The mechanism of fretting corrosion of details from alloy with shape memory effect

D U Khasyanova
Mechanical Engineering Research Institute of the Russian Academy of Sciences,
Moscow, Russian (IMASH RAN)
dinara.khasyanova@mail.ru

Abstract. The article presents the fretting wear features of details from alloys with shape memory effect as applied to pipe connections using couplings from alloy with SME (shape memory effect); describes the mechanism of fretting corrosion in the thermomechanical connections using couplings alloy based TiNi with shape memory effect and superplasticity (SU).

1. Introduction
The fretting wear or fretting corrosion is a common type of wear that accompanies the operation of many contact connections that are subject to small tangential displacements during operation. For the appearance of this type of wear sufficient relative movements of surfaces with an amplitude of 0.025 microns are sufficient. Fretting wear occurs in rivet, threaded, spline, keyway and pin joints, fit parts with tension, steel ropes, hinges, couplings, springs, valves, electrical contact regulators, Cam mechanisms, automatic helicopter screw skewers, gas turbine engine details. The greatest interest is represented by pipeline connections using couplings from alloy with shape memory effect (nitinol), since during experimental testing of pipeline connections using TMC (thermos-mechanical connection) couplings, it was found that the using of damping elements in structures can significantly smooth the transition zone of stress and reduce the processes of fretting corrosion. However, these experiments are staged and haven't deep development.

2. Features of occurrence of fretting wear
The fretting wear characterizes by difficult wear particles removal from the contact zone and a large role of chemical processes in the formation of wear products (fretting corrosion) and activates by cyclic mechanical influences. Fretting corrosion is a phenomenon occurs during the movement of contact surfaces relative to each other and corrosion-mechanical wear of the pressed surfaces during slightly oscillating movements. Fretting wear is a special form of corrosion in terms of the conditions of occurrence and the nature of the manifestation, which differ from the usual friction that occurs during unidirectional sliding. The differences are the speed of relative movement of the contact surfaces in comparison with sliding friction is significantly less and does not exceed 5 mm·s⁻¹.

The amplitude of movement of the contact surfaces during the occurrence of fretting is within 0.03 mm, which significantly complicates the removal of wear products from the contact centre, and the presence of oxygen in contact with a fresh and newly developed active surface forms oxides that aggravate damage.
Most often, fretting occurs when press fitments, keyway, rivet, screw, bolt and similar connections, including couplings, which include pipeline connections with TMC. Schematically, the process of creating connections with TMC is shown in figure 1. The connected pipelines must be in an elastic-plastic condition [1].

![Figure 1. Scheme of formation of all-in-one connections by TMC couplings: 1 – initial condition: the inner diameter of the coupling is less than the outer diameter of pipes; 2 – deformation coupling diameter: inner diameter of the coupling larger than the diameter of the pipes; 3 – finished joint: after Assembly of the clutch restores its shape, is reduced in diameter and tightly compresses the pipe ends.]

The using of all-in-one thermos-mechanical connections (TMC) with couplings from alloys with shape memory effect (SME) has the following advantages:

- the strength of the connections is determined by the strength of the pipe in the supply, including heat-strengthened;
- the endurance limit of the connections is within 0.9-0.96 of the endurance limits of the connected pipes;
- the complexity of installation and assembly work is less than 2 minutes;
- high density of installation, including in hard-to-reach places;
- corrosion resistance of TMC couplings is not lower than stainless steel and titanium alloys;
- used for connecting pipes of various thicknesses, including thin-walled (from 0.2 mm), allowed a combination of different brands of materials.

The intensity of fretting formation depends on the amplitude of relative displacements determined in the range from $8 \times 10^{-7}$ mm. For steel, the most intense fretting occurs at amplitudes of 0.1-0.2 mm [2]. The intensity of wear depends on the amplitude and the types and contacted materials properties, stresses, surface micro relief, and operating conditions.

Fretting phenomena of intergranular corrosion can occur even at low stresses when combined with minuscule amplitudes for such materials that are prone to sticking and picking, as well as those circumstances that almost all metals and refractories are dissolved in titanium and its alloys.

One of the features of the surface properties of titanium alloys, which significantly distinguishes them from alloys based on many metals, is the high reactivity of the surface, which causes a low load of contact setting during friction, high values of the friction coefficient and wear rate. The sliding friction of titanium on any metal leads to sticking to its surface and the material seems to get stuck caught in a sticky layer of titanium, which leads to rapid wear.

Factors contributing to the manifestation of fretting: establishment of a time factor for specifically contacted materials that contributes to the violation of the continuity of the surface layer, leading to deep breakouts of the material and depending on the amplitude and frequency of relative displacement, chemical activity of surface energy, fatigue strength determined by the number of cycles and operating stresses.

Factors contributing to the reduction of fretting: design solutions for creating such stress Conditions that reduce or increase the amplitude of mutual movements from the zone of 0.1-0.2 mm, the using of damping elements that prevent vibration in the contact zones.
Titanium nickelide is consist of half of titanium like all titanium alloys has a tendency to stick and is character by a high coefficient of friction in both the austenitic and martensitic conditions. In addition, titanium nickelide exhibits SME and SU, and has a high ability to move each other in the contact zone, up to 8% [3].

Taking into account the fact that in this issue the goal is to fully consider the fretting corrosion of TiNi alloy, it should be noted that the causes of fretting corrosion, such as accelerated metal oxidation due to continuous removal of the oxide layer and metal wear due to friction are the most important [4].

Titanium nitride is a golden yellow film that has a high microhardness, but does not show sufficient plasticity, which does not allow maintaining the integrity of traditional protective coatings. Depending on the production method, the ratio of nitrogen atoms per titanium atom can vary in titanium nitride from 0.6 to 1 [5].

3. The mechanism of fretting corrosion

The main driving force in the process of fretting corrosion is friction [6]. The interaction of surfaces during friction is concentrated in a certain volume of material endowed with elastic-viscous properties. This volume can be considered as the so-called "third body". When the surfaces move relative to each other, the surface layer is destroyed and a "third body" is formed at the same time. As a rule, the contact zone of two surfaces is usually characterized by the presence of an intermediate layer between the solids, which is a film (lubricant) of oxide, adsorbed water steam and a film of degraded material. The area consisting of the film and the degraded coating material is called the "third body". A generalized approach to the mechanism of corrosion of titanium alloys allows using to distinguish three main stages of development of fretting corrosion of metal and its alloys under friction conditions.

At the first stage of the fretting process, there is a hardening of the contacting surfaces of the material and cyclic fluidity of the thinnest surface layers, most of the protrusions interact with each other plastically. This is facilitated by the setting of metal in contiguous micro-surfaces after the destruction of natural oxide films. Protrusions that have collapsed due to fatigue and cut-off set points create primary products of destruction, some of which are oxidized. However, most of the wear products at this stage of fretting are metal particles. The transition of the surface layers to the dispersed and ultra-disperse conditionals accelerates the oxidation reactions. At the second stage of fretting corrosion, fatigue damage continues to accumulate in the surface layers. Simultaneously with fatigue damage in the form of an ultrafine layer of metal particles and their oxides, a corrosive environment is formed in the friction zone due to adsorption on oxygen oxides. The rate of wear at this stage is low, and wear is mainly associated with the destruction of oxide films formed on the friction surfaces in those areas where there is an intensive destruction of surface oxide films, setting processes are intensively developed. The intensity of their development is further increased due to the fact that during the formation of wear products, the working area of the contact surfaces is sealed. Accordingly, the access of oxygen to this zone is practically stopped, and therefore the processes of formation of oxide films are sharply slowed down, and contact is made on clean surfaces that are more prone to setting. At this stage, there is a special (mechanical and chemical) mechanism for intensifying the oxidation of metal surfaces, due to the fact that during alternating contact interactions in the thinnest surface layers, a fine structure appears that is prone to active oxidation. Later, in the surface layer, a mixed structure is formed - from the coating metal and oxides of this metal, which can play a protective role, reducing the wear rate. In the second period of fretting corrosion, under optimal conditions of the formed contact, the pre-hardened coating layers experience more moderate cyclic loads, but further accumulation of fatigue damage occurs in them, which is aggravated by corrosion processes. High-dispersion oxides formed during fretting corrosion of metals, being semiconductors, give the process a catalytic character [7]. This effect of oxides is manifested in accelerating the processes of oxygen adsorption in active radicals and ion-radical forms. In this case, a reaction electrolytic medium is formed between the contacting surfaces of the electrical contacts. The third stage of fretting corrosion is associated with the final destruction of the damage zones of contact surfaces that have already been loosened by fatigue and corrosion processes. Taking into account the possibility of electrochemical processes, this stage can be called the stage of corrosion-fatigue failure. During this period, the surface layers of metal that have been subjected to cyclic deformations for a long time become so softened.
that they lose their stability, and their progressive separation begins, which is manifested in the rate of wear. The mechanism of destruction of the surface layers of the contacting surfaces is shown in figure 2.

Figure 2. Contact diagram of two bodies: 1 — "third body"; 2 — adsorbed layer; 3 — oxides and other chemical compounds; 4 — loosened layer; 5 — the main coating material.

During experimental testing of pipeline connections with TMC couplings, it was found that the use of damping elements in structures can significantly smooth the transition zone of stress and reduce the processes of fretting corrosion.

However, these experiments were considered as staged and did not have deep development. On the surface of samples from titanium alloys damaged by fretting, the consequence of mechanical action on the surface of a solid abrasive and the impact of a viscous amorphous medium formed by the study of the physical and chemical properties of damage products formed during fretting on the contact surfaces cannot be considered objective, since they are rather a consequence of the process, and not a real factor in fretting.

More reliable testing of both structural elements of TiNi damping devices and materials that show and do not show SU during operation, as well as modes and methods of applying titanium nitride (sputtering or gas nitriding) is necessary. Consider the influence of these processes on the fatigue strength of materials, as well as the use of surface films made of colloidal graphite to prevent oxidation of transition zones between titanium nitride and TiNi [8].

4. Results
The mechanism of corrosion in TiNi-based alloys with shape memory effect is described, which identifies three main stages of development of fretting corrosion of metal and its alloys under friction conditions. In the course of the work, it was found that on the surface of samples from titanium alloys damaged by fretting, the consequence of mechanical action on the surface of a solid abrasive and the effect of a viscous amorphous medium formed by the study of the physical and chemical properties of damage products formed during fretting on the contact surfaces cannot be considered objective, since they are a consequence of the process rather than a real factor in fretting.

5. Discussion
Nitinol has a high complex of mechanical properties. The high corrosion resistance of titanium and its alloys is due to the formation of a protective oxide film on their surface, which prevents the release of ions into the medium. However, titanium alloys have low wear resistance, which makes them vulnerable to fretting corrosion. The mechanism of fretting corrosion in TiNi-based alloy with shape memory effect compounds presented in this paper gives an idea of the sequence of fretting corrosion development, but does not take into account all the factors that affect this process. Therefore, in future work, it is necessary to study the factors that affect the intensity of fretting corrosion, such as temperature, composition and corrosion activity of the medium, the value of the specific load, and the
number of loading cycles. To analyse what methods can be applied to improve tribological characteristics and resistance to fretting corrosion of titanium alloys.

6. Conclusion
The paper presents the features of fretting wear of parts made of an alloy with the shape memory effect in relation to pipeline connections using couplings made of an alloy with SME. The mechanism of training-corrosion in TiNi-based alloy compounds with shape memory effect is described.

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