Abstract: The article presents results obtained during the plasma powder surfacing of steel S690Q. The tests involved the use of the NiBSi-based EuTroLoy PG 6503 powder with a tungsten carbide addition as well as the making of overlay welds on 30 mm thick plates. The tests involved the making of both simple and overlap runs with an overlap of 30÷70%. The overlay welds were subjected to hardness tests, abrasive wear tests as well as macro and microscopic tests. The tests made it possible to obtain high-quality overlay welds within a wide range of process parameters.

Keywords: Plasma Powder Surfacing, S690Q Steel, EuTroLoy PG 6503

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Introduction
The past 80 years have seen the nearly five-fold increase in the strength of structural steels, ranging from low-carbon steel S235J2G3 having a tensile strength of approximately 200 MPa, through normalised high-strength low-alloy steels ($R_e$ – ca. 350 MPa) or TMCP (thermomechanical control processed and fast cooled) steels ($R_e$ – 450-700 MPa) to toughened steels of the yield points reaching 1300 MPa [1, 2].

Properties of steels can be improved through the process of toughening, i.e. hardening and tempering. Toughened steels, characterised by a tensile strength of 690 MPa, are often used as structural materials in civil engineering or in load-bearing elements of industrial machines. However, mechanical properties are not the only criterion adopted when selecting materials. Another important factor is appropriate resistance to abrasion and other wear-related phenomena. Exemplary applications of toughened steels include critical elements of mining equipment operated in the chemically aggressive environment and subjected to significant abrasion. Other applications of toughened steels include working elements of construction equipment such as excavator scoops, transport worms, drop forging dice, crusher hammers, rolls used in steelworks etc. [1, 6, 7, 8, 9, 10].

Operating conditions of machinery elements made of toughened steels often require the additional protection of surface (because of insufficient hardness). The selection of a protective measure should be preceded by the determination of wear-related phenomena and material weldability. One of the more precise methods
enabling the protection of surface is PTA (plasma transferred arc) powder surfacing making it possible to surface layers with the minimum stirring of the material and the significantly reduced effect of heat on the base material \[2, 3, 4, 5\].

**Objective and Scope**

The research work aimed to develop the technology of the plasma powder welding of 30 mm thick toughened steel S690Q. The research-related tests involved the use of specimens having dimensions of 150 mm × 300 mm. The abrasion resistant surfaced material was powder NiBSi with an addition of tungsten carbides \[3\]. The material was selected to protect steel S690Q against intense abrasion. The significant content of tungsten carbides (approximately 60%) and the high hardness of the matrix itself (approximately 49 HRC) make the weld deposit of the above-named powder resistant to abrasive wear. Table 1 presents the chemical composition of the PG 6503 powder used in the tests.

The EuTroLoy PG 6503 powder is made through atomisation in gas. The powder granularity is restricted within the range of 63 to 180 μm. The powder matrix hardness was restricted within the range of 45 to 49 HRC. The hardness of carbides amounted to 2000 HV10.

All of the overlay welds on steel S690Q plates were made using a robotic station equipped with a SRV6 welding robot (Reis Robotics) and an EuTronic GAP 2000 DC plasma device (Castolin Eutectic) combined with a GAP E52 plasma torch mounted on the robot arm. The station enabled the swinging motion of the torch. The process of surfacing was performed using plasma gas, powder carrier gas and shielding gas (pure argon).

The identification of the field of the plasma powder surfacing of plates made of steel S690Q performed using the EuTroLoy PG 6503 powder required the performance of surfacing tests involving the making of simple runs and enabling the determination of the following:

- surfacing current range, A,
- powder feeding rate, g/min (Table 2).

To determine the field of the parameters of the plasma powder surfacing of 30 mm thick toughened steel S690Q it was necessary to make a number of overlap overlay welds. The adopted variable parameters were the following:

| Specimen no. | Surfacing current, A | Powder feeding rate, g/min |
|--------------|----------------------|--------------------------|
| no. 1        | 55 A                 | 25 g/min                 |
| no. 2        | 55 A                 | 30 g/min                 |
| no. 3        | 55 A                 | 35 g/min                 |
| no. 4        | 65 A                 | 25 g/min                 |
| no. 5        | 65 A, 30 g/min       |                          |
| no. 6        | 65 A                 | 35 g/min                 |
| no. 7        | 75 A                 | 25 g/min                 |
| no. 8        | 75 A                 | 30 g/min                 |
| no. 9        | 75 A                 | 35 g/min                 |

Table 1. Chemical composition of powder EuTroLoy PG 6503 [3]

| Chemical composition, % | Ni | Si | Fe | B | C |
|-------------------------|----|----|----|---|---|
| Rest                    |    | 3.5| 3.0| 2.3| 0.2|

Note: tungsten carbide constitutes 60% of the powder mass.

Table 2. Overlay welds made using simple runs
- surfacing current, A,
- surfacing rate, mm/s,
- powder feeding rate, g/min,
- overlay weld overlap, %.

All of the tests involved the use of a plasma gas (Ar) flow rate of 3.5 l/min, a shielding gas (Ar) flow rate of 9 l/min, a powder carrier gas (Ar) flow rate of 2.5 l/min and the distance between the torch nozzle and the material amounting to 8 mm.

All of the overlay welds were subjected to visual and macroscopic tests as well as hardness measurements performed in the base material, HAZ and in the overlay weld. Table 3 presents the macroscopic metallographic photographs and photographs of exemplary overlay weld faces.

The subsequent stage of the research involved the performance of hardness measurements. The measurements were performed on the cross-section of the specimens, in one measurement line in the base material, HAZ and in the overlay weld, maintaining appropriate distances between successive measurement points (Fig.1). Microhardness measurements were performed using a Micro Vickers 401 MVD hardness tester. The results of the visual, metallographic and hardness tests of the overlay welds were used to select 2 groups of parameters related to the surfacing of toughened steel S690Q performed using the PTA method and the EuTroLoy PG 6503 powder and applied in abrasive wear resistance tests (Table 5).

Table 3. Photographs of the overlay weld face and the cross-sectional macroscopic metallographic photographs of the overlay welds with the overlap run; etchant: Adler’s reagent.

| Specimen no. | Photograph of overlay weld face | Overlap size, % | Overlay weld cross-sectional macroscopic photograph |
|--------------|---------------------------------|----------------|--------------------------------------------------|
| 1            | ![Image](1)                      | 30             | ![Image](2)                                      |
| 2            | ![Image](3)                      | 50             | ![Image](4)                                      |
| 3            | ![Image](5)                      | 70             | ![Image](6)                                      |
| 4            | ![Image](7)                      | 30             | ![Image](8)                                      |
The subsequent stage of the research work involved Rockwell hardness tests performed on the ground faces of overlay weld specimen nos. 8 and 15 as well as steel Hardox 400 (as a reference standard). The hardness measurements were performed using a Wilson Wolpert Rockwell Hardness 600MRD hardness tester. Hardness was measured at 5 points on each test specimen. The HRC hardness tests were performed on 6 specimens described below. The hardness measurement results are presented in Table 6.

- specimen 8-1: overlay weld no. 8 (surfacing parameters in Table 4),
- specimen 8-2: overlay weld no. 8 (surfacing parameters in Table 4),
- specimen 15-1: overlay weld no. 15 (surfacing parameters in Table 4),
- specimen 15-2: overlay weld no. 15 (surfacing parameters in Table 4),
- specimen H-1: steel Hardox 400,
- specimen H-2: steel Hardox 400.

The subsequent stage of research involved the performance of microscopic metallographic tests. The tests included the taking of photographs of the base material, the interface with the HAZ and of the overlay weld (Fig. 2÷9). The images were magnified 200 and 500 times.

### Abrasive Wear Resistance Tests

Tests aimed to identify the abrasive wear resistance of the layers applied using plasma surfacing and the EuTroLoy PG 6503 powder and of steel Hardox 400 (used as a reference standard) were performed in accordance with ASTM G 65-00, Procedure A. The test specimens (75 × 25 × 10 mm) were cut out of plates subjected to plasma powdersurfacing performed using the EuTroLoy PG 6503 powder and steel.
HARDOX 400, and, subsequently, subjected to grinding. Following the recommendations of ASTM G 65-00, before and after the abrasion tests, all of the specimens were weighed on a laboratory scale using an accuracy of up to 0.0001 g (Table 7). The mass decrement of the specimens subjected to plasma surfacing performed using the EuTroloy PG 6503 powder were compared directly with that of the specimens made of steel HARDOX 400. The volume mass decrement was calculated using the measured density of the sprayed (surfaced) layer and the specimen mass decrement (Table 8).

**Analysis of Test Results**

The surfacing tests performed using variable parameters revealed their effect on the geometry and the content of the base material in the overlay weld. In terms of the parameters subjected to the tests, the maximum penetration depth was restricted within the range of 0.85 to 1.67 mm, whereas the penetration area was restricted within the range of 10.20 to 38.79 mm². The shallowest penetration depth of 0.85 mm was obtained using a welding current of 55 A, a filler metal powder filling rate of...
25 g/min, an overlap of 30% and a welding rate of 1.2 mm/s. In turn, the deepest penetration depth of 1.67 mm was obtained using a welding current of 65 A, a filler metal powder filling rate of 30 g/min, an overlap of 50% and a welding rate of 1.2 mm/s.

The Vickers (HV1) hardness tests revealed that the base material was characterised by a hardness of 280 HV1. The cross-sectional hardness measurements of the overlap overlay welds made of steel S690Q subjected to plasma powder surfacing performed using the EuTroLoy PG 6503 powder revealed that the hardness in the HAZ was restricted within the range of 264 to 389 HV1, whereas the hardness of the overlay weld was restricted within the range of 680 to 400 HV1.

The Rockwell hardness tests involving the ground face of the overlay welds revealed hardness values restricted within the range of 39.6 to 50.2 HRC. It can be assumed that the abovenamed range was consistent with the matrix hardness-related data provided by the producer.

The microscopic tests revealed that the base material structure was composed of tempered martensite and that the HAZ contained martensitic structures having a hardness of 400 HV1. The structure of the overlay welds consisted of...
solution \( \gamma \) with boride silicate eutectics with visible tungsten carbides. It was observed that the effect of the surfacing thermal cycle led to the dissolution of carbides located in the matrix, which, in turn, triggered changes in the functional properties of the coatings. The size of overlay weld grains was not significantly affected by the welding linear energy.

The test results concerning the metal-mineral type abrasive wear resistance of the layers subjected to plasma surfacing performed using the EuTroLoy PG 6503 powder and the specimens made of steel Hardox 400 revealed the mass decrement restricted within the range of 0.9046 g to 1.5009 g. The measured volume decrement was restricted within the range of 109.6689 mm\(^3\) to 184.4898 mm\(^3\). The above-presented data were used to calculate relative abrasive wear, referring to the test results concerning the abrasive wear resistance of steel Hardox 400. The best result was obtained in terms of specimen no. 8, where the abrasive wear resistance amounted to 1.64 in relation to steel Hardox 400. In turn, as regards specimen no. 15, the abrasive wear resistance amounted to 1.24 in relation to steel 400.

It was possible to observe the effect of welding linear energy on the abrasion resistance of overlay welds nos. 8 and 15. The specimens cut out of overlay weld no. 8, where linear energy amounted to 2.251 kJ/mm, were characterised by higher abrasion resistance. In turn, specimens cut out of overlay weld no. 15, where linear energy amounted to 2.766 kJ/mm, were characterised by slightly lower abrasion resistance. Higher welding linear energy increases the content of the base material in the overlay weld, which significantly affects abrasive wear resistance.

Conclusions

The test results concerning the plasma powder surfacing of 30 mm thick toughened steel S690Q using the NiBSi-based EuTroLoy PB 6503 containing a tungsten carbide addition revealed the following.

1. It is possible to make high-quality welding imperfection-free overlap overlay welds within a wide range of surfacing parameters (surfacing current restricted within the range of 55A to 75A, filler metal wire feeding rate restricted within the range of 25 g/min to 35 g/min and an overlap restricted within the range of 30% to 50%).
2. The overlay welds were characterised by the nickel matrix containing tungsten carbides and a hardness of 600 HV1. The HAZ structure was martensitic and characterised by a hardness of approximately 400 HV1. The base material structure was composed of tempered martensite.
3. The hardness of the ground overlay weld face amounted to 45 HRC, which was consistent with the data provided by the filler metal manufacturer.
4. Resistance to metal-mineral abrasion of the overlay welds was higher by approximately 30 to 70% in comparison with that of steel Hardox 400.
5. The abrasive wear was affected by welding linear energy. An increase in welding linear energy was accompanied by an increase in the content of the base material in the overlay weld, which, in turn, led to a decrease in abrasive wear resistance.

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