Accuracy and Roughness of TiN Coatings Deposited by Vacuum Arc Plasma

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Abstract. Nitride coatings were deposited by vacuum arc plasma in an atmosphere of argon and nitrogen using different deposition conditions of part location and configuration, angle between plasma flow and processing surface. The coating thickness, part dimensions and surface roughness were measured before and after coating deposition. The type of part poor shape precision after coating deposition by vacuum arc plasma was defined. An impact of coating deposition by vacuum arc discharge on the part dimensional and form accuracy was revealed. The effect of parts location on dimensional and radial surfaces form accuracy was induced. The effect of coating surface polythickness on part dimensional and form accuracy for parts with different stiffness was defined. The impact of part location area and parts quantity on coating thickness, surface roughness, dimensional and form accuracy of part was revealed. The coating thickness distribution law, parts quality class and accuracy degree after vacuum ion plasma coating deposition were assigned.

1. Introduction
Required coating thickness, surface roughness, form and dimensions accuracy after coating deposition by vacuum arc plasma assurance leads to quality conformance of high precision parts [1-2]. Precision of vacuum arc plasma coating is determined by coating thickness scatter. Influence of deposition conditions on coating thickness was studied earlier [3-7]. Known data is impossible to use during accuracy assessment, as real parts have dimensions and complicated configuration.

2. Experimental technique and equipment

TiN coatings were deposited by vacuum arc plasma on plants with different cathode diameters (80mm and 180 mm).

An effect of cathode material and coating thickness on surface roughness was studied on TiN, ZrN, CrN, CrCN, MoN, TiC, CrC, TiCN coatings. Pieces of heat-resistant steel 13Cr11Ni2W2MoV (Ø15 mm, h=10 mm) were finally processed by grinding (Ra = 1.0 - 1.5 µm) and smoothing (Ra = 0.02 µm).

Influence of pre-process machining (turning, air dynamic hardening, grinding, superfinishing) and coating thickness on surface roughness was studied on structural alloyed steel 30CrMnSiNi pieces. Effect of plasma source – coated surface spatial relationship on coating thickness and surface...
roughness was studied on flat pieces of size $14 \times 20 \times 2$ mm with different initial surface roughness ($Ra$ 0.63 $\mu$m and $Ra$ 0.04 $\mu$m).

Effect of simultaneously processed parts quantity on coating thickness scattering was studied on bushing batches. The bushings were located parallel to the plasma flow (Fig. 1). The location areas were 60 and 200 mm in size (radius). The batch quantities were 50 and 100 parts, respectively.

3. Results
Surface roughness depends on coating thickness and type of preprocess machining, and may decrease (if initial $Ra > 1.6$ $\mu$m) or increase (if initial $Ra < 1.6$ $\mu$m). The surface roughness increases by the coating thickness increasing. Cathode material affect the surface roughness as follows: $Ra$ (Ti) > $Ra$ (Cr) > $Ra$ (Zr) > $Ra$ (Mo);

Table 1. Dependence of TiN and ZrN coating roughness from coating thickness. Coatings were deposited on motionless substrates.

| Coating thickness $h$, $\mu$m | 8    | 16   | 24   | 32   |
|-------------------------------|------|------|------|------|
| TiN coating surface roughness $Ra$, $\mu$m | 0.2  | 0.2  | 0.23 | 0.25 |
| ($Ra_{initial} = 0.02\mu$m)   |      |      |      |      |
| TiN coating surface roughness $Ra$, $\mu$m |      | 2.0  | 2.0  | 2.3  |
| ($Ra_{initial} = 1.0-1.5\mu$m) |      |      |      |      |
| ZrN coating surface roughness $Ra$, $\mu$m | 0.11 | 0.11 | 0.13 | 0.14 |
| ($Ra_{initial} = 0.02\mu$m)   |      |      |      |      |

Surface roughness after deposition by vacuum arc plasma (initial roughness $Ra = 0.01–0.63$ $\mu$m, coating thickness $h = 5–15$ $\mu$m) can be defined from the following expression:

$Ra = C + Ra_{initial}$.

$C=0.2$ $\mu$m for Ti; $C=0.15$ $\mu$m for Cr; $C=0.1$ $\mu$m for Zr; $C=0.07$ $\mu$m for Mo.

Figs 2-5 display surface roughness of TiN coatings. The arithmetic average roughness values of pieces, located on the axis of the particle flux at a distance of 200 mm from cathode are almost the same for samples with different initial roughness and spatial orientation.
Table 2. Dependence of TiN and ZrN coating Roughness thickness on coating thickness. Coatings were deposited on rotated substrates.

| Coating thickness h, μm | TiN | Zr |
|-------------------------|-----|----|
| 5                      | 10  | 15 |
| 10                     |     |    |
| 15                     |     |    |

Coating surface roughness Ra, μm (Rₐₐₐ = 1.0-1.5μm)

| Coating surface roughness Ra, μm (Rₐₐₐ = 0.02μm) |
|-----------------------------------------------|
| 1.4  | 1.4  | 1.7  | 1.1  | 1.5  | 1.6  |
| 0.19 | 0.19 | 0.2  | 0.11 | 0.11 | 0.12 |

Figure 2. Dependence of surface average roughness Ra on the transverse distance dₓ from the symmetry axis of plasma flow for different distances L to cathode. Initial average roughness Ra=0.04 μm. Cathode diameter 80 mm. 1 – L = 200 mm; 2 – L = 300 mm; 3 – L = 400 mm. Pieces are oriented perpendicular to plasma flow.

Figure 3. Dependence of surface average roughness Ra on the transverse distance dt from the symmetry axis of plasma flow for different distances L to cathode. Initial average roughness Ra=0.04 μm. Cathode diameter 80 mm. 1 – L = 200 mm; 2 – L = 300 mm; 3 – L = 400 mm. Pieces are oriented parallel to plasma flow.
Perpendicular location of coated surface leads to maximum surface average roughness $Ra=1.2 \, \mu m$ for both initial surface roughness. Parallel location of coated surface leads to maximum surface average roughness $Ra=0.8 \, \mu m$ and depends on initial surface roughness. Maximum roughness corresponds to the deflection angle from the axis of the particle flux 25-30°. The average roughness decreases nonlinearly with a distance from the cathode increasing. At a distance from cathode of 400 mm average roughness $Ra = 0.63 \, \mu m$ is achievable. Higher roughness decreases and lower increases during coating deposition by vacuum arc plasma.

Cylindrical surfaces ovality after 4 µm TiN coating deposition by vacuum arc plasma (Fig.6) hasn’t changed and depends on pre-process machining. TiN vacuum arc coating of 4 µm thickness deposition on cylindrical surfaces leads to diameter scattering increase from 4 µm up to 7 µm.

Fig. 7 displays the TiN vacuum arc coating thickness distribution on bushing batches. The distribution curve shows correlation with normal distribution law.
The thickness scattering for vacuum arc coating deposition depends on the size (radius) of workpieces location area. For example, reducing the size of workpieces location area from 200 mm to 60 mm leads to coating thickness standard deviation decrease from $\sigma = 2.13 \, \mu m$ to $\sigma = 0.78 \, \mu m$. The coating thickness scatterings were 4 $\mu m$ and 11 $\mu m$ for 60 and 200 mm workpieces location area, respectively. The coating thicknesses were $6^{+4}_{-4} \, \mu m$ and $3^{+11}_{-11} \, \mu m$ for 60 and 200 mm workpieces location area, respectively.

Effect of coating deposition on form error was studied on thin-walled circular-shaped parts (Fig. 8). Following deposition modes were selected:

a) aflat plasma source spatial orientation;

b) upright plasma source spatial orientation.

Parts were oriented parallel to plasma flow.

As is known increasing of layers quantity leads to parts operating ability increase through decreasing of coating locked-up stresses. So coatings were deposited under two techniques: single-layer TiN coating; multilayer Ti-TiN coating.

Calculated coating thickness, ovality and conicity of thin-walled circular-shaped parts are given in table 3.

Measurement results of thin-walled circular-shaped parts after coating deposition are given in table 4. The experimental data show that coating deposition with aflat plasma source spatial orientation and parts planetary parts rotation leads to ovality tolerance exceeding. Coating deposition with upright plasma source spatial orientation and parts planetary parts rotation fulfil requirements of form accuracy.
### Table 3. Calculated ovality and conicity

| Plasma source spatial orientation | Rotation type | Coating thickness, µm | Ovality, µm | Conicity, µm |
|----------------------------------|---------------|-----------------------|-------------|--------------|
| aflat                            | about table axis | 1.7±2.2              | 8.1         | 1.7          |
|                                  | planetary      | 1.5±1.6              | 6.5         | 1.3          |
| upright                          | about table axis | 4.6±1.9              | 1.8         | 0.5          |
|                                  | planetary      | 5.3±0.7              | ~0          | 0.3          |

### Figure 8. Thin-walled circular-shaped parts in vacuum chamber.

### Table 4. Results of thin-walled circular-shaped parts form measurement

| Process parameters | Coating type | Coating thickness, µm | Ovality, µm | Conicity, µm |
|--------------------|--------------|-----------------------|-------------|--------------|
| Plasma source spatial orientation | Rotation type | min | max |               |              |
| Aflat               | planetary    | single-layer          | 2 | 7 | 15.5 | 10 |
|                     |              | multilayer            | 11 | 8 |
| Upright             | planetary    | single-layer          | 7 | 7 |
|                     |              | multilayer            | 7 | 6 |

Multilayer coating in comparison with the single-layer leads to essential decrease of form error. That can be explained by decreasing of coating locked-up stresses through structural changes in coating [4]. Experimental data agree with calculated data (taking into account parts initial form error). According to experimental data the fact of ovality initiation after coating deposition by vacuum arc plasma was established. An ovality originates from polythickness of the coating through the part surface. Form error decreasing can be achieved by multilayer coating deposition [1] and polithickness decreasing [1,4].
4. Conclusion

- Surface roughness after coating deposition by vacuum arc plasma depends on the manufacturing inheritance (due to the surface roughness after machining), the material evaporation by vacuum arc (due to the microdroplets presence) and coated surface location;
- Vacuum arc plasma coating thickness distribution, as was established, corresponds with normal distribution law. The vacuum arc plasma coating inaccuracy strongly depends on parts location area. The accuracy of coating deposition by vacuum arc plasma depends on part location area radius (Rpa) to cathode radius (Rc) ratio.
- At the ratio \( \frac{R_{pa}}{R_{c}} \leq 1 \) plasma flow homogeneity from vacuum arc plasma source is enough to secure required part accuracy and surface quality of high precision parts. The parts location area can be enlarged by cathode radial dimensions increasing or by such parts with plasma source relative movement, which allow to secure deposition conditions equality for different processing surface areas.
- Thin-walled circular-shaped parts form error after deposition by vacuum arc plasma depends on coating polythickness. Deposition of 5 µm coating on 5 accuracy rating parts leads to accuracy deterioration to 7 accuracy rating. Uniform coating deposition does not change accuracy rating at the same time. The ovality after coating deposition is produced from heating and coating locked-up stresses.

Acknowledgments

The study was supported by the grant from the Russian Science Foundation (#15-19-10030)

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