Analysis of the welded pipe joints state and the methods for increasing the bearing capacity of gas transmission systems’ pipelines

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Abstract. The changes in the structural state of the weld material of gas pipes at different seam cross-sections are considered. The classification of external and internal weld defects caused by different types of factors carried out, the stress concentration in the transition zone of the weld to the pipe metal is the most significant factor. The analysis of atmospheric effects on the welded seams of pipelines, that initiate adsorption and electrochemical processes of the metal microstructure, which cause corrosion on the external surface of the weld, is given. Taking into account the non-stationary loading mode of pipes due to fluctuations in the internal gas pressure, corrosion and fatigue damages are also added to these defects, which cause the development of fatigue cracks, leading to a violation of the system's tightness and even to the welds destruction. The method for increasing the bearing capacity of pipelines is proposed by applying a technological operation of the external surface plastic deformation of the weld and of the transition zone to the pipe metal, which creates residual compressive stresses that relieve working tensile stresses in the stress concentration zone.

Introduction
The development of the main spheres of industries, agriculture of the countries requires consecutive expansion of the gas transmission system (GTS), the expansion of which over the past decades has been interstate and regional, and requires overcoming of difficult relief, climatic zones and water (sea) areas. At the same time, an important technological problem is the main pipelines network creation by using the large-diameter steel pipes connected by welds, and this process is constantly being improved in order to accelerate the laying time, ensure the necessary operational reliability and extend the service life of pipeline structural elements [1, 2, 3].

According to statistical data and the results of technical survey and expertise carried out by the relevant divisions of gas transmission organizations, it was fixed that about 70...75% of failures and damage to GTS elements are fatigue-related, and 20...25% of failures are caused by corrosion. Taking into account the continuous growth of production and transport services over the past decades, emissions of industrial waste and transport gases into the atmosphere are increasing annually, which leads to increased corrosion effects on various purposes metal structures, including GTS. Corrosion losses are estimated at up to 30% of the weight of structural steels and alloys in the form of unacceptably deformed or destroyed structural elements which need repair or replacement, of which
about 5...7% permanently disappear in the form of corrosive dust or various chemical compounds. This dictates the necessity for a detailed study of corrosion processes in GTS structures and the development of effective anti-corrosion procedures in order to minimize the losses volume of structural steels and alloys, the cost of which tends to increase due to the interstate GTS network expansion [4, 5, 6, 7, 8].

**Corrosion phenomena in GTS structural elements**

Corrosion of structural steels and alloys is usually manifested in two types - chemical and electrochemical. In the first form, it occurs and develops as a result of contact with various gases and liquids which do not have electrical or electromagnetic properties [4, 5, 6]. More common type is electrochemical corrosion, when contact occurs with moist air, water, salt and acid solutions, etc., in which anodic and cathodic interaction processes occur in metal microstructures and in liquids’ electrolytes, herewith the intensity and the corrosion process speed depends on the pH hydrogen index of the liquid (Figure 1.a). The most significant type of GTS welded joints destruction in a corrosive environment is the O2 and H2 adsorption in ionic, atomic or molecular states in the metal surface layer and the creation of oxide and hydride phases caused by embrittlement and delamination of this layer and the appearance of surface micro cracks (Figure 1.b). Eventually, significant decrease in the physical and mechanical characteristics of the alloy under static and cyclic loading occurs [6, 8]. Since the corrosion process is continuous, physical limits of strength and endurance are not observed, which compel, to determine their values, to fix the service life of the structure in the interval of durability of \( N = 5 \cdot 10^4 \cdots 8 \cdot 10^8 \) loading cycles and obtain the corresponding experimental functions. But as fatigue tests show, the gradient of these functions varies in the \( N \) interval, due to the different nature of the corrosion failure mechanism [3, 9, 10, 11].

**Figure 1.** Scheme of electrochemical corrosion in an aquatic environment. a - oxygen depolarization of the steel microstructure, b - development of a corrosion crack that causes the metal surface layer cracking.

In many studies, the hypothesis of adsorption-electrochemical corrosion failure has been put forward, which more precisely represents the specified changes in the corrosion process. Under more common loading modes (re-static and cyclic), local micro-fractures and the first fatigue micro-cracks also appear in the areas where dislocations reach the metal surface. Anodic processes, occurring inside micro cracks, stimulate to their growth, and at high cyclic overstrainions, the adsorption process increases and prevails. At low overstrainions, cyclic micro-damages mainly occur due to electrochemical processes, when overstrainions destroy the oxide micro-layers of the surface and stimulate to the penetration of the corrosive medium into new metal layers [5, 6, 12].
Structural state of the pipelines weld material
The operating conditions of the GTS network are characterized by internal gas pressure, which creates a static or variable stress state in the system, and by variable temperature conditions (-45...+50°C), as well as natural and climatic conditions of the region (landscape, solar radiation, atmospheric pressure, wind, humidity, rainfall, etc.), which form a natural corrosive environment that can cause irreversible physical and chemical changes in the welded joint and the pipe’s metal of the pipeline due to corrosion, sorption, erosion and other processes that eventually lead to micro-damage, loss of strength and structural failure [1,10, 11, 12, 13, 17].

The pipeline network, usually, formed using circular butt welds, which are the main type of welded joints in GTS. In this case, the weld and the pipe’s metal in the cross section have a layered microstructure consisting of several sections (Figure 2) [4, 14].

![Figure 2. Micro structural layers in the contact zone of the weld and the pipe’s metal.](image)

Section I, immediately adjacent to the weld, is a zone of thermal influence, where the welding temperature reaches up to \( t_1 = 1000 \cdots 1100^oC \), has a thickness of \( \delta_1 \approx 2 \, mm \) and a characteristic coarse-grained microstructure. Section II \( (\delta_2 = 0.5 \cdots 2.0 mm) \) undergoes recrystallization and gets a micro grain structure, and the temperature regime is close to the thermal normalization process \( (t_2 = 800 \cdots 900^oC) \). Section III of incomplete recrystallization is located in the \( \delta_3 = 0.5 \cdots 1.0 \, mm \) zone \( (t_3 = 720 \cdots 900^oC) \), where a partial change of grains in the micro structure of the pipe metal occurs.

On sections IV \( (\delta_4 = 2 \cdots 5 \, mm, t_4 = 500 \cdots 550^oC) \) and V \( (\delta_5 = 4 \cdots 5 \, mm, t_5 = 200 \cdots 350^oC) \) there are no visible microstructural changes and thermal aging processes occur.

The hardness of these sections’ layers is also variable, it increases close to the seam. Since the stress concentrators are located in the weld fusion zone, sections I and II are of the main interest.

Defects and damages of GTS welded joints
Butt joints have the greatest endurance of all types of welded joints, but even in this case, the stress concentration and residual tensile stresses that occurred during the formation of the joint in this zone significantly affect the fatigue joint strength. Even in the case of proper implementation of welding technologies, absence of defects, cracks, and nonmetallic inclusions the weakest link in determining the bearing capacity of the connection is the transition area of the weld to the pipe’s metal (Figure 2), and only in the presence of significant defects and damages in another section of the weld residual tensile stresses can be moved to this section [2, 3, 12, 13, 18].

Technological process of welding has its own features and quality of its implementation depends on the following factors:
- poor pipe’s material quality,
- inaccurate pre-processing of the edges of the seams,
- presence of delamination and corrosion layer on the surfaces of the seam edges,
- stress concentration in the transition zone of the weld to the pipe’s metal,
- violation of the welding mode - fluctuations in the electric current voltage, changes in the movement and location speed, as well as the number of the electrode passes,
poor qualified service personnel.
These factors predetermine the appearance of various types of seam defects which can be classified as follows:
1. *By time*- during the seam edges preparation before welding and occurred during welding,
2. *According to the location in the cross-section of the seam*- internal and external.
- The most characteristic defects of this type are: improper processing of the seam edges, which causes a non-constant gap between the edges and mismatch of their joined areas along the entire circumference of the seam, delamination of the surface layer of the seam edges and unacceptable surface irregularities after the mechanical treatments, that will lead to the formation of an inhomogeneous structure in the cross-section of the seam.
- After welding, the seams may have irregularities and deviations from the profile due to unstable welding mode, speed and incorrect electrode supply. Herewith, incisions may appear on the surface layer of the seam, which reduce the cross-section of the seam and cause stress concentration. Internal seam defects include cracks that are sharp stress concentrators and most often appear during welding of high-carbon and alloy steels as a result of sharp cooling of the seam after its installation. Pores and slag inclusions are formed due to the presence of scale and rust in the welding zone, and non-welding and non-melting–at a gap between the edges or a small angle of their bevel, as well as at incorrect electrode supply and high speed of the welding process.
These defects, if they are located unfavorably in the seam section, can also violate the tightness of the pipeline, so after performing welding operations, additional technological operations are mandatory: mechanical cleaning and grinding of the weld contour, strengthening the joint and applying an anti-corrosion coating in order to increase the tightness, corrosion resistance and strength of the welded joint.

The environmental impact on GTS elements is enhanced in the case of the above-mentioned defects and technological omissions presence in the welded joints of pipelines, where corrosion processes are initiated, which would eventually lead to the destruction of welds [7, 12].

The main types of corrosion failure of welded joints are (Table):
1. Entire or common corrosion - can be evenly distributed over the entire surface of the welded joint and the role of the stress state is secondary. It becomes more dangerous, if it is concentrated in a certain welding zone: on the surface of the seam, in the zone of thermal influence, or on the base of the pipe’s metal,
2. Local corrosion is more dangerous than the first type and depends on the stress state, which can lead to a sudden failure of the pipeline. Intergranular corrosion significantly reduces the bearing capacity of pipes made of chromium and aluminum alloys, in which the pitting corrosion can also be developed [3, 6, 18].
3. Static and fatigue corrosion are the most dangerous types of failure when the combined action of the corrosive environment and the stress state caused by extreme static or re-static and cyclic loads. In the first case, static cracking occurs, and in the second, inter-crystalline or trans-crystalline corrosion-fatigue failure of the weld occurs.

**Table.** Main types, forms and pattern of corrosion damage of welded joints.

| N  | Type of destruction   | Forms of destruction | Pattern of destruction |
|----|----------------------|----------------------|-----------------------|
| 1  | General corrosion    | Equal                |                       |
| 2  | On the weld          |                      |                       |
| 3  | In the zone of thermal influence | | |
|   | Description                                      |
|---|-------------------------------------------------|
| 4 | On the pipe’s metal                            |
| 5 | Inter-crystalline, in the zone of thermal influence |
| 6 | In the fusion zone                             |
| 7 | In welds                                       |
| 8 | Pitting                                        |
| 9 | Statical and fatigue corrosion                 |
| 10| Corrosion-fatigue                              |

A significant factor affecting the bearing capacity of GTS elements also is the stress concentration in the welded joint caused by the structural form, assembly technology and operation of the system [18]. The stress concentration zone is a section of the weld where structural and technological defects and various types of damage can be accumulated.

A similar effect is also affected by the material science factor - the heterogeneity of the mechanical properties of the metal in the weld zone, where other types of defects may occur, which will lead to a decrease in the joint strength. During the application of high-strength and alloy steels which are more sensitive to these defects and stress concentrations, the reduction will become more noticeable [1, 2, 3]. For this reason, for the GTS structures, preference is given to low-carbon and low-alloy structural steels, which have good weldability and low sensitivity to these factors’ effects [15].

**Methods for improving the performance of GTS welded joints**

Increasing the bearing capacity, corrosion resistance and fatigue strength of GTS welded joints is mainly implemented by materials science and technological methods, which include the following procedures [1, 2, 3, 16, 18]:

- selection of the type and grade of the steel pipe’s metal, as well as the hardening method that ensures the strength of the welded joint with minimal expenses of the hardening process and relatively low cost of pipe material,
- reduction of stress concentration by means of mechanical processing of the seam surface and by creating a smooth transition zone to the metal of pipe,
- complete formation of the weld volume and elimination of non-welding in its lower part in order to prevent a new zone of stress concentration and microcracks,
- cleaning the surface layers of the weld and the transition zone from non-metallic coatings and inclusions which occurred during welding,
• additional heat treatment of the weld by means of using an electric arc operation in a CO₂ or inert gas environment to regulate the microstructural state and to reduce internal tension in the seam area,

• creation of residual compressive stresses in the weld zone by the methods of plastic deformation of the seam surface layer and the transition zone to the pipe metal – shot blasting, stamping, rolling by rollers,

• application of new protective coatings made of polymer composite materials which increase the corrosion and crack resistance of welds.

The structural strength of GTS pipelines in the area of welds depends on the mechanical characteristics of the metal to plastic deformation and the performance of the weld hardening process, as well as the type of heat treatment. For these steels, plastic deformation of the surface layers of welded joints can increase their endurance limits up to 1.5...2.0 times. In this case, the weld and the metal of pipe act as a joint force system with mutual penetration of their microstructural layers in the contact zone. Strengthening the contour of the welded joint in the surface layer creates residual compressive stresses, which interact with the residual tensile stresses resulting from the welding process, as well as with the operating stresses from the gas pressure [17], reduce the effect of stress concentration and ensure the normal loading mode of the GTS elements [10,11].

The most technologically advanced and easily implemented of these hardening methods is the method of plastic deformation by rolling rollers, which create a uniform layer of deformation on the welded joint surface. The resulting residual compressive stresses C (Figure 3, curve 2) compensate for the influence of residual tensile stresses C (Figure 3, curve 1), creating a favorable initial stress state (Figure 3, curve 3) for receiving operating stresses.

Surface plastic deformation has also a positive effect on the bearing capacity of welded joints under the negative temperatures influence \( t_i = 0 \cdots -50^\circ C \) and corrosive environments, actually, being a universal technology for increasing the corrosion-fatigue strength of these joints. Another important advantage of this technique is its implementation by mechanisms and devices that have a simple, reliable and portable design that makes it possible to perform weld strengthening in the field conditions, directly during welding operations and laying the GTS pipeline [1, 2, 11, 17,18].

![Figure 3. Stress distribution in the area of the welded joint:](image)

1, 2- residual tensile and compressive stresses, accordingly,

3-initial total stresses before the start of the GTS operating mode.

For medium-, high-carbon and alloy structural steels that are not sensitive to plastic deformation, and the stress concentration degree after welding is significant, heat treatment is preferable (quenching with high tempering), which reduces the stress concentration and provides favorable microstructural changes in the weld material.

The application of new protective coatings made of polymer composite materials, due to their high adhesive properties, not only increases corrosion resistance and tightness, but also due to
micropores and cracks on the surface of the weld, reduces the effect of stress concentration and increase the fatigue strength of welded joints.

**Summary**
The increased volume of engineering work on the design and laying of main pipelines of the GTS brings new requirements for ensuring the reliable operation of the mentioned big engineering structures. To implement this research, it is necessary to perform the following works:
1. Study, analysis and classification of all possible defects and damages of critical structural elements of the existing GTS, which include welded pipe joints;
2. Development of new design and technological measures to improve their performance over the pipeline service life [1, 2, 3];
3. On the basis of the activities performed according to the paragraphs 1 and 2, creation of a mathematical model of the specified design and technological procedures for its further application in the designed main pipelines of the GTS [3, 10, 11, 17].

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**Acknowledgements**

This work has been carried out in the frame of “Creating the ways for sustainable urban, architectural and construction complexes development in Republic of Armenia and elaboration of directions with use of permanent monitoring system” programme, financed by Science Committee of Republic of Armenia.