




# On the replacement of steel by NITINOL as coupling agent in automobile shaft

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## Abstract

Automobile couplings generally fail due to excessive misalignment in shafts and torque overload which ultimately generates vibration in the assembly. These vibrations weaken the coupling structure and ultimately get transmitted to the shaft leading to fatigue failure. Additionally, the complexity in the design of standard coupling is related to lower durability. In this system, when the radial space is larger, it triggers a bulkier transmission. Shape memory alloy such as NITINOL is a special class of smart material that possesses superelasticity which means it can retain deformation of about 8%. This material has a high degree of strength, greater elastic and shear modulus than existing coupling materials, such as steel, and has unique vibration damping features. Coupling made of NITINOL is simple in design and requires lesser space with minimal maintenance. They provide higher durability and are much reliable in operation over a wide range of temperatures. This paper aims to review the NITINOL material used in coupling technology industries and the parameters governing its shape memory effect. The knowledge gathered from this work enables to further extend the technological contribution to NiTi coupling at large-scale production in the automobile sector with direct effect on longer life for the transmission system.

**Keywords** Coupling · Automobile · NITINOL · Shape memory effect · Coupling durability

## Introduction

All automobiles are made up of several machine elements with the role of transmitting the power. Once the engine generates the power, it is transmitted to the wheels through the shaft. If the transmission distance is too long and if any

non-coaxial shafts are used for the power transmission, then vibrations will be induced due to shock and overload, which give rise to premature failure of these shafts. The coupling is used from the driver shaft to the driven shaft for effective power transmission to eliminate these issues. Coupling is a mechanical device that connects two shafts at their ends for power transmission. They are generally used in coaxial shafts, angular misaligned shafts, lateral misaligned shafts, axial misaligned shafts. Couplings are broadly divided into two categories: (1) rigid coupling (Muff, Split Muff, and Flange) for collinear or coaxial shafts and (2) flexible couplings (Bush pin type flange, Oldham, Universal) for noncollinear or non-coaxial shafts (Bhandari 2001). Certain factors need to be considered while designing a coupling for connecting shafts considering certain influencing parameters that govern its dynamics and applicability. Table 1 represents those factors and the parameters influencing them during the selection of the coupling agent.

Couplings are generally designed considering a certain torque limit, and it is advisable to operate under that limit

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**Table 1** Factors considered during the shaft coupling selection

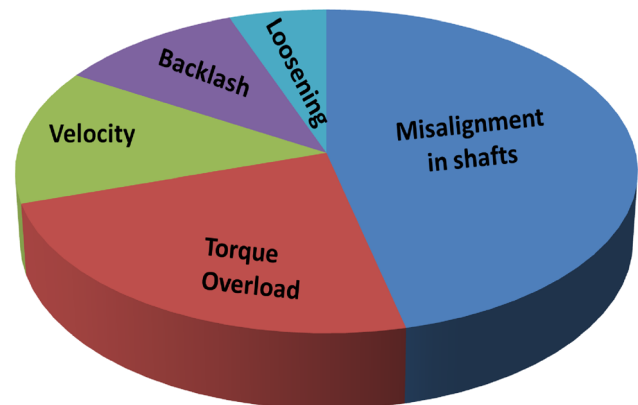
Factors	Respective influencing parameters
Material factors	Strength
	Weight
	Bore diameter of shaft
	Moment of Inertia
	Axial and radial forces
	Torsional moment
	Bending moment
	Torque rating
	Torsional stiffness and torsional rigidity
	Torsionally flexible
	Backlash
	Space requirement
	Misalignment capacity
Operational factors	Balancing
	Engaging
	Disengaging
	Safety flange
	Service factor
	Operating time
	Start per hour
	Electricity supply frequency
	Maintenance
External factors	Temperature
	Corrosive wear
	Abrasive wear
	Vertical and horizontal shafts
	Fits
Others	Alignment
	Internal standards
	Cost
	Coupling safeguards
	Replaceable wear elements
	Downtime

only. Sometimes heavy torque fluctuations are seen in the automobile from an engine firing cylinder or reciprocating pumps, which causes significant damage to couplings. High magnitude torque fluctuations cause severe vibration from unbalancing forces unless the load is so monstrous that sudden failure is observed at a different parts of coupling thereby leading to failing catastrophically (Khan 2019). Misalignment between shafts, when connected through rigid or stiff coupling at even the slightest, creates an unbalanced force component which is converted into external excitation. These vibrations weaken the structure causing the shaft assembly to fail prematurely. In general, vibrations of the shafts are minimized so that they will not

achieve their natural frequency. Otherwise, resonance comes into play, and high amplitude excitations are generated. It also results in the loosening of the shaft coupling system which hinders smooth rotation and power transmission. The consequences also include worn-off components and slow gear speed, hence vibration mitigation is much essential for parametric design (Stephen et al. 2013). The problem could be solved by using NiTi SMA coupling. The inherent behavior of this superelastic coupler gives advanced vibration damping capacity under cyclic torsional loading results in strong fatigue resistance (Wolfgang et al. 2006). Enhancement of fatigue limit allows a high absorption capacity of torsional oscillation and provides the operator with a broader safe zone (Raphael and Thiago 2021). Besides this, the coupling can adjust the misalignment in shafts and provides a long-lasting tightened joint that is pre-stressed by residual compressive forces. To counteract misalignment, a flexible coupling could be used. But they fail due to torque overload and its parts gradually wear off as in the case of rubber used in couplings. Flexible couplings such as leaf spring coupling in heavy vehicles can cause velocity loss between shafts. The loss in velocity affects the orientation and position of the shafts due to which vibrations are induced which wears off bearings/gears. In general, failure in shaft and coupling assembly is observed mainly due to misalignment, torque overload, loosening, velocity loss, and backlash. Out of these failure conditions, misalignment in shafts and torque overload are the prime causes of failure during operation (Bhandari 2001; Khan 2019; Stephen et al. 2013). The contributions to different failure modes of automobile shaft is shown in Fig. 1.

To prevent the harmful effect from spreading to other parts of rotating machinery, periodic maintenance is required which is again a costly affair. Vibration-based condition monitoring is generally deployed for periodic

### Failure Modes in Coupling

**Fig. 1** Percentage of failure for different modes in automobile shaft

maintenance which includes equipment such as accelerometers, data acquisition, and signal processing systems. (Deepam and Pabla 2015). On the other hand, damaged coupling leads to standstill operation of the rotating system. The installation of a new coupling also requires a skilled operator and an adequate time. In contrast, SMA coupling is much promising and can be installed within (30–60) sec as used during pipe joining applications in aircrafts. SMA coupling also requires very less maintenance (Pamela 1987).

In the present scenario, materials used for rigid coupling and hubs of flexible coupling are available in gray cast iron, aluminum, stainless steel, alloy steel, brass, and advanced thermoplastics. In general, aluminum is the best default choice for metallic coupling because of its economical cost. Also, because it is able to sustain well the coating process which improves the corrosion resistance and wear characteristics (Kai and Sirong 2020). Alloy steel and brass being cheaper are also used as coupling materials for low-pressure fuel lines. However, stainless steel provides excellent corrosion resistance and high strength over a wide range of temperatures and its property is attributed to fine grain structure hence used in universal coupling (Wagner and Cooney 1979). For flexible couplings, materials such as nylon and high-temperature molded rubber are used as per their convenience and level of misalignment between shafts. NITINOL can withstand more to wear than steel alloys used in conventional coupling due to its harder surface characteristics. It can also withstand extreme vibrations and not loosen due to its elastic preloaded condition without using adhesives to hold the assembled components and/or the connector itself together (Manoj et al. 2020). In most practical applications, NiTi Smart materials are replacing the conventional ones due to their intrinsic and extrinsic healing abilities and better anti-corrosive properties than steel (Cuia and B. 2020). Besides this, steel has a high coefficient of thermal expansion (at temperature around 300 °C), steel loses its properties. Further, beyond 400 °C, their loss in strength is drastic, which can be detrimental to the overall component, whereas NiTi alloy possesses better thermal stability with microstructural enhancement and can resist temperature up to 600 °C (Mehmet et al. 2017). Joints in coupling made of steel are brazed which provides weaker strength and gives different properties, when heated to a higher temperature, whereas NITINOL coupling is joined by shape memory effect without any special tools or manufacturing process. Furthermore, SMA coupling can be used for dissimilar materials which cannot be welded. NiTiNOL (6450 kg/m<sup>3</sup>) is comparatively less dense than steel (8050 kg/m<sup>3</sup>) making the system lighter and compact. Along with it, the installation is quite convenient and takes around 30 s to complete the joint and sealing of tubes as seen in pipe

joining application in the Chinese Y12F aircraft hydraulic system (Du and Xu 2015). Juergen et al. (Juergen 1983) conducted an experiment taking stainless steel and NiTi wire of various cross sections and performed stepwise twisting using a torque meter. He found that the elastic range of NITINOL wire with respect to permanent angulations was approximately double that of stainless steel. In a wire of the nominal dimensions (0.017 × 0.025), it was observed that to produce a 20° progressive torque having a magnitude of  $20 \times 10^{-3}$  N.m, the stainless steel wire was twisted through 150°, whereas NITINOL wire was turned through 300°. This indicated that the stiffness of stainless steel wire was higher, and hence, it resists angular deformation nearly twice that of the NITINOL wire of the same dimension. Upon changing the cross section, the stiffness changes which thereby changes the torquability of these materials but it was observed that the trend remains the same. When the experiments were conducted for a wire of circular cross section of NITINOL provided at 1, 3, and 25 mm nominal diameter, the optimum results were observed in the case of wire of 3 mm diameter where it was able to sustain a permanent torque of around  $41 \times 10^{-3}$  N.m and a torque angulation up to 135° before failure. The excellent torquability of NITINOL compared to steel and stable operation over a wider range of temperature is attributed to its low coefficient of thermal expansion at the austenitic phase. Being superelastic in nature, the Young's modulus of NITINOL is low but it can withstand more tensile load until failure due to its higher ultimate tensile strength. The ultimate strength of a standard SMA coupling was found to be around twice that of traditional interference fit coupling upon performing load testing. SMA coupling was able to bear a tensile load over 4000 N when designed to be as small as one cubic centimeter (Crane et al. 2014). These couplings despite being very simpler in design and mechanism offers amazing results. Table 2 gives a comparative study of the mechanical properties of NITINOL and steel.

As per the previous literature, there is limited information related to smart automobile coupling. Therefore, this paper focused on reviewing the NITINOL coupling in various automobile parts. NITINOL is a special class of smart material that possesses superelasticity properties to recover its shape at its working temperature. In addition, this material provides greater elastic and shear modulus as compared to steel and vibration damping features along with the shape recovery phenomenon. All the major influencing parameters associated with the coupling agent have been discussed in this work.

**Table 2** Comparison between NITINOL and stainless steel

Properties	NITINOL	Stainless steel
Recovered elongation	8%	0.8%
Youngs modulus	Martensite—25 GPa Austenite—75 GPa	193 GPa
Torque ability	Excellent	Poor
Density	6.45 g/cm <sup>3</sup>	8.03 g/cm <sup>3</sup>
UTS	Approx. 1240 MPa	Approx. 760 MPa
Thermal expansion coefficient	Martensite- $6.6 \times 10^{-6}$ cm/cm/°C Austenite- $11.0 \times 10^{-6}$ cm/cm/°C	$17.3 \times 10^{-6}$ cm/cm/°C

## Historical background of NiTi coupling

The year 1962 paved the way for SMA in the form of NITINOL (Ni<sub>50</sub>Ti<sub>50</sub>) developed by the Naval Ordnance Laboratory. NiTi alloy was found to possess shape memory properties upon stress-induced heating. After its discovery, the application of NITINOL spread into many diverse sectors where its properties were exploited for industrial application as well. In 1969, NITINOL was shaped as a coupler used for joining pipes. The initiative was taken by Raychem's Corporation who had wide expertise in heat-shrinkable plastics. The coupler was named Cryofit or Shrinko-fit pipe coupler which was used to join hydraulic fluid lines in the F-14 jet fighter built by Grumman Aerospace Corporation (Liu et al. 2006). Further, it was used to join titanium tubes in the U.S. Navy. The product was a line of 3000 psi hydraulic coupling. It was commercialized, and over 3 million couplings were put to service in the year 1971 (Tabesh et al. 2017). After a decade, SMA coupling became widely popular, and in 1974, it was used as connectors in the navigation system of the Trident missile. These connectors were primarily very reliable under the high shock and vibration environment of the missile system. In 1975, the British Royal Navy implemented 6000psi coupling for its Trafalgar class Nuclear submarines. Later in 1976, U.S. Navy used it on its surface ships. These couplings used NiTi-Fe alloy as the coupling material. During the beginning of 1980, NiTi alloy, such as NiTiNb, connectors were used in the FMC Bradley Fighting vehicle, piezoelectric accelerometers, tube fittings used in naval gage lines, and other Military and Aerospace applications (George and Isaac 1997). Beginning in 1989, NiTi-Fe rings were used to clamp polyurethane hose to the fittings in sonar towered arrays. During 1990, NiTiNb rings were used for metal wiring conduits on domestic civilian aircraft. Influenced by its benefits, Raychem launched a standardized line of SMA fastener rings in 1992 under the name UniLok®. By 1993, the rings find uses in a broad range of new applications, including clamping a bundle of optical components in a particle counter, sealing a cover to

a pressure sensor, joining aerospace valve components, retaining a 10-inch diameter nuclear seal, and providing a stop on a rocket motor shuttle valve. SMA tube in sealing connection of hydraulic system on Y12F airplane was tested on three planes with 400 h of flight, and no case of leakage was found by the Chinese Air-force (Du and Xu 2015). SMAs are now used as actuators, controllers, vibration isolators, sensors, dampers, and structural connectors. SMA of NiTi is commonly implemented in oil and gas industries for piping networks (Patil and Song 2016). SMA couplers are recently used in offshore hydraulic control equipment as a tubing solution replacing welded joints (Karakoc et al. 2021). Recently, it has been reported to be used in nuclear reactors (high energy particle accelerators) as beam pipe connectors providing temperature-induced clamping and unclamping with remote activation (Niccolia et al. 2017). This NiTi coupling is now known as smart coupling.

## Smart effect in coupling

SMA is a functional material with a high energy density that can provide maximum work output per unit volume. NiTi alloy is produced using a process chain that starts with the fabrication of predetermined composition, primary shaping process, pretreatment, and training. It can be fabricated by both conventional and non-conventional methods such as casting, powder metallurgy process, selective laser melting, selective laser sintering, and electron beam melting (Sharma et al. 2015). At high temperatures, NITINOL exists in a simple cubic BCC structure referred to as austenite which on cooling gets converted into a more complicated monoclinic crystal structure spontaneously, known as martensite. This crystal structure has the ability to undergo limited deformation by atomic shear without breaking the bonds. This phenomenon is characterized by twinning and de-twinning which is the collective motion of atoms on distances smaller than lattice parameters (Nnamchi et al. 2019). This means if the NITINOL wire is

bend, the internal structure remains intact. Upon heating, the SMA recognizes its initial shape and the de-twinned martensite structure is converted to austenite, its original dimension. To account for the thermal motion, the atoms slip back to their original lattice configuration from the austenite phase retaining their original shape. In NITINOL, an overall strain approaching 8% can be attributed to martensite shear conveying superelasticity or pseudo-elasticity behavior (Otsuka and Ren 2005). This property is often called the two-way property of shape memory alloy. In non-memory metals, the atoms in the crystal lattice are held rigidly. They can compensate for deformation under the elastic limit only. Beyond the yield point, plastic deformation takes place where atoms slip to the nearest position out of their unit cell and bond weakens. This phenomenon is irreversible, hence a permanent plastic deformation is observed in the form of non-recoverable strain energy as shown in Fig. 2a. In NITINOL, however, atoms move along with their lattice position instead of leaving their unit cell which gets restored upon heating above austenite transformation temperature as shown in Fig. 2b (Naresh et al. 2016). All the phase transformation in NiTi smart system is known as Military transformation, which is the responsible factor for recovery.

### External coupling concept

Tabesh et al. (2012) fabricated a NITINOL alloy coupler at room temperature originally in the austenite phase to the required coupling dimensions. The coupling size (D1) was made smaller with respect to the shaft or pipe diameter (D2), as shown in Fig. 3a. To produce the desired coupling effect, the coupler was placed in a liquid nitrogen bath at  $-120\text{ }^{\circ}\text{C}$  where the austenite grains are converted to

elastic martensite. There the coupler was radially expanded to a diameter of  $D_m$  slightly above the outer diameter of the shaft or pipe to be joined, as shown in Fig. 3b. This was accomplished by forcing an oversize tapered mandrel longitudinally through the coupler bore. When continually cooled in liquid nitrogen, the coupler remained stably expanded. Coupling two sections of hydraulic pipe or shaft were then accomplished by simply inserting the pipe or shaft ends into the expanded NITINOL coupler, and then the coupler was allowed to warm to its near original, or memory, diameter ( $D_1$ ) on heating. But the contraction was restricted to the outer diameter of the pipe, allowing it to have a diameter ( $D_f$ ). The rest of the restricted strain was converted into residual compressive stress, ensuring that all recovery strain was used as joining force. The procedure takes nearly half a minute for the coupler to touch the skin of the pipe, as shown in Fig. 3c. The radial contraction of the coupler, combined with the very high associated force, provided a continuously clamping and sealed joint (Tabesh et al. 2012).

If we consider a shaft having a nominal diameter of 100 mm, under 3% tolerance, the outer diameter will be between 97 and 103 mm. For an SMA coupling, the inner diameter must be enlarged to not less than 103 mm during in martensitic phase. Then, the SMA joint must be warmed or heated to achieve an inner diameter of not more than 97 mm. Hence, for the SMA coupling, it is expected to provide a shape memory effect of six percent at a minimum. It is evident that the shape memory capacity must be twice that of the tolerance of the shaft. Since the circumference of the shaft is a function of its diameter, it is possible to predict SMA capacity with the diameter of the shaft (William 2010). In this regard, the tolerance of the shaft is a prime variable while selecting SMA coupling.

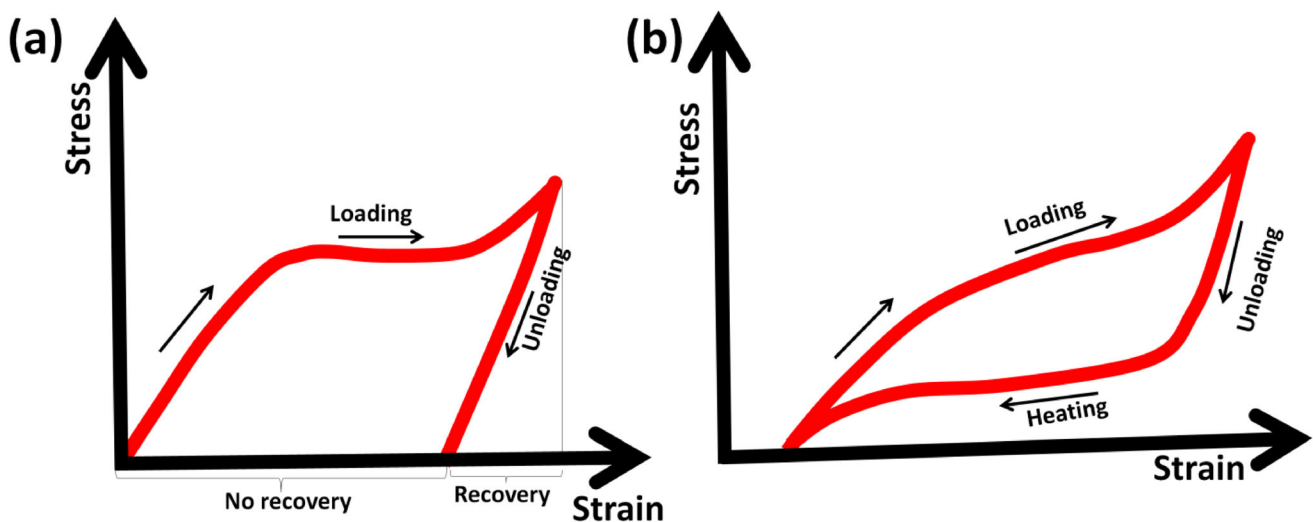
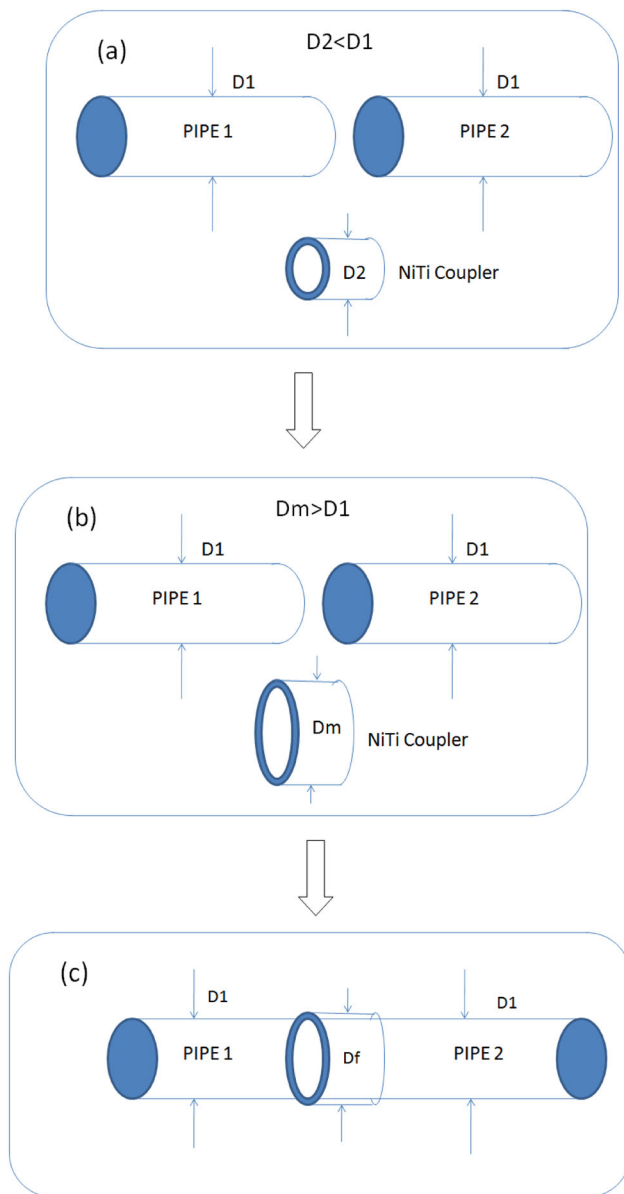


Fig. 2 Stress–strain behavior of a conventional material. b Pseudo-elasticity in SMA



**Fig. 3** Installation procedure of SMA coupling: **a** coupling agent in austenite phase, **b** expanded martensite phase in liquid  $N_2$ , and **c** re-conversion to austenite upon cooling forming tight joint

However, NiTi coupling provides 8% shape memory capacity which is quite sufficient enough to accommodate the tolerance limit as compared to the other materials alternatives (Wada and Liu 2005).

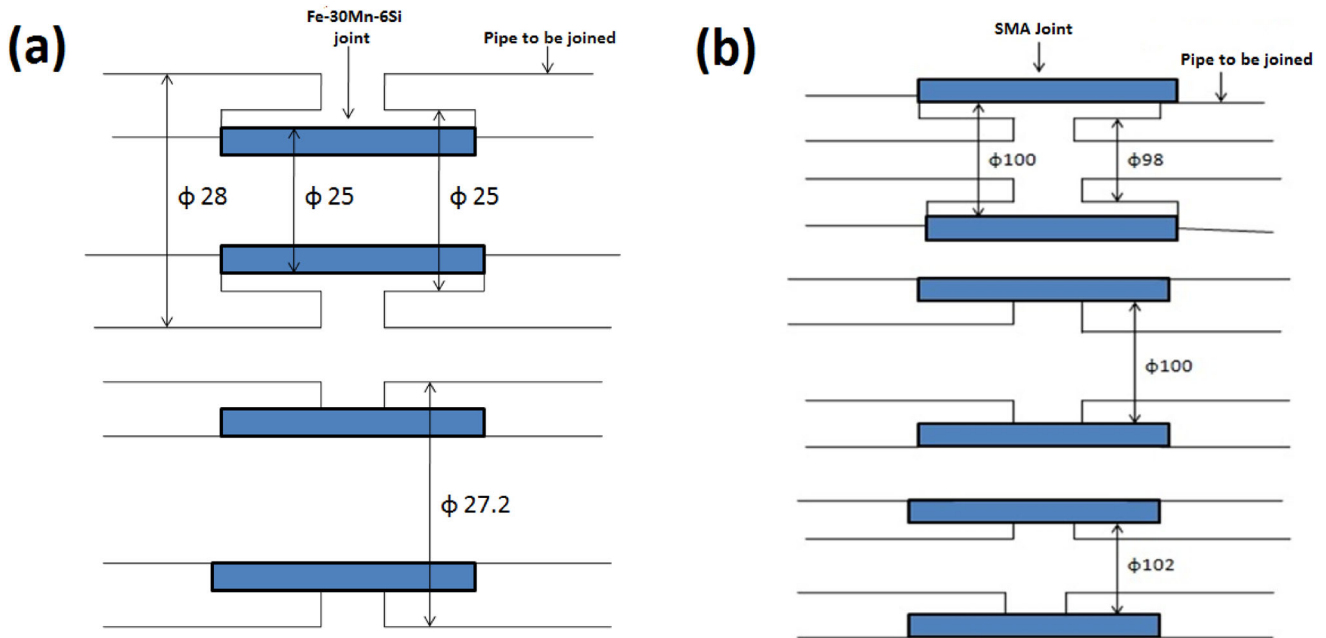
The contact stress increases linearly after heating it to austenite due to the difference in the coefficient of thermal expansion. Complete recovery is achieved by heating it beyond contact temperature. In NITINOL application, the transformation temperature is designed to be less than  $-120\text{ }^\circ\text{C}$  ( $-184^\circ\text{F}$ ), which is the required minimum operating temperature. Researchers have developed finite element analysis of the NiTi coupling considering

actuation temperature and contact pressure and measured the same experimentally through a strain gauge installed at the inner surface of the coupling. The finite element analysis results showed an excellent match with experimental plots (Tabesh et al. 2018; Chen et al. 2020). The installation of SMA coupling is quite simple and convenient but there are certain procedures to be followed to obtain desired shape memory effect (Broyles and Jervis 1973). This technique was applied in F-14 fighter Aircraft and Petrochemical plants and was highly effective in producing leak-proof joints.

### External coupling concept

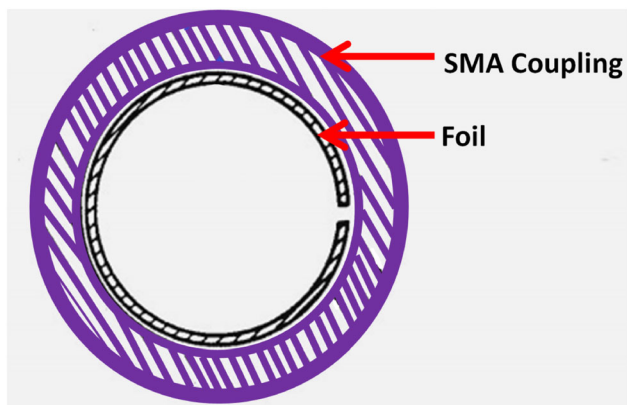
Jee et al. (2006) investigated the joints between pipes. He proposed an internal coupling application that can compensate for different tolerance between pipes and alloy with low shape memory capacity. This technique used Fe-30Mn-6Si SMA coupling which was inserted inside the pipes, both the coupling and the pipes were deformed simultaneously. Two pipes were taken having ID 25 mm and OD 28 mm and SMA coupling was taken of 25 mm OD and 22 mm ID. These both the pipes were uniformly contracted to a diameter of 27.2 mm OD. Then, the assembly was heated to 673 K where the coupling contracted on regaining its original shape and simultaneously the pipe expanded upon heating having a positive coefficient of thermal expansion. This anti-directional movement of pipe and coupler induced residual stresses because the strain was restricted and a strong joining force was obtained between the SMA and the steel pipes. Figure 4a represents the Fe-30Mn-6Si SMA coupling which was installed inside the pipes and both the pipe and the coupler were deformed upon heating above transformation temperature (austenite) unlike Fig. 4b where the NiTi coupler was placed outside the pipes, in which the coupler gets contracted and no significant deformation in pipes was observed.

Most of the conventional method uses coupling agent in the interior of the joining of two pipes, whereas smart coupling system is used typically at the exterior position of the joining. Mori et al. (1997) investigated a similar coupling where he observed that pipe tolerance was eliminated during the process, there was no shape memory capacity loss due to tolerance. Accordingly, it is possible to apply alloys having a low shape memory capacity. Unlike NITINOL, where the coupling is subjected to extremely low temperature, the SMA could be deformed not only below but above reverse transformation temperature. However, it is worth noting that the deformed pipes undergo permanent dimension change when heated along with the coupling and this process cannot be applied for joining shafts. In addition to it, there is always a constant



**Fig. 4** Installation of SMA coupling **a** Fe-based SMA, **b** NiTi-based SMA

fear that the coupling joined by this process may deform when the temperature reaches the transformation temperature. If such a situation arises, then component failure will be observed due to loosening in driving and driven shaft/pipe. Additionally, the pipes to be joined contain surface defects especially due to manufacturing or welding operations. Sometimes, the roundness of the pipes is not perfect or the diametrical tolerance is too large which results in not too tight coupling and non-uniform stress distribution due to improper skin contact. This eventually leads to failures in the system. These problems could be solved by providing an artificial joint between the coupling and shaft/pipe during heating. Researchers have invented a pipe coupling arrangement as shown in Fig. 5 which is comprised of a shape memory alloy cylindrical coupling



**Fig. 5** Coupling agent and foil arrangement in a coupling system

member and a foil of low melting point attached to the inner surface of the coupling. Upon heating above  $A_f$ , the foil gets melted between the coupler and the pipe providing an additional joint. This technique can be used in internal and external coupling methods as well (Duerig et al. 2013; Hagio et al. 1992).

Another interesting way of providing constraint between coupler and shaft is to create a locking mechanical component that could be easily installed and would provide sufficient locking force and hold the components under temperature variations as well. Justis (2001) invented a device and method which acts as a locking mechanism following stress-induced martensitic change rather than temperature-induced. Mechanical restraint is used initially to deform the SMA to the desired dimension after removal of which the SMA regains its original shape. There is no involvement of temperature whatsoever, and this technique is idle for application where the environmental temperature is above the transformation temperature of the alloy. Stress-induced martensite transformation offers higher control over the other and reduces mating part tolerance requirements.

### Underwater coupling concept

Nonetheless, it is generally observed that upon continuous exposure to saline and corrosive media such as grease and chemicals, NiTi coupling could, however, develop surface degeneration which is undesirable for such a costly material. Damage of SMA was observed particularly through

galvanic corrosion due to existing high-temperature water inside or outside of pipes. Protecting it against the harmful effect of corrosion would require the addition of alloying elements like chromium but again its shape memory effect is compromised, and it is a costly affair as well. Its remedy could be provided by shielding SMA with another material, so that SMA would not be in direct contact with corrosive agents. Mori et al. (1996a) developed a coupling that could be used in underwater pipes, as shown in Fig. 6. The pipe coupling consists of two pipes carrying water inside made of stainless steel, a tube of NiTi SMA enclosed within a cover of stainless steel having higher corrosion resistance to protect it against the risk of pitting corrosion, crevice corrosion, stress corrosion, and hydrogen embrittlement. Upon crack propagation, the coupling loses its functionality which should be avoided. The thickness of the cover was between 0.5 and 5 mm, which is sufficiently smaller than the thickness of the SMA coupler, so that the stainless steel tube would deform simultaneously with the deformation of the SMA tube.

### NiTi shaft coupling system

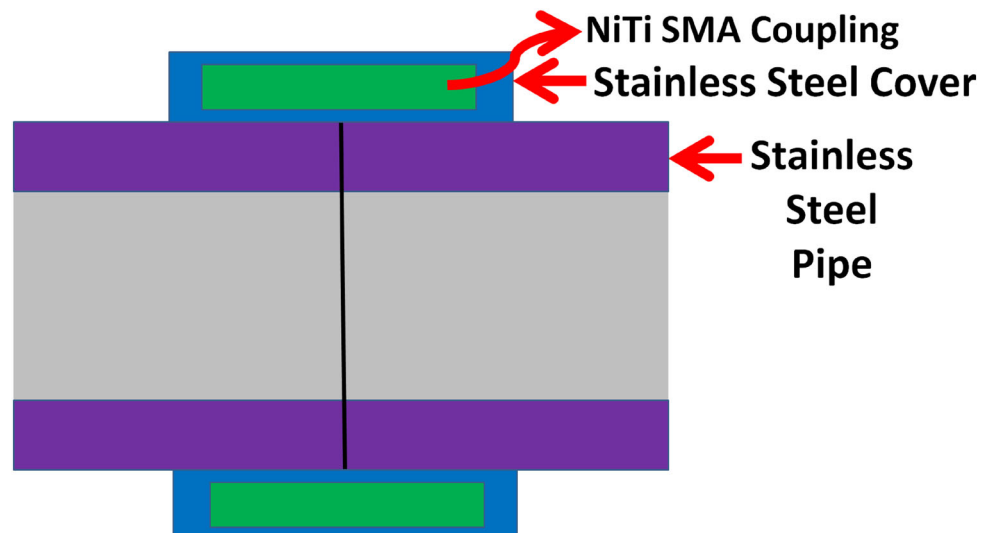
Superelasticity in NiTi coupling is also induced by applying stress instead of temperature. A similar shaft coupling arrangement for torque transmission is shown in Fig. 7, which can be used also for orthopedic drilling and reaming devices (Mori et al. 1996b). The assembly consists of a shaft made of NiTi alloy for transmitting torque, a tool fitting of cutting tool configuration, a radially movable flexible collet which is an integral part of the fitting, and a compression sleeve that act as a dampener. The shaft slid inside the collet forming an interference fit between the outer diameter of the shaft and the inner diameter of the collet. This interference made the collet bend outward

forming a flower-shaped finger-like configuration. Afterward, the sleeve is slid over the collet and is welded at the junction. As the shaft, collet, and sleeve are assembled, the collet is forced radially onto the shaft and stress-induced transformation is activated thereby forming a secure coupling. This superelastic reaction made the fingers come in contact with the shaft throughout the length forming surface-to-surface contact. This created frictional force enables a relative movement which is essential for transmitting torque (Loughrin et al.).

### Factors influencing smart coupling

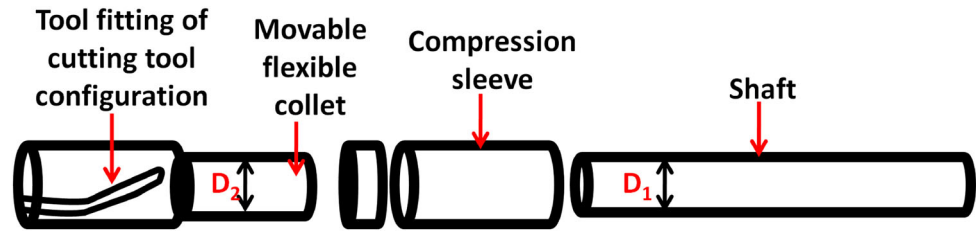
The thermally induced contact stress of smart coupling depends on several factors, among which dimension and material properties of the shaft and the coupler are of prime importance. NiTi SMA absorbs and dissipates energy which is governed by temperature change, and this thermo-mechanical property can be manipulated by adjusting the alloy composition in the matrix. For an idle SMA coupling, the shape memory effect is best observed and preserved if temperature hysteresis is wide enough. The SMA must remain in the austenite phase during operation or motion of conduit to avoid possible re-conversion of austenite to martensite, thereby causing re-expansion, which would directly lead to loosening of residual compressive forces (Uchida et al. 2008). In order to safeguard the situation, the  $M_s$  must be somewhat lower than the lowest temperature encountered, and  $A_f$  must also be not high enough; otherwise, complete conversion of maximum residual stress would not be possible for the SMA coupling. In general,  $M_s$  and  $A_f$  should be kept low as possible. However, choosing SMA with very low  $A_f$  would cause premature contraction before or during installation which is needed to be taken

**Fig. 6** NiTi coupling enclosed within stainless steel tubes for underwater application





**Fig. 7** Driveshaft coupling assembled system



care of while selecting SMA suitable for a particular operating condition. The temperature gap between martensite transformation and austenite transformation is desired to be wider enough (Ortin and Delaey 2002). The desired property of NITINOL can be achieved by adding alloying elements, heat treatment, or a combination of both. The crystalline structure of shape memory alloys is strongly affected by heat treatment (Yan and Humbeeck 2011).

### Effect of the additional element

Aluminum plays a significant role in the NiTi smart system in order to increase the ductility without affecting the shape memory effect. Ni<sub>2</sub>Ti Al phase shows similar characteristics compared to NiTi( $\beta_2$ ) alloy phase. Compressive strength is seen to improve drastically at room temperature and higher temperature by substitution of Ti with Al. It was observed that an alloy with 8.4 mol% Al showed compressive yield strength as high as 2300 MPa at room temperature and 200 MPa at a temperature of around 1000 °C. Although ductility was decreased in the 8.4% Al alloy, a compression deformation of 5.2% is obtained. Upon further exceeding the Al content up to 11 mol%, Ni<sub>2</sub>Ti Al phase gets deposited as a dendrite, reducing the strength. The  $\beta_2$  single phase 4.4% Al alloy is stronger or equivalent compared with NiTi and Ni-base superalloy. Heat treatment through solution and aging is proven effective at 800 °C, carried out for a shorter time in 7.1 mol% Al and 8.4 mol% Al at ( $\beta_2 + \beta'$ ) two-phase region (Koizumi et al. 1997). The addition of Cu to NiTi alloys reduces the transformation temperature hysteresis. Hence, they are suited for actuators, heat engine nozzle, and similar machines, but they are not idle to be used as couplers. However, the addition of Nb does the opposite, the transformation hysteresis gets widened, which is desired for a shape memory coupler. Most of the intermetallic phases dissolve into the B2 matrix with the solid solution treatment of NiTi parts. A microstructure consisting of a B2 matrix and nanoscale precipitation of Ni<sub>4</sub>Ti<sub>3</sub> is achieved upon quenching the sample. The presence of the precipitate improves the strength of the material. The addition of Nb enhances the morphology of the precipitates leading to superior properties in the alloy while eliminating

the R-phase in the martensitic transformation (Zhang et al. 2018).

The TiNiNbSMA has a high transformation temperature hysteresis and has thus been used in pipe joints and similar applications. Uchida et al. (2007) manufactured the alloy in a high-frequency induction vacuum furnace and prepared two samples: One sample with Ni/Ti atomic ratio equal to 1, and Nb concentration between 0 and 15 mol%, whereas another sample contains Nb concentration 6 mol%, and the Ni/Ti ratio was changed from 1.025 to 1.1. Transformation temperature decreased with increasing Nb content in the first sample, and a huge deviation was recorded with Nb being 12 mol%, the second sample having Ni/Ti ratio is 1.088. The transformation temperature decreased by performing heat treatment at 673 K and 773 K. This alloy is found to be more effective. Commercial Ni<sub>46.4</sub>Ti<sub>45.0</sub>Nb<sub>8.5</sub> SMA rings were analyzed for applications as beam pipe coupling devices in radioactive places. A shape memory capacity of around 6% was observed by heating and cooling at 200 °C and 25 °C, respectively. Repeated mounting and dismounting were made possible due to the two-way SMA property (Niccoli et al. 2017). Earlier, it was believed that  $\beta$ -Nb particles in NiTiNb alloy produced wide hysteresis (Duerig et al. 1990), but later, it was observed that low Nb content upon pre-deformation could achieve significant transformation hysteresis due to changed kinetics of martensitic transformation, thereby stabilizing it. The Ni<sub>49.6</sub>Ti<sub>45.9</sub>Nb<sub>4.5</sub> alloy exhibited similar characteristics compared to Ni<sub>47</sub>Ti<sub>44</sub>Nb<sub>9</sub> alloy (Wang et al. 2012). Substituting Fe with Ti concentration significantly reduces the cost, and the SMA is found to exhibit good shape memory characteristics. Fe–15Mn–5Si–9Cr–5Ni showed 83% shape recovery for a 3.6% diameter expansion and 95% recovery for a 3% deformation which is acceptable for industrial applications. This alloy is produced by sand molding followed by annealing at 800 °C. The structure possessed a high density of stacking faults and high-strength austenite. The Young's modulus of the alloy is 123.6 GPa, and after yield, the hardening rate decreases continuously. The maximum stress of 880 MPa is attained after a total elongation of about 16% and brittle fracture can be observed (Drukera et al. 2014).  $M_s$  and  $A_f$  decrease with increased Cr concentration. The ternary addition of Cr affects martensite transformation temperatures,  $M_s$ , as well

as mechanical properties of off-stoichiometric NiTi alloys.  $M_s$  and  $A_s$  decrease with decreasing Ti concentration and change slightly when Ti concentration exceeds 52 at.%, where the alloys are in the two-phase region. Significantly,  $M_s$  and  $A_s$  decreased with increasing Cr content at a constant Ti concentration. It was suggested that Cr atoms will substitute Ni sites preferably if only  $M_s$  changes are observed. Based on the characteristic stress–strain curves presented, the stress-induced martensitic transformation (SIMT) occurs at 196 C (Hosoda et al. 1998). Zr is added to the NiTi system in an attempt to improve the corrosion resistance. When the amount of Zr is increased, it led to an increase in the oxidation rate. However, the corrosion rate decreases with the addition of Zr. The reduction in the corrosion rate is attributed to the presence of oxide films. Additionally, when the content of Zr is below 10%, the martensitic transformation temperature decreases and leads to a rapid rise in the transformation temperature when the content is more than 10%. With the presence of multiple phases due to the addition of the alloying element, there is a reduction in the maximum shape recovery (Khan et al. 2017).

## Smart materials in automobile applications

The use of NiTi SMA in the automobile industry is noted significantly in sports cars where performance is the prime objective. Many automotive manufactures are actively implementing this technology to simplify and improve driver control.

### SMA leaf spring

Leaf springs are heavy-duty slender arc-shaped suspension system which are stacked in descending order of their sizes and bolted together. They are designed to deflect under the action of tensile or compressive load enabling them to bear high stresses and shocks. They are conventionally made of steel but sometimes due to excessive shock load, it gets permanently deformed or loosen and eventually get damaged. In order to achieve its previous dimensions and properties, using an SMA is quite beneficial in which due to temperature-induced change, it can be brought back to its original state. Integrated composite materials with NiTi SMA are successfully applied as leaf spring in heavy vehicles (Amar et al. 2016).

### SMA actuators and valves

SMA is extensively used as actuators and valves in various sectors. It is truly a design miracle where a single SMA wire can replace a complex mechanical system used for

actuation. The effect can be created by temperature-induced shape change either due to the application of heat or electric current. An interesting application is a temperature-controlled governor valve that controls shifting in an automatic transmission system. As shown in Fig. 8, at one end, there is a spring coil made of steel, and at the other end, there is an SMA spring coil. At low temperature, the SMA coil is in the martensitic state which have lower strength than that of steel, as a result, the spring force of the steel overcomes that of SMA. The valve is now closed as the movable piston is moved by the steel spring. When the temperature of the transmission system increases and reaches the transformation temperature of austenite, SMA strengthens and imparts greater force than steel thereby pushing the piston in the reverse direction which opens the valve. This ensures smooth operations at low temperatures, controls fuel consumption, and improves cold starting (Dieter 2013).

This technology is identified in the automatic transmission system of Mercedes Benz for smooth gear shifting (Stöckel 1995). These pneumatic valves were mass-produced by AlfmeierPräzision and were successfully implemented in car seats for providing lumbar support to the driver. Observing the benefits of this technology, many automobile manufacturers nowadays are installing SMA device such as Porsche, Hyundai, Ford Motors, and Volkswagen (Jani et al. 2014). Another similar application of the SMA actuator is observed in the general motor's Chevrolet Corvette where the actuation is electrically controlled to open and close the trunk more easily. In the previous models, the trapped air inside the vent makes the lid difficult to function. In this mechanism, the SMA wire contracts once activated, moving a lever arm to open the vent and thereby closing the trunk lid. When the trunk lid is closed, the electrical current is turned off, providing enough time for the wire to cool down and regain its original shape, closing the vent and keeping the cabin at a comfortable temperature (G. M. 2013). In the automobile industry, different types of couplings have been implemented in different sectors according to their design consideration, material behavior, and load orientations (axial, transverse). It is very crucial to select and design a coupling for a particular operation. The following Table 3 describes different couplings used for various applications by their designing parameters. Complexity in geometry is observed with greater load-carrying capacity; for lighter load, rigid coupling such as a sleeve or split muff is used. For heavy-duty applications, gear or flange couplings are used as complex parts.

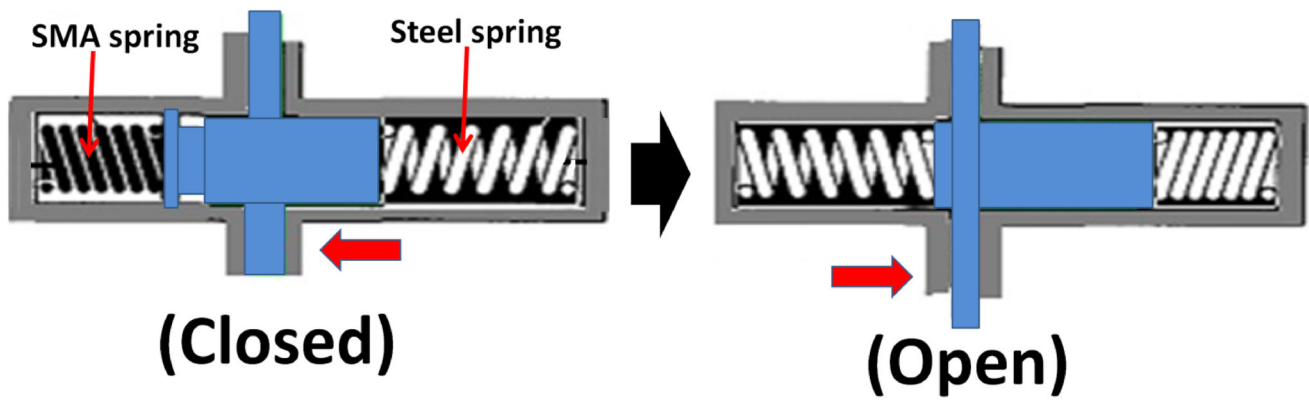


Fig. 8 SMA actuator configuration (Singh et al. 2018)

**Table 3** Installation of coupling (Bush 1936; Bhattacharjee et al. 2020; Wang et al. 2018; Sawalhi et al. 2019; Ahmed et al. 2014; DaSilva et al. 2008; Medrea et al. 2013; Valentini 2014; Vesali et al. 2012)

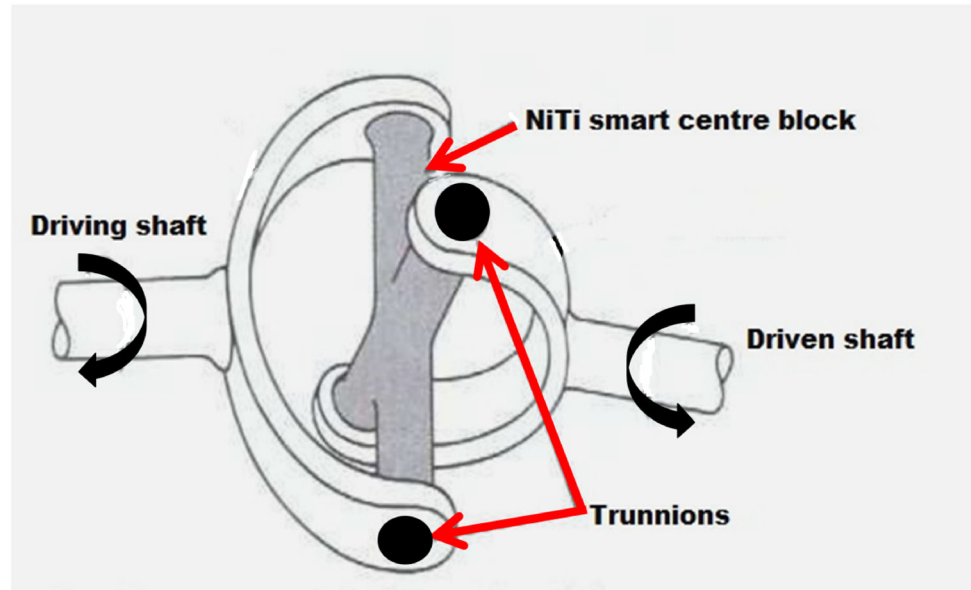
Type	Design consideration	Application
Muff or sleeve coupling	Load capacity is light to medium duty	Power transmission in shafts, joints
Split muff coupling	Medium to heavy load with moderate speed	Line shaft in power transmission
Flange coupling	Medium to heavy-duty industrial application	Connect the electric motor to the pump or compressor
Bush pin type flexible coupling	Medium duty applications permitting little angular, parallel or axial misalignments	Electric motors and machines
Gear coupling	Heavy-duty application where the requirement of torque transmission is high	Power transmission in cars
Fluid coupling	Marine and industrial application Can provide controlled power transmission	Semi-automatic and automatic transmission
Oldhams coupling	Used where lateral misalignments are there	Robotics, printers
Rzeppa joint	Used in vehicles with independent rear suspension	Wheels of rickshaws
Universal joint	Accommodate angular misalignments Used where space restriction is there	Power transmission through propeller shafts (trucks), Aircrafts, driveshaft

### Universal coupling drive shaft concept

A universal joint, also known as a universal coupling (Fig. 9), a U-joint, a Cardan joint, a Hardy-Spicer joint, or a Hookes joint, is a joint or coupling in a rigid rod that causes the rod to “bend” in any direction. It is widely used in shafts that convey rotary motion permitting angular misalignment. Universal joints (or U-joints) are located at both ends of the driveshaft in rear-wheel-drive trucks. U-joints are connected to yokes, which allow drive shafts to move fore and aft as cars travel over bumps and dips in the road, effectively shortening or lengthening the shaft. When these constant velocity joints in front-drive cars wear out, they also make a clicking noise. Protective rubber boots are used to cover CV joints, and if the boots crack or are otherwise damaged, the joints will lose their lubrication and become damaged by dirt and moisture (Bayrakceken

et al. 2007). The Cardan joint has one major flaw: The output drive shaft rotates at a variable speed, causing vibration and wear even when the input drive shaft rotates at a constant speed. A damaged Cardan joint also causes severe vibrations in the output shaft. Such vibrations can severely harm other components of the power transmission mechanisms (Vesali et al. 2012). However, with NiTi smart center block use, vibration mitigation can be successfully carried out with prolonged life expectancy and no external protective covering will be needed. Also, the center block can accommodate excessive misalignment and vibrations when the vehicle is subjected to base excitations on the road or uneven power generation from the engine under variable load conditions. The improved torsional ability and high strength of this SMA universal coupling over steel (material) enable the user with smoother driving and safety.

**Fig. 9** NiTi smart universal joint (<http://img.style-js.com/a.aspx?cid=40&cname=cross+type+universal+joint>)

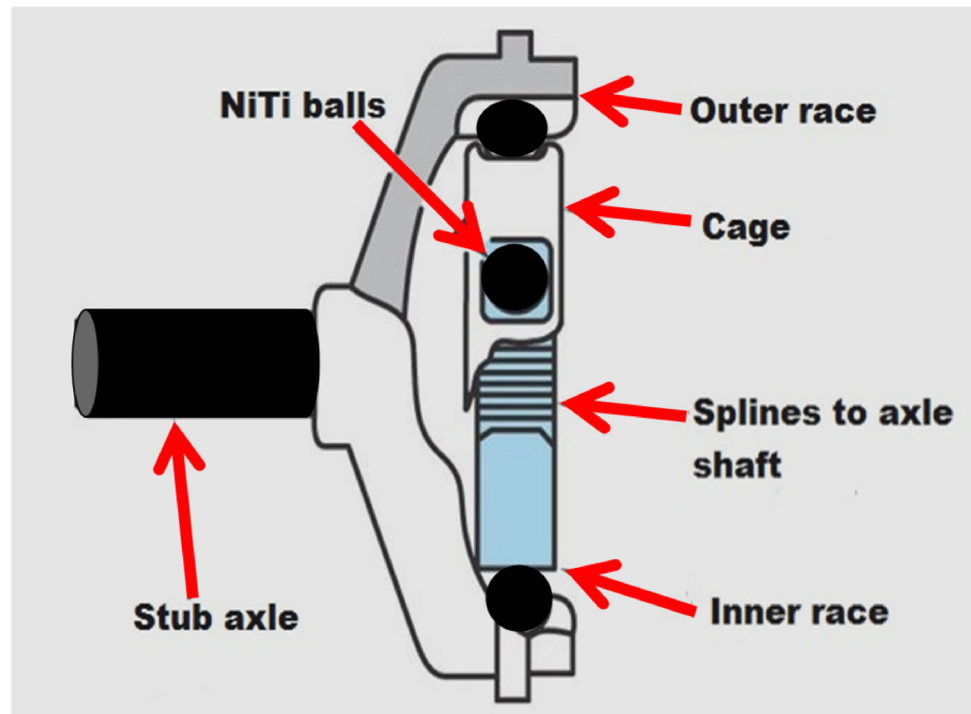


### Rzeppa joint concept

A self-supported constant velocity joint with an outer and inner race connected by balls positioned in the constant velocity plane by axially offset curved grooves is known as a Rzeppa Joint. For transmitting rotational motion between two misaligned shafts, ball-type constant velocity joints (also known as Rzeppa ball joints in Fig. 10) are commonly used. Here, the balls are involved in transmitting torque, these are the key elements whose relative

coordination supports motion (Shina et al. 2018). The balls used in the Rzeppa joint are susceptible to corrosion, rapid pitting in the races leading to early failure of the system. Corrosion-proof bearings offer low strength and fail prematurely due to accelerated wear and fatigue during operation. However, balls made of NiTi provide resistance against corrosion in most of the corrosive agents. These SMA balls are designed and tested successfully in a ball-bearing arrangement. Its improved mechanical properties against fatigue and its higher strength as compared to steel

**Fig. 10** NiTi ball elements in Rzeppa joint (<https://slideplayer.com/slide/3867278/>)



SMA-assisted part do not fluctuate even at elevated temperatures, making it a better alternative than conventional ones (Gerald 2005). This study suggested that these balls can be used in the Rzeppa joint on account of which they can adjust themselves for angular misalignment to protect the coupling against high amplitude vibrations, providing stable working.

### Gear coupling concept

A gear coupling is the first choice of many companies to swap movements from one component to the next, regardless of industry type or size. This mechanical component allows us to pair two drive components while also transmitting power perfectly (Fig. 11). Even with near-perfect alignment, gear couplings can produce significant static forces and moments that can affect turbomachinery vibrations. This theory has been confirmed through various testing and case studies. These forces have the potential to transform bearing loads, stiffness, and damping, resulting in high vibration (Palazzolo et al. 1992). Installing gear assembly made of NiTi SMA can suppress excessive vibrations, prevent interference, backlash, fatigue failure over a wide range of temperatures. Aiding to its vibration damping properties, the gear made of NiTi maintains contact by decreasing the amount of backlash without tooth failure and is capable of withstanding heavy friction (Kacalak et al. 2018).

### Advantages and limitation of NiTi coupling

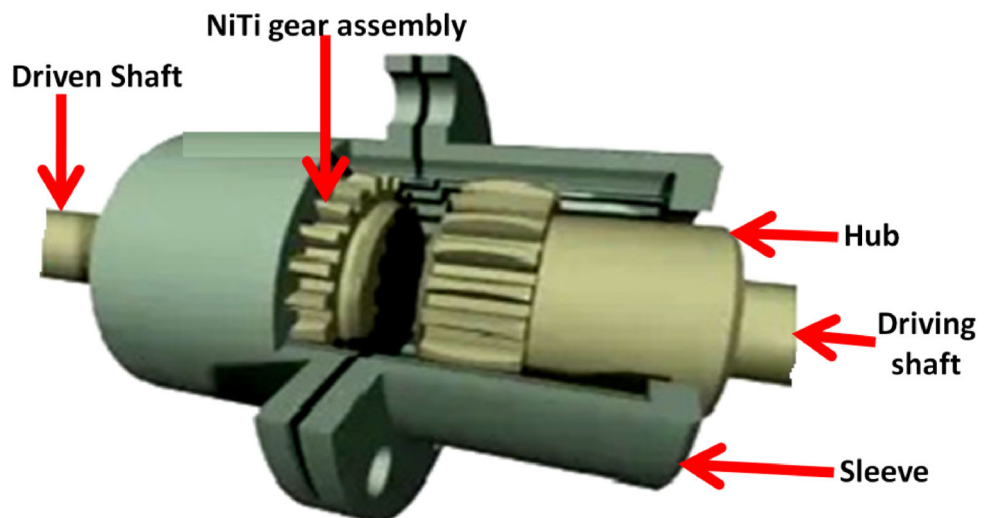
NITINOL has many advantages over steel as coupling material in different sectors like aerospace, shipbuilding, hydraulic lines, space satellite. Now, it is time to

implement this technology in the automobile industry because of its superelasticity, torsional strength, and vibration damping properties. Although its initial cost is high, however, they work remarkably in the automobile sector by reducing the maintenance cost of the final product due to its technical benefits. So, it is a major challenge for the researchers to make use of this coupling technology in the automobile industry, considering consumer acceptance from the economic point of view. NITINOL SMA coupling offers many advantages, such as:

- a. No expansive tooling
- b. Leak-proof and permanent connection
- c. Lightweight design
- d. Quick and easy installation
- e. Lower space is required around the pipes or shafts.

However, transportation and storage cost are considerable for NiTi SMA. NITINOL is kept below its transformation temperature which is around  $-100\text{ }^{\circ}\text{C}$  maintained inside liquid nitrogen during transportation to the manufacturing unit. Later, at this temperature, the coupling joins the shaft or pipe. This degree of sub-cooling maintained throughout the process increases the overall cost of SMA coupling (Vinothkumar et al. 2015). Storage and transportation of NITINOL are costly at cryogenic temperature, devising a proper technique to facilitate its storage at room temperature becomes a research direction of SMA. NITINOL is expensive, its application is limited to high-end applications where cost is not a factor, its production cost is a major drawback in setting it for commercial purposes, a cheaper production method could be invented, and material exhibiting similar shape memory capacity should be researched in future.

Fig. 11 Gear coupling (<https://kapent.com/what-are-couplings-types-of-couplings-and-their-application/>)



## Summary and future prospect

Metal alloys with shape memory belong to a group of smart materials that can be used as a coupling agent. SMA coupling systems are an excellent example of a product that helps significantly reduce process costs in comparison with traditional assembly methods, such as welding, brazing, or swaging. The presented coupling and its examples are very much effective and reliable for connecting shafts in the transmission line of automobiles and can be implemented in place of conventional couplings. The method of installation and variable parameters are mentioned for effective joining, analogous to propeller shafts in cars. This alternative coupling is a solution for design simplicity of structure, durability, and shorter processing. If properly designed and engineered, SMA couplers provide a product that can enhance shaft fitting in various industrial applications. The design characteristics of small mass and single-motion actuation of the SMA interference coupling should allow for a wide range of latch and fastener applications. Alternatively, the scale of the SMA interference coupling need not be limited to small sizes but could be scaled up in size and strength to meet other types of coupling needs. Featuring simplicity, strength, and reliability, the SMA interference coupling proved a useful component in the automobile industry.

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