in tube production, gears
- Ordnance components and fasteners.

Properties of Maraging Steels

Abstract:

The **18% Ni**-maraging steels, which belong to the family of iron-base alloys, are strengthened by a process of martensitic transformation, followed by age or precipitation hardening. Precipitation hardenable stainless steels are also in this group. Maraging steels work well in electro-mechanical components where ultra-high strength is required, along with good dimensional stability during heat treatment.

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Maraging steels work well in electro-mechanical components where ultra-high strength is required, along with good dimensional stability during heat treatment. Several desirable properties of maraging steels are:

- Ultra-high strength at room temperature
- Simple heat treatment, which results in minimum distortion
- Superior fracture toughness compared to quenched and tempered steel of similar strength level
- Low carbon content, which precludes decarburization problems
- Section size is an important factor in the hardening process
- Easily fabricated
- Good weldability.

These factors indicate that maraging steels could be used in applications such as shafts, and substitute for long, thin, carburized or nitrided parts, and components subject to impact fatigue, such as print hammers or clutches.

Tempering of maraging steels

Tempering as an operation of heat treatment has been well known from the Middle Ages. It is used with martensite-quenched alloys. The processes of tempering will be considered here for steels only, since steels constitute an overwhelming majority of all martensite-hardenable alloys.

Maraging steels are carbonless **Fe-Ni** alloys additionally alloyed with cobalt, molybdenum, titanium and some other elements. A typical example is an iron alloy with **17-19% Ni, 7-9% Co, 4.5-5% Mo** and **0.6-0.9% Ti**. Alloys of this type are hardened to martensite and then tempered at 480-500 °C. The tempering results in strong precipitation hardening owing to the precipitation of intermetallics from the martensite, which is supersaturated with the alloying elements. By analogy with the precipitation hardening in aluminum, copper and other non-ferrous alloys, this process has been termed ageing, and since the initial structure is martensite, the steels have been called maraging.

The structure of commercial maraging steels at the stage of maximum hardening can contain partially coherent precipitates of intermediate metastable phases **Ni₃Mo** and **Ni₃Ti**. Ni₃Ti phase is similar to hexagonal ϵ -carbide in carbon steels. Of special practical value is the fact that particles of intermediate intermetallics in maraging steels are extremely disperse, which is mainly due to their precipitation at dislocations.

The structure of maraging steels has a high density of dislocations, which appear on martensitic rearrangement of the lattice. In lath (untwined) martensite, the density of dislocations is of an order of 10^{11} - 10^{12} cm⁻², i.e. the same as in a strongly strain-hardened metal. In that

respect the substructure of maraging steel (as hardened) differs appreciably from that of aluminum, copper and other alloys which can be quenched without polymorphic change.

It is assumed that the precipitation of intermediate phases on tempering of maraging steels is preceded with segregation of atoms of alloying elements at dislocations. The atmospheres formed at dislocations serve as centers for the subsequent concentration stratification of the martensite, which is supersaturated with alloying elements.

In maraging steels the dislocation structure that forms in the course of martensitic transformation, is very stable during the subsequent heating and practically remains unchanged at the optimum temperatures of tempering (480-500 °C). Such a high density of dislocations during the whole course of tempering may be due to an appreciable extent, to dislocation pinning by disperse precipitates.

A long holding in tempering at a higher temperature (550 °C or more) may coarsen the precipitates and increase the interparticle spacing, with the dislocation density being simultaneously reduced. With a long holding time, semi coherent precipitates of intermediate intermetallics are replaced with coarser incoherent precipitates of stable phases such as **Fe₂Ni** or **Fe₂Mo**.

At increased temperatures of tempering (above 500 °C), maraging steels may undergo the reverse $\gamma \rightarrow \alpha$ martensitic transformation, since the as point is very close to the optimum temperatures of tempering. The formation of austenite is then accompanied with the dissolution of the intermetallics that have precipitated from the α -phase.

Variations of Properties in Maraging Steels

The dependence of mechanical properties of maraging steels on the temperature of tempering is of the same pattern as that for all precipitation-hardenable alloys, i.e. the strength properties increase to a maximum, after which softening takes place. By analogy with ageing,

the stages of hardening and softening tempering may be separated in the process.

The hardening effect is caused by the formation of segregates at dislocations and, what is most important, by the formation of partially coherent precipitates of intermediate phases of the type Ni_3Ti or Ni_3Mo . The softening is due, in the first place, to replacement of disperse precipitates having greater interparticle spacing and, in the second place, to the reverse $\text{f} \rightarrow \text{f}'$ martensitic transformation which is accompanied by the dissolution of intermetallics in the austenite.

The ultimate strength of maraging steels increases on tempering roughly by 80% and the yield limit, by 140%, i.e. the relative gain in strength properties is not greater than in typical age-hardening alloys, such as beryllium bronze or aluminum alloy **Grade 1915**, but the absolute values of ultimate and yield strength on tempering of maraging steels reach record figures among all precipitation hardening alloys. This is mainly due to the fact that maraging steels have a very high strength (**$R_m = 1100 \text{ MPa}$**) in the initial (as-hardened) state.

The high strength of maraging steels on tempering at 480-500 °C for 1-3 hours may be explained by the precipitation of very disperse semi coherent particles of the size and interparticle spacing of an order of 10^3 nm in the strong matrix, these intermetallic precipitates also possessing a high strength. Thus, with the same dispersity of precipitates as that of G. P. zones in precipitation, hardening non-ferrous alloys, maraging steels possess an appreciably higher ultimate strength (**$R_m = 1800-2000 \text{ MPa}$**).

As compared with martensite-hardenable carbon-containing steels, carbonless maraging steels show, for the same strength, a substantially greater resistance to brittle fracture, which is their most remarkable merit. On tempering to the maximum strength, the ductility indices and impact toughness, though diminish somewhat, still remain rather high. The high ductility of the carbonless matrix and the high dispersity of

uniformly distributed intermetallic precipitates are responsible for a very high resistance to cracking, which is the most valuable property of modern high-strength structural materials.

The properties of maraging steels clearly indicate that these steels have many potential applications in mechanical components of electro-mechanical data processing machines. Use of these steels in shafts that require good dimensional control following heat treatment should be pursued for two reasons. First, maintaining dimensions should be easier because quenching and tempering are not necessary. Second, wear data indicate that equivalent or better wear resistance is obtained from the maraging steel than from the more commonly used shaft materials.

Impact-fatigue strength of **18% Ni**-maraging steels indicates that these steels could be used in repeated impact loading situations. The good fracture toughness, compared to that of quenched and tempered alloy steels at the same strength level, indicates possible use in high-impact low-cycle load applications.

Finally, due to the relatively low temperature of aging, the use of the maraging steels for long, thin parts should be considered. Here, their use as a replacement for some case hardened or nitrided components is indicated that the potential application should be carefully studied.

Intermetallic

Intermetallic or **intermetallic compound** is a term that is used in a number of different ways. Most commonly it refers to solid-state phases involving [metals](#). There is a "research definition" adhered to generally in scientific publications, and a wider "common use" term. There is also a completely different use in [coordination chemistry](#), where it has been used to refer to complexes containing two or more different metals.

Although the term *intermetallic compounds*, as it applies to solid phases, has been in use for many years, its introduction was regretted, for example by [Hume-Rothery](#) in 1955.^[1]

Note that many intermetallic compounds are often simply called '[alloys](#)', although this is somewhat of a misnomer. Both are metallic phases containing more than one element, but in alloys, the various elements substitute randomly for one another in the [crystal structure](#), forming a [solid solution](#) with a range of possible compositions, while in intermetallic compounds, different elements are ordered into different sites in the structure, with distinct local environments and often a well-defined, fixed stoichiometry. Complex structures with very large [unit cells](#) can be formed.

Definitions

Research definition

Schulze in 1967,^[2] defined intermetallic compounds as *solid phases containing two or more metallic elements, with optionally one or more non-metallic elements, whose crystal structure differs from that of the other constituents*. Under this definition the following are included

- Electron (or Hume-Rothery) compounds
- Size packing phases. e.g. [Laves phases](#), [Frank–Kasper phases](#) and [Nowotny phases](#)
- [Zintl phases](#)

The definition of a metal is taken to include:

- the so-called [poor metals](#), i.e. aluminium, gallium, indium, thallium, tin and lead
- some, if not all, of the [metalloids](#), e.g. silicon, germanium, arsenic, antimony and tellurium.

[Alloys](#), which are homogeneous [solid solutions](#) of metals, and [interstitial compounds](#) such as the [carbides](#) and [nitrides](#) are excluded under this definition. However, interstitial intermetallic compounds are included as are alloys of intermetallic compounds with a metal.

Common use

In common use, the research definition, including [poor metals](#) and [metalloids](#), is extended to include compounds such as [cementite](#), Fe₃C. These compounds, sometimes termed [interstitial compounds](#) can be [stoichiometric](#), and share similar properties to the intermetallic compounds defined above.

Intermetallics involving two or more metallic elements

Intermetallic compounds are generally brittle and high melting. They often offer a compromise between [ceramic](#) and metallic properties when hardness and/or resistance to high temperatures is important enough to sacrifice some [toughness](#) and ease of processing. They can also display desirable [magnetic](#), superconducting and chemical properties, due to their strong internal order and mixed ([metallic](#) and [covalent/ionic](#)) bonding, respectively. Intermetallics have given rise to various novel materials developments. Some examples include [alnico](#) and the [hydrogen](#) storage materials in [nickel metal hydride](#) batteries. [Ni₃Al](#), which is the hardening phase in the familiar

nickel-base [superalloys](#), and the various [titanium](#) aluminides have also attracted interest for [turbine blade](#) applications, while the latter is also used in very small quantities for [grain refinement](#) of [titanium alloys](#). [Silicides](#), intermetallics involving silicon, involving many of the elements have been studied for, and some utilized as, barrier and contact layers in [microelectronics](#).^[4]

Properties and examples

- [Magnetic materials](#) e.g. [alnico](#); [sendust](#); Permendur, FeCo
- [Superconductors](#) e.g. [A15 phases](#); [niobium-tin](#)
- [Hydrogen storage](#) e.g. AB₅ compounds ([nickel metal hydride batteries](#))
- [Shape memory alloys](#) e.g. Cu-Al-Ni (alloys of Cu₃Al and nickel); [Nitinol](#) (NiTi)
- Coating materials e.g. NiAl
- High-temperature [structural materials](#) e.g. [nickel aluminide](#), Ni₃Al
- [Dental amalgams](#) which are alloys of intermetallics Ag₃Sn and Cu₃Sn
- [Gate contact/ barrier layer](#) for [microelectronics](#) e.g. TiSi₂^[5]
- [Amorphous metals](#) or [metallic glasses](#) are a recent elaboration of the concept of intermetallic materials.
- [Laves phases](#) (AB₂), e.g., MgCu₂, MgZn₂ and MgNi₂.

The formation of intermetallics can cause problems. [Intermetallics of gold and aluminium](#) can be a significant cause of [wire bond](#) failures in [semiconductor devices](#) and other [microelectronics](#) devices. There are five intermetallic compounds in the [binary phase diagram of Al–Au](#). AuAl₂ is known as "purple plague". Au₅Al₂ is known as "white plague".

History

Examples of intermetallics through history include:

- Roman yellow [brass](#), CuZn
- Chinese high tin [bronze](#), Cu₃₁Sn₈
- [type metal](#) SbSn

German type metal is described as breaking like glass, not bending, softer than copper but more fusible than lead.^[6] The chemical formula does not agree with the one above; however, the properties match with an intermetallic compound or an alloy of one.

Metallic glasses - Types and Applications.

Metallic glasses are a relatively new class of materials whose dominant characteristic is non crystalline which is unlike normal metal alloys that have crystalline structure. In this article I have provided brief description about Metallic glasses.

What is Metallic glass ?

Metallic glasses are those which share the properties of both metals and glasses. In general, they are strong, ductile, malleable, opaque and brittle. They also have good magnetic properties and corrosion resistance. It was discovered in the year 1970. They are also called as **amorphous metals**.

Types of Metallic glasses:

There are two types of Metallic glasses

1. Metal - metal metallic glasses.
2. Metal - metalloid metallic glasses.

1. Metal - metal metallic glasses.

They are formed by combination of metals.

Example:

1. Ni - Nb (Nickel & Niobium).
2. Mg - Zn (Magnesium & zinc).
3. Cu - Zr (Copper & Zirconium).
4. Hf - V (Hafnium & Vanadium).

2. Metal - metalloid metallic glasses.

They are formed by combination of metals and metalloid.

Example:

Metals like Fe, Co, Ni and metalloid such as B, Si, C, P.

Applications of metallic glasses:

In Electrical and Electronics

Since metallic glasses have high electrical resistance, they are used to make accurate standard resistance, computer memories and magnetic resistance sensors.

Nuclear reactor engineering

1. The magnetic properties of metallic glasses are not affected by irradiation and so they are useful in preparing containers for **nuclear waste disposal and magnets for fusion reactors**.
2. Chromium and phosphorous based metallic glasses have high corrosion resistances and so they are used in inner surface of the reactor vessels.

Bio - Medical Industries

1. Due to high resistance to corrosion, metallic glasses are suitable for cutting and making surgical instruments.
2. They may also be used as prosthetic materials for implantation in human body.

Other Applications

1. They possess high physical and tensile strength. They are more superior than common steels and thus they are useful as reinforcing elements in concrete, plastic and rubber.
2. Strong ribbons of metallic glasses can be used for simple filament winding to reinforce pressure vessels and also to construct large fly wheels for energy storage.
3. Due to their good strength, high ductility and good corrosion resistance, they are used to make **razor**

blades and different kinds of springs.

4. Since metallic glasses have soft magnetic properties, they are used in tape recorder heads, cores of high-power transformers and metallic shields.

5. Superconducting metallic glasses are be used to produce **high magnetic fields and magnetic levitation effect**.

I. What are Shape Memory Alloys?

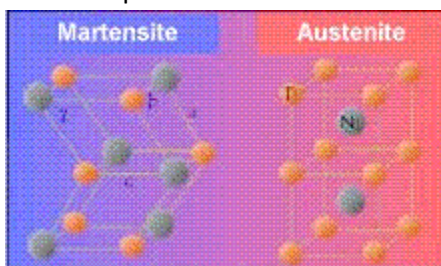
Shape memory alloys (SMA's) are metals, which exhibit two very unique properties, [pseudo-elasticity](#), and the [shape memory effect](#). Arne Olander first observed these unusual properties in 1938 (Oksuta and Wayman 1998), but not until the 1960's were any serious research advances made in the field of shape memory alloys. The most effective and widely used alloys include NiTi (Nickel - Titanium), CuZnAl, and CuAlNi.

II. Applications of Shape Memory Alloys

The unusual properties mentioned above are being applied to a wide variety of applications in a number of different fields. The buttons below are links to pages about some of the most promising applications of SMAs. Each page contains information about the application as well as videos and interactive applets which allow you to become more familiar with the behavior of SMAs.

III. How Shape Memory Alloys Work

Figure 1: The Martensite and Austenite phases



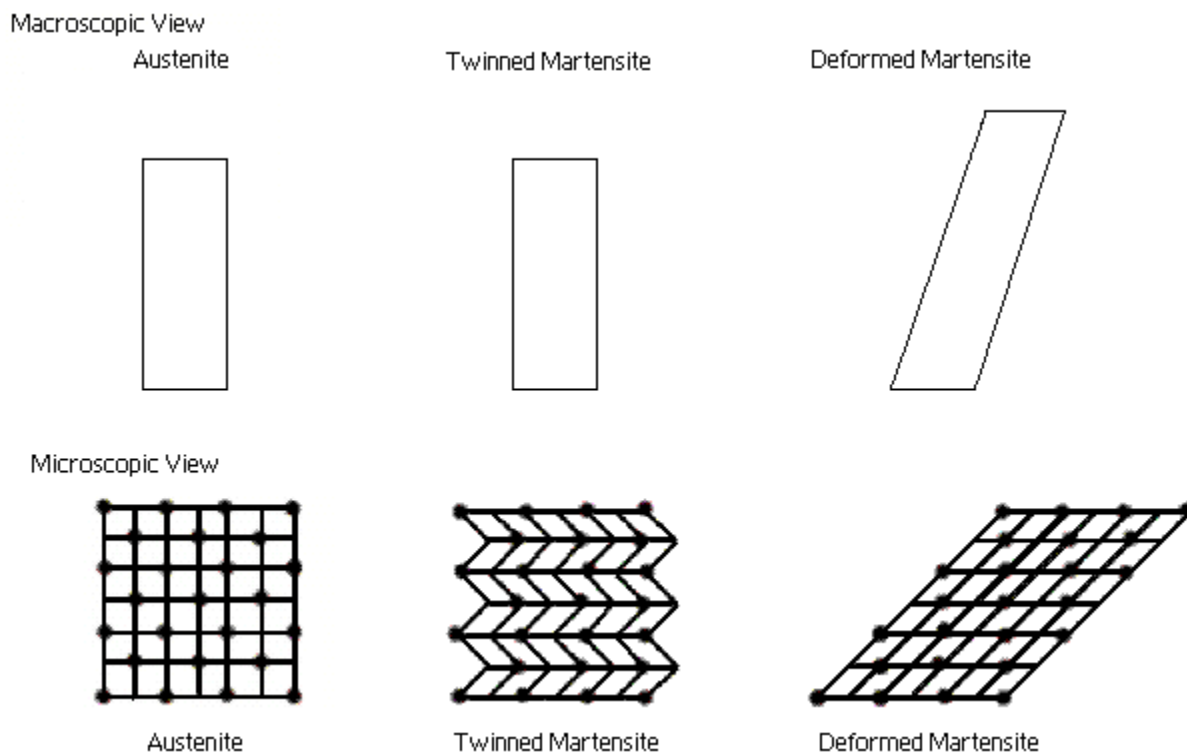
The two unique properties described above are made possible through a solid state phase change, that is a molecular rearrangement, which occurs in the shape memory alloy.

Typically when one thinks of a phase change a solid to liquid or liquid to gas change is the first idea that comes to mind. A solid state phase change is similar in that a molecular rearrangement is occurring, but the molecules remain closely packed so that the substance remains a solid. In most shape memory alloys, a temperature change of only about 10°C is

necessary to initiate this phase change. The two phases, which occur in shape memory alloys, are [Martensite](#), and [Austenite](#).

Martensite, is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned which is the configuration shown in the middle of Figure 2. Upon deformation this phase takes on the second form shown in Figure 2, on the right. Austenite, the stronger phase of shape memory alloys, occurs at higher temperatures. The shape of the Austenite structure is cubic, the structure shown on the left side of Figure 2. The un-deformed Martensite phase is the same size and shape as the cubic Austenite phase on a macroscopic scale, so that no change in size or shape is visible in shape memory alloys until the Martensite is deformed.

Figure 2: Microscopic and Macroscopic Views of the Two Phases of Shape Memory Alloys

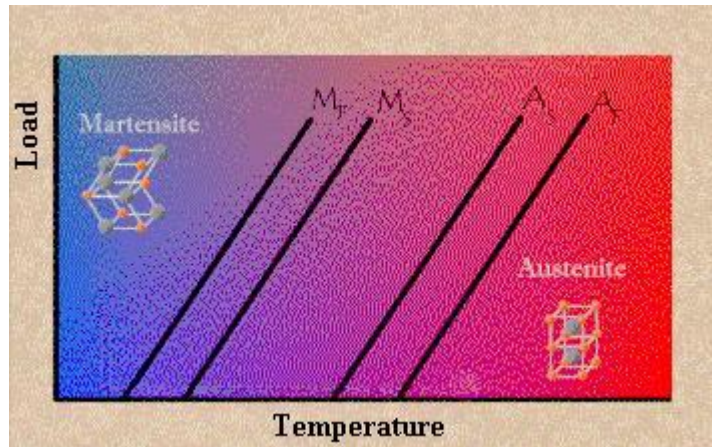


Oulu University - <http://herkules.oulu.fi/isbn9514252217/html/x317.html>

The temperatures at which each of these phases begin and finish forming are represented by the following variables: [Ms](#), [Mf](#), [As](#), [Af](#). The amount of loading placed on a piece of shape memory alloy

increases the values of these four variables as shown in Figure 3. The initial values of these four variables are also dramatically affected by the composition of the wire (i.e. what amounts of each element are present).

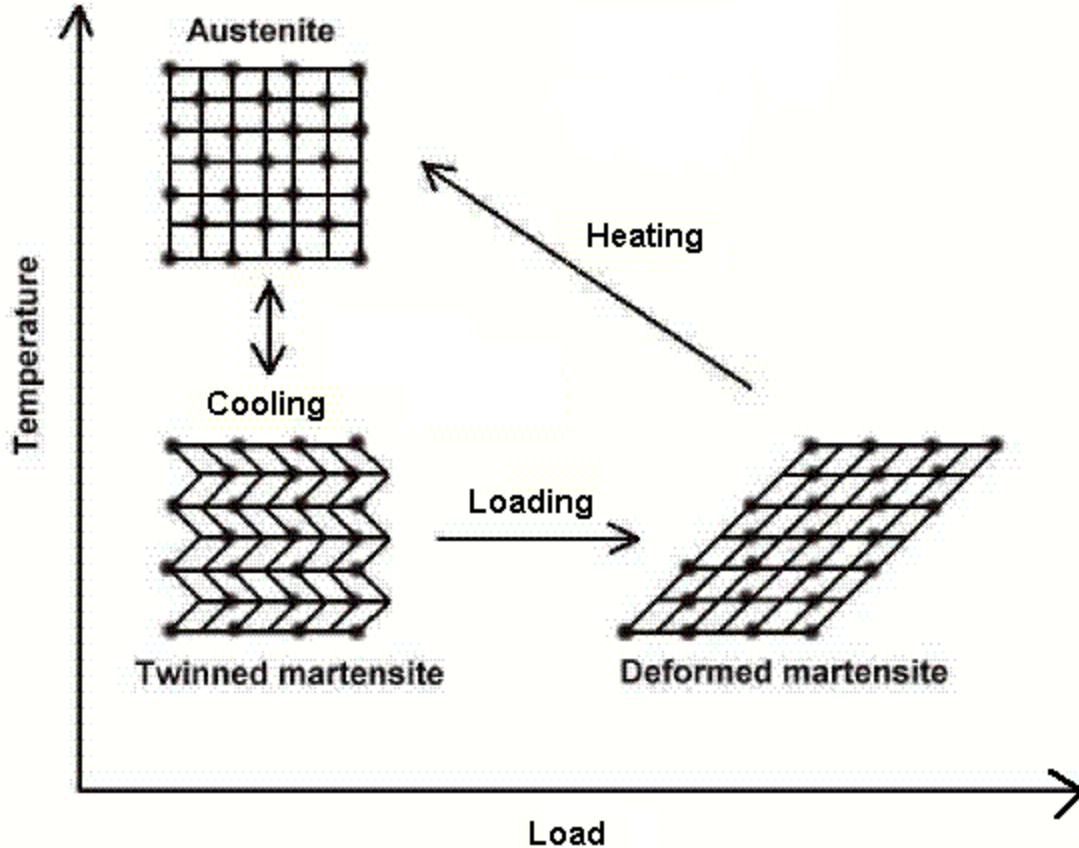
Figure 3: The Dependency of Phase Change Temperature on Loading



Texas A&M SMART Lab - <http://smart.tamu.edu/>

Shape Memory Effect

Figure 4: Microscopic Diagram of the Shape Memory Effect



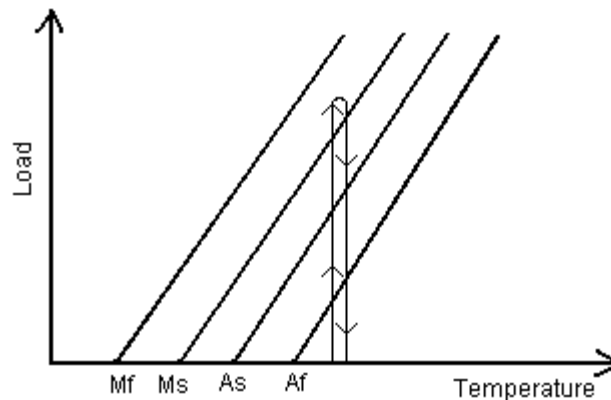
The shape memory effect is observed when the temperature of a piece of shape memory alloy is cooled to below the temperature M_f . At this stage the alloy is completely composed of Martensite which can be easily deformed. After distorting the SMA the original shape can be recovered simply by heating the wire above the temperature A_f . The heat transferred to the wire is the power driving the molecular rearrangement of the alloy, similar to heat melting ice into water, but the alloy remains solid. The deformed Martensite is now transformed to the cubic Austenite phase, which is configured in the original shape of the wire.

The Shape memory effect is currently being implemented in:

- Coffepots
- The space shuttle
- Thermostats
- Vascular Stents
- Hydraulic Fittings (for Airplanes)

Pseudo-elasticity

Figure 5: Load Diagram of the pseudo-elastic effect Occurring



Pseudo-elasticity occurs in shape memory alloys when the alloy is completely composed of Austenite (temperature is greater than A_f). Unlike the shape memory effect, pseudo-elasticity occurs without a change in temperature. The load on the shape memory alloy is increased until the Austenite becomes transformed into Martensite simply due to the loading; this process is shown in Figure 5. The loading is absorbed by the softer Martensite, but as soon as the loading is decreased the Martensite begins to transform back to Austenite since the temperature of the wire is still above A_f , and the wire springs back to its original shape.

Some examples of applications in which pseudo-elasticity is used are:

- Eyeglass Frames
- Bra Underwires
- Medical Tools
- Cellular Phone Antennae
- Orthodontic Arches

IV. Advantages and Disadvantages of Shape Memory Alloys

Some of the main advantages of shape memory alloys include:

- Bio-compatibility
- Diverse Fields of Application
- Good Mechanical Properties (strong, corrosion resistant)

There are still some difficulties with shape memory alloys that must be overcome before they can live up to their full potential. These alloys are still relatively expensive to manufacture and machine compared to other materials such as steel and aluminum. Most SMA's have poor fatigue properties; this means that while under the same loading conditions (i.e. twisting, bending, compressing) a steel component may survive for more than one hundred times more cycles than an SMA element.

Shape memory alloys (SMAs) are metals that "remember" their original shapes. SMAs are useful for such things as actuators which are materials that "change shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature or electromagnetic fields" (Rogers, 155). The potential uses for SMAs especially as actuators have broadened the spectrum of many scientific fields. The study of the history and development of SMAs can provide an insight into a material involved in cutting-edge technology. The diverse applications for these metals have made them increasingly important and visible to the world.

History

Nickel-titanium alloys have been found to be the most useful of all SMAs. Other shape memory alloys include [copper-aluminum-nickel, copper-zinc-aluminum, and iron-manganese-silicon alloys](#). (Borden, 67) The generic name for the family of nickel-titanium alloys is Nitinol. In 1961, Nitinol, which stands for Nickel Titanium Naval Ordnance Laboratory, was discovered to possess the unique property of having shape memory. William J. Buehler, a researcher at the Naval Ordnance Laboratory in White Oak, Maryland, was the one to discover this shape memory alloy. The actual discovery of the shape memory property of Nitinol came about by accident. At a laboratory management meeting, a strip of Nitinol was presented that was bent out of shape many times. One of the people present, Dr. David S. Muzzey, heated it with his pipe lighter, and surprisingly, the strip stretched back to its original form. (Kauffman and Mayo, 4)

Crystal Structures

Exactly what made these metals "remember" their original shapes was in question after the discovery of the shape-memory effect. Dr. Frederick E. Wang, an expert in crystal physics, pinpointed the structural changes at the atomic level which contributed to the unique properties these metals have. (Kauffman and Mayo, 4)

He found that Nitinol had phase changes while still a solid. These phase changes, known as martensite and austenite, "involve the rearrangement of the position of particles within the crystal structure of the solid" (Kauffman and Mayo, 4). Under the transition temperature, Nitinol is in the martensite phase. The transition temperature varies for different compositions from about -50°C to 166°C (Jackson, Wagner, and Wasilewski, 1). In the martensite phase, Nitinol can be bent into various shapes. To fix the "parent shape" (as it is called), the metal must be held in position and heated to about 500°C . The high temperature "causes the atoms to arrange

themselves into the most compact and regular pattern possible" resulting in a rigid cubic arrangement known as the austenite phase (Kauffman and Mayo, 5-6). Above the transition temperature, Nitinol reverts from the martensite to the austenite phase which changes it back into its parent shape. This [cycle](#) can be repeated millions of times (Jackson, Wagner, and Wasilewski, 1).

Manufacture

There are various ways to [manufacture](#) Nitinol. Current techniques of producing nickel-titanium alloys include vacuum melting techniques such as electron-beam melting, vacuum arc melting or vacuum induction melting. "The cast ingot is press-forged and/or rotary forged prior to rod and wire rolling. Hot working to this point is done at temperatures between 700 ° C and 900 ° C" (Stoeckel and Yu, 3).

There is also a process of cold working of Ni-Ti alloys. The procedure is similar to titanium wire fabrication. Carbide and diamond dies are used in the process to produce wires ranging from 0.075mm to 1.25mm in diameter. (Stoeckel and Yu, 4) Cold working of Nitinol causes "marked changes in the mechanical and physical properties of the alloy" (Jackson, Wagner, and Wasilewski, 21). These processes of the production of Nitinol are described in greater detail in Jackson, Wagner, and Wasilewski's report (15-22).

Properties

The [properties](#) of Nitinol are particular to the exact composition of the metal and the way it was processed. The physical properties of Nitinol include a melting point around 1240 ° C to 1310 ° C, and a density of around 6.5 g/cm³ (Jackson, Wagner, and Wasilewski, 23). Various other physical properties tested at different temperatures with various compositions of elements include electrical resistivity, thermoelectric power, Hall coefficient, velocity of sound, damping, heat capacity, magnetic susceptibility, and thermal conductivity (Jackson, Wagner, and Wasilewski, 23-55). Mechanical properties tested include hardness, impact toughness, fatigue strength, and machinability (Jackson, Wagner, and Wasilewski, 57-73).

The large force generated upon returning to its original shape is a very useful property. Other useful properties of Nitinol are its "excellent damping characteristics at temperatures below the transition temperature range, its corrosion resistance, its nonmagnetic nature, its low density and its high fatigue strength" (Jackson, Wagner, and Wasilewski, 77). Nitinol is also to an extent impact- and heat-resistant (Kauffman and Mayo, 4). These properties translate into many uses for Nitinol.

Applications

Nitinol is being used in a variety of applications. They have been used for military, medical, safety, and robotics applications. The military has been using Nitinol couplers in F-14 fighter planes since the late 1960s. These couplers join hydraulic lines tightly and easily. (Kauffman and Mayo, 6)

Many of the current applications of Nitinol have been in the field of [medicine](#). Tweezers to remove foreign objects through small incisions were invented by NASA. [Anchors](#) with Nitinol hooks to attach tendons to bone were used for Orel Hershisser's shoulder surgery. Orthodontic wires made out of Nitinol reduces the need to retighten and adjust the wire. These wires also accelerate tooth motion as they revert to their original shapes. Nitinol [eyeglass frames](#) can be bent totally out of shape and return to their parent shape upon warming. (Kauffman and Mayo, 6) Nitinol needle [wire localizers](#) "used to locate and mark breast tumors so that subsequent surgery can be more exact and less invasive" utilize the metal's shape memory property. Another successful medical application is Nitinol's use as a [guide](#) for catheters through blood vessels (Stoeckel and Yu, 9-10).

There are examples of SMAs used in safety devices which will save lives in the future. Anti-scalding devices and fire-sprinklers utilizing SMAs are already on the market. The anti-scalding valves can be used in water faucets and shower heads. After a certain temperature, the device automatically shuts off the water flow. The main advantage of Nitinol-based fire sprinklers is the decrease in response time. (Kauffman and Mayo, 7)

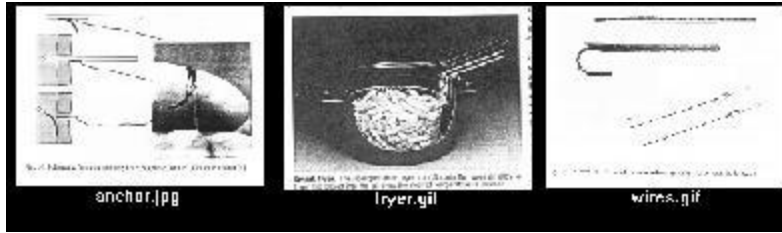
Nitinol is being used in robotics actuators and micromanipulators to simulate human muscle motion. The main advantage of Nitinol is the smooth, controlled force it exerts upon activation. (Rogers, 156)

Other miscellaneous applications of shape memory alloys include use in household appliances, in clothing, and in structures. A [deep fryer](#) utilizes the thermal sensitivity by lowering the basket into the oil at the correct temperature. (Falcioni, 114) According to Stoeckel and Yu, "one of the most unique and successful applications is the Ni-Ti underwire brassiere" (11). These bras, which were engineered to be both comfortable and durable, are already extremely successful in Japan (Stoeckel and Yu, 11). Nitinol actuators as engine mounts and suspensions can also control vibration. These actuators can help prevent the destruction of such structures as buildings and bridges. (Rogers, 156)

Other applications:

- [European Space Agency](#)
- [SMA INC.](#)

Here are some of the pictures available from this section:



Future Applications

There are many possible applications for SMAs. Future applications are envisioned to include engines in cars and airplanes and electrical generators utilizing the mechanical energy resulting from the shape transformations. Nitinol with its shape memory property is also envisioned for use as car frames. (Kauffman and Mayo, 7) Other possible automotive applications using SMA springs include engine cooling, carburetor and engine lubrication controls, and the control of a radiator blind ("to reduce the flow of air through the radiator at start-up when the engine is cold and hence to reduce fuel usage and exhaust emissions")

SMAs are "ideally suited for use as fasteners, seals, connectors, and clamps" in a variety of applications . Tighter connections and easier and more efficient installations result from the use of shape memory alloys.

Conclusion

The many uses and applications of shape memory alloys ensure a bright future for these metals. Research is currently carried out at many [robotics](#) departments and materials science departments. With the innovative ideas for applications of SMAs and the number of products on the market using SMAs continually growing, advances in the field of shape memory alloys for use in many different fields of study seem very promising.

Titanium aluminide

Titanium aluminide, [TiAl](#), is an [intermetallic chemical compound](#). It is lightweight and resistant to oxidation ^[1]and heat, however it suffers from low [ductility](#). The density of [gamma](#) TiAl is about 4.0 g/cm³. It finds use in several applications including automobiles and aircraft. The development of TiAl based alloys began about 1970; however the alloys have only been used in these applications since about 2000.

Applications

Titanium aluminide has three major intermetallic compounds: gamma TiAl, alpha 2-Ti₃Al and TiAl₃. Among the three, gamma TiAl has received the most interest and applications. Gamma TiAl has excellent mechanical properties and oxidation and corrosion resistance at elevated temperatures (over 600 degrees Celsius), which makes it a possible replacement for traditional Ni based [superalloy](#) components in aircraft [turbine](#) engines.

TiAl based alloys have a strong potential to increase the thrust-to-weight ratio in the aircraft engine. This is especially the case with the engine's low pressure turbine blades and the high pressure compressor blades. These are traditionally made up of Ni based superalloy, which is nearly twice as dense as TiAl based alloys.

Smart material

Smart materials or [designed materials](#) are materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as [stress](#), [temperature](#), moisture, [pH](#), [electric](#) or [magnetic](#) fields.

There are a number of types of smart material, some of which are already common. Some examples are as following:

- [Piezoelectric](#) materials are materials that produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied.
- [Shape-memory alloys](#) and [shape-memory polymers](#) are materials in which large deformation can be induced and recovered through temperature changes or stress changes ([pseudoelasticity](#)). The large deformation results due to martensitic phase change.
- [Magnetostrictive](#) materials exhibit change in shape under the influence of magnetic field and also exhibit change in their magnetization under the influence of mechanical stress.
- [Magnetic shape memory](#) alloys are materials that change their shape in response to a significant change in the magnetic field.
- [pH-sensitive polymers](#) are materials that change in volume when the pH of the surrounding medium changes.
- [Temperature-responsive polymers](#) are materials which undergo changes upon temperature.
- [Halochromic](#) materials are commonly used materials that change their colour as a result of changing acidity. One suggested application is for paints that can change colour to indicate [corrosion](#) in the metal underneath them.
- [Chromogenic systems](#) change colour in response to electrical, optical or thermal changes. These include [electrochromic](#) materials, which change their colour or opacity on the application of a voltage (e.g., [liquid crystal displays](#)), [thermochromic](#) materials change in colour depending on their temperature, and [photochromic](#) materials, which change colour in response to light—for example, light sensitive [sunglasses](#) that darken when exposed to bright sunlight.

- [Ferrofluid](#)
 - [Photomechanical materials](#) change shape under exposure to light.
 - [Self-healing materials](#) have the intrinsic ability to repair damage due to normal usage, thus expanding the material's lifetime
 - [Dielectric elastomers](#) (DEs) are smart material systems which produce large strains (up to 300%) under the influence of an external electric field.
 - [Magnetocaloric materials](#) are compounds that undergo a reversible change in temperature upon exposure to a changing magnetic field.
 - [Thermoelectric materials](#) are used to build devices that [convert temperature differences into electricity and vice-versa](#).
-

Smart Materials



A smart fluid developed in labs at the Michigan Institute of Technology

Science and technology have made amazing developments in the design of electronics and machinery using standard materials, which do not have particularly special properties (i.e. steel, aluminum, gold). Imagine the range of possibilities, which exist for special materials that have properties scientists can manipulate. Some such materials have the ability to change shape or size simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when near a magnet; these materials are called smart materials.

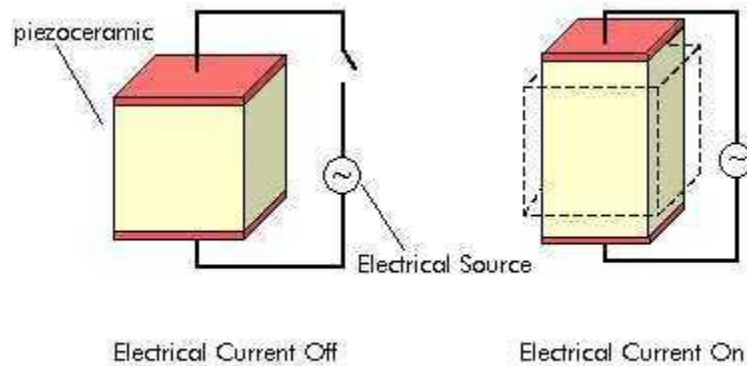
Smart materials have one or more properties that can be dramatically altered. Most everyday materials have physical properties, which cannot be significantly altered; for example if oil is heated it will become a little thinner, whereas a smart material with variable [viscosity](#) may turn from a fluid which flows easily to a solid. A variety of smart materials already exist, and are being researched extensively. These include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, and shape memory alloys. Some everyday items are already incorporating smart materials (coffeepots, cars, the International Space Station, eyeglasses) and the number of applications for them is growing steadily.

Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume, and conductivity. The property that can be altered influences what types of applications the smart material can be used for.

I. Piezoelectric Materials

Piezoelectric materials have two unique properties which are interrelated. When a piezoelectric material is deformed, it gives off a small but measurable electrical discharge. Alternately, when an electrical current is passed through a piezoelectric material it experiences a significant increase in size (up to a 4% change in volume)

Piezoelectric materials are most widely used as sensors in different environments. They are often used to measure fluid compositions, fluid density, fluid viscosity, or the force of an impact. An example of a piezoelectric material in everyday life is the airbag sensor in your car. The material senses the force of an impact on the car and sends an electric charge deploying the airbag.



An illustration of the Piezoelectric Effect

II. Electro-rheostatic and Magneto-rheostatic

Electro-rheostatic (ER) and magneto-rheostatic (MR) materials are fluids, which can experience a dramatic change in their viscosity. These fluids can change from a thick fluid (similar to motor oil) to nearly a solid substance within the span of a millisecond when exposed to a magnetic or electric field; the effect can be completely reversed just as quickly when the field is removed. MR fluids experience a viscosity change when exposed to a magnetic field, while ER fluids experience similar changes in an electric field. The composition of each type of smart fluid varies widely. The most common form of MR fluid consists of tiny iron particles suspended in oil, while ER fluids can be as simple as milk chocolate or

cornstarch and oil.

MR fluids are being developed for use in car shocks, damping washing machine vibration, prosthetic limbs, exercise equipment, and surface polishing of machine parts. ER fluids have mainly been developed for use in clutches and valves, as well as engine mounts designed to reduce noise and vibration in vehicles.

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