Prospects for the use of martensites in the manufacture of adaptive anti-slipping spikes

I P Voiku, T V Sergeeva and A V Strikunov

Pskov State University, 2, Lenin Square, Pskov, 180000, Russian Federation

E-mail: voiku-ivan@yandex.ru

Abstract. The article substantiates the relevance of the development of an innovative device, namely an adaptive anti-slipping spike, and the prospects for the use of martensites in its manufacture. The device belongs to the automotive industry, specifically to the anti-slipping spikes. Tire treads of vehicles are equipped with these spikes to increase their adhesion to the roadway. The use of traditional anti-slipping spikes does not allow solving two problems at the same time: to ensure maximum adhesion of the vehicle’s wheel to the road surface and to minimize the destructive effect of anti-slipping spikes on the road surface. These tasks are solved by the fact that the proposed device is made according to the shape and size of traditional anti-slipping spikes but contains a retractable pin. The pin can be operated either by the substances with a negative coefficient of thermal expansion or martensitic materials. The article describes the prospects and features of their use.

1. Introduction
The use of traditional anti-slipping spikes does not allow solving two problems at the same time: to ensure maximum adhesion of the vehicle’s wheel to the road surface and to minimize the destructive effect of anti-slipping spikes on the road surface. Unpredictable conditions of tire slippage on the roadway actualize the adaptability of the mode of change of the tire-to-surface adhesion coefficient.

According to the research carried out by the Russian experts in 2011, one automobile wears out about 24 g of coating material for 1 km of run, and the wear-out of one spike is 100 mcg. About 90 % of wheel tracking in some sections of roads can be caused by spikes usage [1].

The European researchers’ calculations show that an increase in the average speed on the road section from 90 km/h to 110 km/h raises the intensity of destruction twice [1]. The industry needs innovations that can reduce losses from the operation of spiked tires while maintaining the achieved level of safety. The innovations should allow spiked tires to provide better adhesion of the car to the road covered with ice and to reduce the wear-out of the road surface at the same time.

2. Materials and methods
The development of this device model was carried out taking into account the requirements of the GOST (State Standard) 33672-2015 “Motor vehicles. Anti-slipping spikes. Technical requirements and test methods.”

Simple substances (eg water, bismuth, gallium, germanium, silicon) and alloy materials (eg bronze, cast-iron, bismuth + lead + antimony) are considered to be the substances with a negative coefficient of thermal expansion. An extensive class of materials (alloy materials based on titanium nickelide, brass and bronze of complex composition, etc.) with the shape memory effect is considered. Two-component
Ni-Ti alloy and three-component Cu-Zn-Al and Fe-Mn-Si alloys are chosen as priority martensitic materials for the prospective use in the suggested innovative device.

3. The adaptive anti-slipping spike and prospects for the use of martensites in its manufacture

Thus, the use of traditional anti-slipping spikes, which the tire treads of vehicles are equipped with, has a negative impact on the road surface. The adaptive anti-slipping spike is a proposed innovative device which is designed to solve the mentioned problem.

The proposed device is made according to the shape and size of traditional anti-slipping spikes (1) but contains a retractable pin (3) (figure 1). The overall size and shape of the proposed anti-slipping spike is accepted according to the existing standards for such devices.

![Figure 1. The configuration of the adaptive anti-slipping spike: a – rest state; b – operating state.](image)

The pin can be operated either by the substances with a negative coefficient of thermal expansion or martensitic materials. The pin is operated by the spike filler (2). The substances with a negative coefficient of thermal expansion or martensitic materials can be considered as the filler.

There is a sufficient set of substances that demonstrate not expansion, but compression as the temperature rises. In other words, such substances have a negative coefficient of thermal expansion. The most well-known substances (or combinations of substances) with a negative coefficient of thermal expansion are water, bismuth, gallium, germanium, silicon, bronze, cast-iron, and some other alloy materials. They provide the longitudinal movement of the pin while the ambient temperature changes (including tires).

| Substance   | Value | Unit         |
|-------------|-------|--------------|
| Water       | 200   | $\beta, 10^{-60} \text{C}^{-1}$ |
| Bismuth     | 13    | $\alpha, 10^{-60} \text{C}^{-1}$ |
| Gallium     | 13    | $\alpha, 10^{-60} \text{C}^{-1}$ |
| Bronze      | 16    | $\alpha, 10^{-60} \text{C}^{-1}$ |
| Cast-iron   | 12    | $\alpha, 10^{-60} \text{C}^{-1}$ |

In the context of solving the technical problem of the innovative device, water has a unique combination of qualities. It has the maximum value of the negative coefficient of thermal expansion among liquids, while the duration of the transition phase is quite narrow – from 0 °C to 3.984 °C.
The principle of operation of the adaptive anti-slipping spike with water as a filler is rather simple. When the ambient temperature drops to the values at which the sign of the coefficient of thermal volumetric expansion changes, water expands, ensuring the extrusion of the pin from the anti-slipping spike. On the contrary, while the ambient temperature rises to values at which the sign of the coefficient of thermal volumetric expansion changes, water compresses, allowing the pin to move back into the spike.

However, the use of water in the device has one major fault, namely the need to ensure leak resistance. This limits the use of water as the filler in the adaptive anti-slipping spikes manufacturing. For this reason, the priority should be given to substances with the memory effect. The memory effect, for example, the shape memory effect, becomes apparent if the plastic deformation has been accompanied by the martensitic transformation [2].

Martensitic metals change their shape while heated or cooled to a certain point of temperature. In this case, the atoms forming their structure suddenly rearrange into another crystalline state [3]. Such a transformation means that martensite can be used as a substance that provides the longitudinal movement of the pin in the innovative device if the ambient temperature changes.

**Table 2. Alloy materials with the shape memory effect [4].**

| Alloy materials       | Concentration of the elements in the alloy materials | Temperature range of transformation, °C | Hysteresis, °C |
|-----------------------|-----------------------------------------------------|-----------------------------------------|----------------|
| Ag-Cd                 | 44/49 atom. % Cd                                    | −190 ÷ −50                              | ≈15            |
| Au-Cd                 | 46.5/50 atom. % Cd                                  | 30 ÷ 100                                | ≈15            |
| Cu-Al-Ni              | 14/14.5 Wt% Al, 3/4.5 Wt% Ni                        | −140 ÷ 100                              | ≈35            |
| Cu-Sn                 | ≈15 atom. % Sn                                      | −120 ÷ 30                               | -              |
| Cu-Zn                 | 38.5/41.5 Wt% Zn                                    | −180 ÷ −10                              | ≈10            |
| Cu-Zn-X (X=Si, Sn, Al) | few Wt% X                                           | −180 ÷ 200                              | +10            |
| In-Ti                 | 18/23 atom. % Ti                                    | 60 ÷ 100                                | ≈4             |
| Ni-Al                 | 36/38 atom. % Al                                    | −180 ÷ 100                              | ≈10            |
| Ni-Ti (nitinol)       | 49/51 atom. % Ni                                    | −200 ÷ 110                              | ≈30            |
| TiNi-Fe               | 3 atom. % Fe                                        | −180 ÷ 100                              | ≈10            |
| TiNi-Cu               | ≈8-20 atom. % Cu                                    | −150 ÷ 100                              | ≈50 ÷ 4        |
| TiNi-Nb               | ≈9-15 atom. % Nb                                    | −200 ÷ 50                               | ≈66–125        |
| TiNi-Au               | 50 atom. % Ni+Au                                    | 20 ÷ 610                                 | -              |
| TiNi-Pd, Pt           | 50 atom. % Ni+5-50 atom.%                           | −200 ÷ 700                              | ≈30 ÷ 100      |
| Fe-Pt                 | ≈25 atom. % Pt                                      | ≈−130                                   | ≈4             |
| Mn-Cu                 | 5/35 atom. % Cu                                     | −250 ÷ 180                              | ≈25            |
| Fe-Mn-Si              | 32 Wt% Mn, 6 Wt% Si                                 | −200 ÷ 150                              | ≈100           |
Undoubtedly, the biggest practical interest for the manufacture of adaptive spikes is presented by the following properties of martensite: the repeated reversibility of deformation due to the changes in temperature only and the absence of the need for external forces for forming. That is why, among all the effects of the martensitic inelasticity, a special place is occupied by the effect which consists of the material ability to accumulate in case of absence of the applied stress under cooling and to return back under heating despite the relatively large deformations (up to 5–8 %) [5].

The best known and explored martensitic material is titanium nickelide (TiNi). This alloy material has excellent corrosion resistance, high strength, and good shape-memory characteristics (e.g., high shape recovery rate and high recovery force). The material deformation up to 8 % can be fully recovered. The shape recovery occurs in a fairly intense form with high values of the reactive voltage: for the TiNi alloy, its value is close to 600–800 MPa [6] and for the Ti-Ni-Hf alloy – up to 1300 MPa [7].

The main disadvantages of the material are high cost and the processing complexity while the material is manufactured, especially, cutting. In addition, the alloy material easily adds nitrogen and oxygen, which requires vacuum equipment and complicates the manufacturing technology.

The Cu-Zn-Al alloy, along with titanium nickelide, also has wide practical application. The temperature of its martensitic transformation is in the range from −170 °C to 100 °C. However, the cheapest alloy materials of this system are Fe-Mn-Si alloys. The maximum shape memory effect in Fe-23%Mn-5%Si alloy reaches 75 % under deformation after hardening from 600...700 °C [8].

In recent years, the properties of the ceramic compound ZrW₂O₈ have been actively studied. This compound tremendously expands under cooling.

Scientists have found out that silver hexacyanocobaltate (Ag₆[Co(CN)₆]) tremendously expands under cooling as well, but with a coefficient of −120×10⁶ K⁻¹. This is about 14 times higher than the result of the previous record holder – ZrW₂O₈. Silver hexacyanocobaltate also expands under heating (along the other axis), and again with the record coefficient: 140×10⁶ K⁻¹. This is 10 times higher than previous records [9].

The major disadvantage of modern martensites is that after repeated changes of shape, the internal pressure appears. It deteriorates mechanical properties and, ultimately, can tear martensites apart [10]. Zn-Au-Cu alloy excludes this disadvantage. It can change its shape under heating and cooling tens of thousands of times without deterioration of properties.

4. Conclusion
The development of an adaptive anti-slipping spike (an anti-slipping spike with retractable pin) is one of the innovative solutions to the problem of ensuring maximum adhesion of a vehicle wheel to the road surface, while minimizing the destructive effect of anti-slipping spikes on the road surface.

The extrusion of the pin from the anti-slipping spike when the temperature decreases and a reverse process in case of the temperature increase can be provided by a filler of the spike. The substances with a negative coefficient of thermal expansion or martensitic materials can be used as the filler.

In terms of solving the technical problem of the innovative device, water has a unique combination of qualities. However, the use of water in the device has one significant disadvantage: while water is used, leak resistance has to be ensured.

For the manufacture of adaptive anti-slipping spikes, martensitic alloys have the greatest prospects. They have such properties as high rate of volumetric expansion and shape recovery; the repeated reversibility of deformation due to temperature changes only; the absence of the need for external forces for forming; and, moreover, low costs.

Such alloy materials characterized by important properties which are necessary for the manufacture of the adaptive anti-slipping spike, of all the alloy materials considered, could be mentioned:

- TiNi – high rate of shape recovery;
- Fe-23%Mn-5%Si – high rate of shape recovery and low costs;
- Ag₆[Co(CN)₆] – the maximum rate of the volume expansion;
- Zn-Au-Cu – the repeated reversibility of deformation due to the temperature changes only.

The further research work is required which will result in the assurance of the technical result of the
proposed innovative device such as self-extension or self-retraction of the pin of the anti-slipping spike when the ambient temperature changes.

References
[1] Merentsova G S and Medvedev N V 2015 Analysis of the conditions for the formation of ice on roads Horizons of Education. Scientific Educational Journal of AltGTU [in Russian – Gorizonty Obrazovaniya. Nauchno-Obrazovatelnyy Zhurnal AltGTU] 1 17
[2] Van Humbeeck J 1999 Mater. Sci. Eng. A 273 134–48
[3] Saburi T and Nenno S 1982 Proc. Int. Conf. Solid-Solid Phase Transformation (Pittsburgh, Pa) (Warrendale, Pa) pp 1455–79
[4] Otsuka K and Wayman C M 1998 Mechanism of shape memory effect and superelasticity Shape Memory Materials ed K Otsuka and C M Wayman (Cambridge: Cambridge University Press) pp 27–48
[5] Hachin V N 1992 Titanium Nickelide Structure and Properties [in Russian – Nikelid Titana. Struktura i svojstva] ed V N Hachin, V G Pushin et al (Moscow: Science) p 160
[6] Lihachev V A 1987 Shape Memory Effect [in Russian – Effekt Pamyati Formy] ed V A Lihachev, S L Kuzmin et al (Leningrad: Leningrad State University) p 216
[7] 1997–1998 Handbook on the Materials with the Shape Memory Effect [in Russian – Spravochnik Materialy s Ehffektom Pamyati Formy] vol 1–4, ed V A Lihachev (Saint Petersburg: Research Institute Saint Petersburg State University)
[8] Husainov M A, Maluhina O A and Andreev V A 2015 Transition phase in titanium nickelide alloys with the shape memory effect Bulletin of Yaroslav The Wise Novgorod State University [in Russian – Vestnik Novgorodskogo Gosudarstvennoy Universiteta im. Yaroslava Mudrogo] 3-2 (86) 81–84
[9] Stepanov A 2008 First law of thermodynamics for materials with negative thermal expansion Materials Research Innovations [in Russian – Innovacii v Issledovanii Materialov] 12(1) 28–29
[10] Kayumov R A and Strahov D E 2014 Patterns of polymer behavior with shape memory effect Proc. of Kazan State University of Architecture and Engineering [in Russian – Izvestiya Kazanskogo Gosudarstvennogo Arhitekturno-Stroitelnogo universiteta] 4(30)