Study of the welded joint of VT1-0 titanium with 1.3343 steel

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Abstract. The work describes a method for obtaining a composite structure of small plates. The resulting plates are a layered structure consisting of a substrate (1.3343 steel) and a titanium coating (VT1-0). A method of resistance welding in the open air was applied to form a layered structure. The resulting titanium-steel compound was tensile tested. The maximum force at break of the welded joint varied in the range from 1.05 to 2.17 kN.

1. Introduction
The development of modern industry is mainly aimed at creating high-tech technologies to increase productivity and reduce the cost of production in oil and gas processing, production of high-tech equipment [1]. One of the innovative directions in these areas is the introduction of technologies involving the use of new materials in the form of composites. In the manufacture of composite materials, depending on the operating parameters, it is required to optimize the technology to achieve the necessary service life.

Production of composite materials largely involves the use of combined methods [2-3]. In many cases, these methods differ a lot from each other. The materials used can be dissimilar in their purpose and mechanical properties as well. In the case of various welding methods in the obtained joints between dissimilar materials, chemical non-homogeneity and intermetallic phases may arise, thus leading to a decrease in physical and mechanical properties [5]. In this regard, an urgent issue in obtaining layered structures is the formation of a high-quality and durable connection that will ensure the reliability and high resource of the finished unit.

The use of titanium-coated steel products has great practical interest. Steel products are used in almost all industries [1,2]. Steel as a structural material has high strength, hardness and elasticity, depending on the alloying elements. However, steel products have low corrosion resistance, which reduces the field of their application and service life [6]. They are covered with various coatings and films in order to increase the latter characteristic.

The known methods of coating deposition frequently require the use of resource-intensive equipment and expensive materials for surface protection. The chemical and mechanical resistance of the resulting coatings in some cases is not high. Resistance welding conducted under certain conditions provides a strong and reliable connection between dissimilar materials [4,5]. In this work, a titanium coating (cp-Ti VT1-0) was applied on a substrate of 1.3343 tool steel (analogous to R6M5). A method of spot resistance welding was used for coating deposition.

2. Methodology
To study the tensile strength of the welded joint, samples of titanium and steel were made. The materials used were 1.3343 steel with a square cross-section with a side of 13 mm, a height of 3.5 mm
and a central hole of 4.2 mm, and VT1–0 titanium in the form of a 70×20 mm plate with a thickness of 0.5 mm.

Before welding, the contact surfaces of the samples were processed with abrasive paper to remove the oxide layer and impart the required roughness parameters. Further the surfaces were degreased in 96% ethanol.

The welded joint of steel with titanium was formed using "Telwin Digital Modular 230" resistance spot welding setup. The constant parameter of resistance welding was the compression force of the electrodes of about 600 N (±10 %) and the operating voltage of 2.5 V. The power and the consumed current were the output characteristics and varied in the following ranges: $P = 3.6–8.2$ kW (power consumption), $I = 17–39$ A (consumed current), and pulse duration $t = 0.1–1.2$ s.

### Table 1. Resistance welding modes

| Sample № | Compression force F, N | Pulse time t, s | Consumed current I, A | Consumed power P, kW |
|----------|------------------------|-----------------|----------------------|---------------------|
| 1        | 600                    | 0.4             | 13                   | 2.9                 |
| 2        | 600                    | 0.4             | 21                   | 4.7                 |
| 3        | 600                    | 0.4             | 29                   | 6.6                 |
| 4        | 600                    | 0.4             | 39                   | 6.6                 |
| 5        | 600                    | 0.4             | 27                   | 5.7                 |
| 6        | 600                    | 0.6             | 28                   | 6.2                 |
| 7        | 600                    | 0.6             | 28                   | 6.2                 |
| 8        | 600                    | 0.9             | 17                   | 3.6                 |
| 9        | 600                    | 1.2             | 23                   | 4.9                 |

Static tensile tests were performed in "Impuls IR5282-100" software-controlled tensile testing machine. The stretching rate was chosen equal to 10 mm/s. When stretching, the maximum force was recorded. After the test, the fracture site was examined using "MBS-10" optical microscope.

### 3. Results

According to the results of a static tensile test, it was revealed that a stable connection was formed in almost all modes (Table 2). Depending on the applied resistance welding modes, the strength properties had significant differences. When analyzing the surface of sample No.1, the area of thermal action in the electrode contact zone was clearly visible. The surface of the sample remained unchanged and slight traces of contact were observed. When tested for rupture, the sample showed one of the highest results, destruction occurred along the metal interface. At a current $I = 39$ A and a pulse duration of $t = 0.4$ s, the surface of the titanium coated sample had macrodefects in the form of dents and metal splashes (Figure 1). This sample was destroyed before the tensile test when clamped.

### Table 2. Maximum breaking force

| Sample № | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Breaking force Fm, kN | 1.87 | 1.37 | 1.05 | -   | 1.77 | 1.08 | 1.83 | 1.37 | 2.17 |
Figure 1. Samples after resistance welding and tensile tests obtained at various modes: $I = 39$ A, $t = 0.4$ s (a); $I = 27$ A, $t = 0.4$ s (b)

Sample No.5 obtained at modes $I = 27$ A, $t = 0.4$ s at rupture showed a close result to the that of sample No.1 (Fig. 1). When analyzing the surface morphology of the parts to be welded, an intense nature of the thermal effect was revealed, which led to the formation of metal splashes. The titanium surface in the contact area was deformed and a clear trace from the electrode appeared. It was destroyed along the metal interface like the rest of samples. When fractured, chipping of the steel base was also observed. This type of destruction showed that hardening had occurred in the steel base. The increase in hardness ultimately led to stresses in the steel and embrittlement. Sample No.7 with modes $I = 28$ A, $t = 0.6$ s in the tensile test showed the same result as sample No.2. However, after welding, the reference planes of the sample surfaces remained undeformed, and traces of a moderate thermal effect of the electrodes were observed. The destruction of the joint occurred along the interface. After breaking, the samples remained intact, which indicated a moderate thermal effect, which did not lead to deterioration in the strength of the metals. Sample No.9 obtained at $I = 23$ A, $t = 1.2$ s had optimal tensile strength. The sample surfaces retained their flatness after resistance welding. There was a well-defined uniform contact plane of the electrodes on the surfaces. The heat trail on the steel base was more pronounced compared to other samples. However, this did not lead to metal splashes. The nature of the fracture of the welded joint was the same as for sample No.5 (tearing off the edge part of the steel base). In this case, the steel was in a stressed state (quenching occurred), but the breaking force $F_m$ was 2.17 kN. In samples No.2, 3, 6, 8 the tensile strength was minimal during tests. For a more detailed analysis, the tensile diagrams of the samples with best strength indexes were considered (Fig. 2).

Sample No.1 had a moderate tensile strength result in a test, while the joint was the least ductile in contrast to the other samples. Sample No.7 turned out to be the most ductile of the selected samples.
Tensile strain was maximal. There were no particularly pronounced areas in the graph, which indicated a uniform elongation without any abrupt transitions. Sample No.9 with the highest strength index had significant elongation before fracture.

Figure 2. Tension diagrams for samples of welded joints: 1 – sample No.1; 2 – sample No.7; 3 – sample No.9.

4. Conclusions

Thus, the application of the resistance spot welding method for the formation of a welded joint between 1.3343 steel and commercially pure titanium was considered. According to the results of the study, it was determined that a pulse with a current strength of about 39 A led to the destruction of the samples. For the duration of 0.4–0.9 s and the current of about 27 A, overheating of the steel substrate and its embrittlement occurred. Static tensile tests of welded joints showed that under the modes $I = 23$ A, $t = 1.2$ s and $I = 28$ A, $t = 0.6$ s, the joint was strong enough and at the same time it had high ductility and required no subsequent heat treatment (tempering, annealing). At the mode $I = 13$ A, $t = 0.4$ s, a sufficiently strong joint with low plasticity was formed compared to other modes, which had a positive effect on the geometry of the final product.

Acknowledgments

The research was supported by the scholarship from the President of the Russian Federation (SP-571.2019.1). Part of the work (optical analysis of the surface morphology of the welded joint) was performed within the framework of the "U.M.N.I.K." program (project 15686GU/2020).

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