CODEN STJSAO ISSN 0562-1887
ZX470/1443 UDK 620.178:620.163.4:539.38

# The Quality Influence of Base Material Surface Preparation on the Durability of a Sprayed Layer Against Radial and Axial Shear

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Preliminary note

For the purpose of this experiment, respective surfaces of 42CrMo4 base material specimens were prepared for spraying using different technologies: turning, cutting of radial notches and cutting of axial notches. Gas aided thermal spraying of wire material was performed, laying a first layer of a nickel aluminum compound and a final Chrome Molybdenum Steel coating. Metallographic structure analysis and hardness measurement suggested that surface preparation quality does not affect hardness of the sprayed layer, but its thickness. Using a suitable tool, specimens were examined on radial and axial shear and these results were compared to previous ones. It could be determined that the notch size significantly affects both the thickness of the intermediate layer and its even distribution around the edge of the notch. A smaller radial notch allows for a higher torque momentum at radial shear, whilst best overall properties are achieved with axial notches subjected to radial loads. Testing axial shear, the cutting power proved dependant of the depth of radial notches, where low depth was inherent with low shear resistance.

**Keywords**

*Base material*
*Metal spraying*
*Radial and axial shear*
*Surface preparation*

**Ključne riječi**

*Naštrcavanje*
*Osnovni material*
*Priprema površine*
*Smik radijalni i smik aksijalni*

**Utjecaj kvalitete pripreme površine osnovnog materijala na otpornost naštrcanog sloja radijalnom i aksijalnom smiku**

Prethodno priopćenje

Na ispitnim uzorcima osnovnog materijala 42CrMo4 izvršene su različite pripreme površine: tokarenjem, narezivanjem aksijalnih i narezivanjem radijalnih utora. Izvršeno je plinsko naštrcavanje žicom: međusloj nikl-aruminid i završnog sloja Cr-Mo čelik. Metalografskim pretragama strukture i kontrolom tvrdoća utvrđeno je da kvaliteta pripreme površine ne utječe značajno na tvrdoću ali utječe na postignutu debljinu sloja. Odgovarajućim alatom izvršena su ispitivanja uzoraka na radijalni i na aksijalni smik. Međusobnom usporedbom rezultata ovih mjerenja s rezultatima kontrole tvrdoće i metalografskim pretragama strukture dolazi se do zaključka da veličina utora značajno djeluje na debljinu podsloja a pogotovo na njegovu ravnomjerno naštrcavanje po obodu utora. Sitniji radijalni utor doprinosi povećanju momenta zakretanja pri radijalnom smiku, ali se najbolja svojstva postižu u uvjetima aksijalnih utora radijalno opterećenih. Pri ispitivanju na aksijalni smik sila odreza ovisi o dubini radijalnih utora pri čemu mala dubina utora daje i malu otpornost na smik.

**Received (primljeno)**: 2009-09-01
**Accepted (prihvaćeno)**: 2010-02-19

## 1. Introduction

Among various methods of repair overhaul of damaged component surfaces, thermal spraying is selected if welding of facings can be anticipated to cause macro deformation of, for example, axles and shafts [1]. Typically, sleeve surface damage on an axle is caused by relative rotation of the inner bearing ring [2], while axial shifting of shrink connections, e.g. screw conveyor segments, may cause superficial shaft damage [3]. Following thermal spraying, the components must be machined to design measurements. During subsequent exploitation, the mechanical properties of the sprayed layer are expected to match the projected lifespan of the respective component [4-7]. Initiated by this assumption, various methods of base material surface preparation for thermal spraying were examined.

In addition to required layer thickness and surface hardness, the sprayed layer is required to withstand radial and axial shear, relative to the axis of the shaft or axle.

**Symbols/Oznake**

| | | | |
|---|---|---|---|
| *MZ* | – torque, Nm<br>– moment zakretanja | *FS* | – shear force, N<br>– sila odreza |
| $\upsilon_p$ | – ring heating temperature, °C<br>– temperatura predgrijavanja prstena | *t* | – time, s<br>– vrijeme |

The goal of this experiment was to determine the influence of surface properties on the mechanical behavior of the coating, relative to previous alterations of shape and surface preparation quality.

## 2. Selection of materials and specimen preparation

As base material, quenched and tempered 42CrMo4 steel was selected for the experiment due to its frequent application in the design of axles and shafts [4]. For thermal spraying, these materials were selected:

For the intermediate layer a Ø3.2 mm wire, METCO 405 (~20 % Al; ~80 % Ni)

For the final layer an Ø3,2 mm wire, METCOLOY 2 (~0,38 % C; 0,75 % Si; 0.38 %Mn; 13.5 % Cr; % Mo).

For the purpose of the experiment, 70 specimens of Ø38/Ø16x12 mm were fabricated from the same base material batch and then subdivided into seven groups of ten samples respectively, differing in their surface quality and surface preparation technology (Type 1 to 7).

Table 1 illustrates this sequence of preparation.

**Table 1.** Surface preparation method prior to thermal spraying

**Tablica 1.** Vrste pripreme površine uzoraka prije naštrcavanja

| Ser.no./<br>R. b. | Surface preparation /<br>Vrsta pripreme povešine | Mark /<br>Oznaka |
|---|---|---|
| 1 | Radial notches, *a*=0.25 mm /<br>Radijalni utori, *a*=0.25 mm | Type 1 /<br>Tip 1 |
| 2 | Radial notches, *a*=0.50 mm /<br>Radijalni utori, *a*=0.50 mm | Type 2 /<br>Tip 2 |
| 3 | Radial notches, *a*=1.00 mm /<br>Radijalni utori, *a*=1.00 mm | Type 3 /<br>Tip 3 |
| 4 | Radial notches, *a*=1.25 mm /<br>Radijalni utori, *a*=1.25 mm | Type 4 /<br>Tip 4 |
| 5 | Axial notches, *a*=1.00 mm /<br>Aksijalni utori, *a*=1.00 mm | Type 5 /<br>Tip 5 |
| 6 | Machine-turned and degreased /<br>Tokareno i odmašćeno | Type 6 /<br>Tip 6 |
| 7 | Emulsion-coated /<br>Uronjeno u emulziju | Type 7 /<br>Tip 7 |

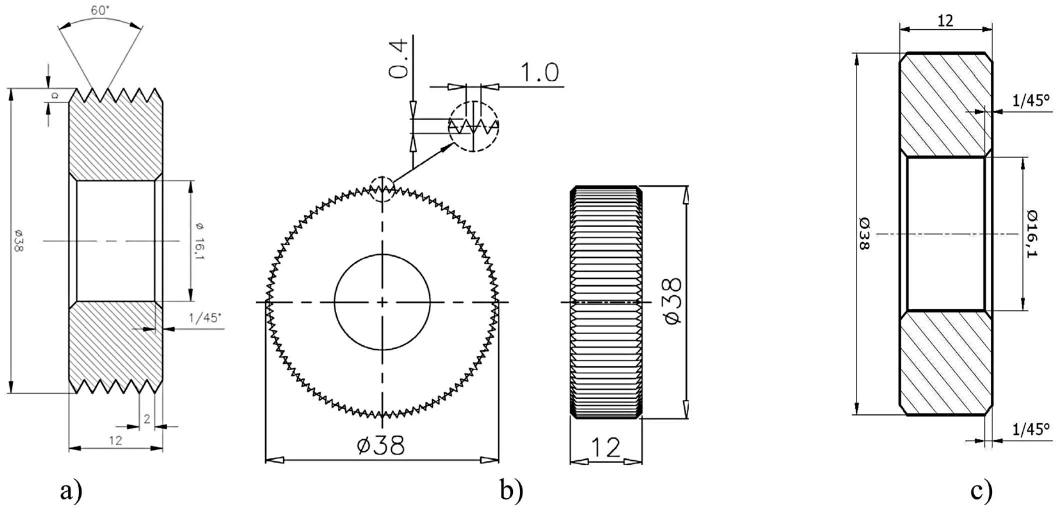
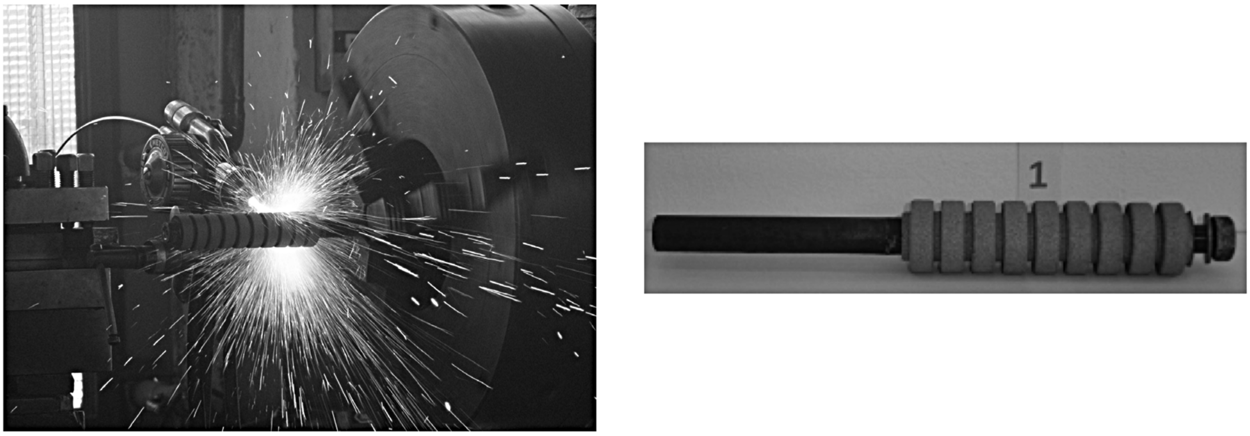



**Figure 1.** Specimens dimensions before coating: a) Type 1, 2, 3 and 4 (radial notches); b) Type 5 (axial notches); c) Types 6 and 7 (smooth, no notches)

**Slika 1.** Dimenzije uzoraka osnovnog materijala prije naštrcavanja: a) Tip 1, 2, 3 i 4 ( radijalni utori); b) Tip 5 (aksijalni utori), c) Tip 6 i 7 (glatko, bez utora)




a) b)

**Figure 2.** Thermal spraying: a) Position of the specimens in the lathe during spraying, b) A set of specimens after spraying

**Slika 2.** Naštrcavanje uzoraka: a) Položaj uzoraka u tokarskom stroju tijekom naštrcavanja dodatnog materijala, b) Set naštrcanih uzoraka

For thermal spraying, a METCO E10 device was used. The round specimens with dimensions as given in Fig. 1 were fixed onto a mandrel and held respectively apart by spacers, Ø30/Ø16x3 mm. The mandrel was bolted onto a lathe chuck and supported by a spire. The distance between the wire tip and the specimens was set at ~220 mm for the intermediate layer and at ~ 180 mm for the final coating, Figure 2.

The feed rate of the spraying unit was set at 3 mm per revolution of the specimen arrangement.

During intermediate layer spraying, the wire tip was 1,5 mm within the air core. For final coating, the gun was adjusted so that the glowing wire tip would protrude from the air core by 12 to 15 mm in order for the filler material to start melting.

## 3. Experiment results

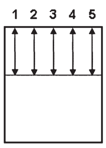
As per Experiment Plan, a random selection of one respective specimen from any coated set would be made and the specimens would then be subjected to metallographic testing and hardness control. The other specimens from each set would be machined to designed size by sanding. Respectively, three of these would undergo radial shear testing (hereinafter: torque) and axial shear testing (hereinafter: shear). The Plan also stipulated the fabrication of a tool suitable to produce both torque and shear.

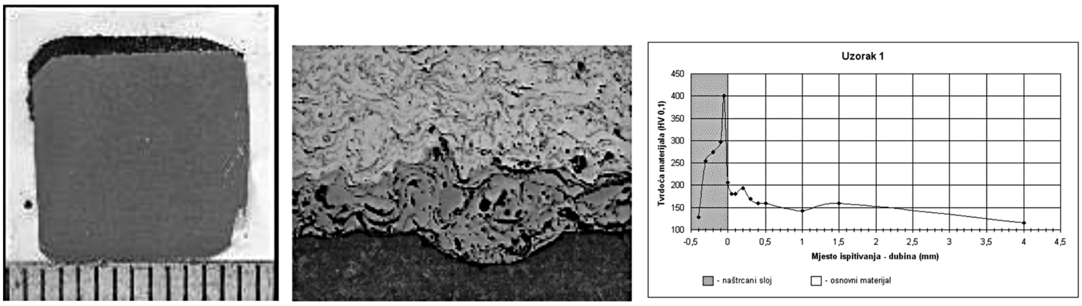
### 3.1. Metallographic examination and hardness control

Figure 3 shows a typical macro of a cross-cut specimen, typical micro-structures and an HV 0,1 hardness distribution diagram. Notably and depending on the specific method of surface preparation, the thickness of sprayed coating varies significantly between different specimens. Consequently, HV hardness distribution was measured across the layer using a force of 1 N (HV 0,1). The thickness of respective layers was measured using a Durimet – unit, alongside five reference lines for each specimen, as shown in Table 2.

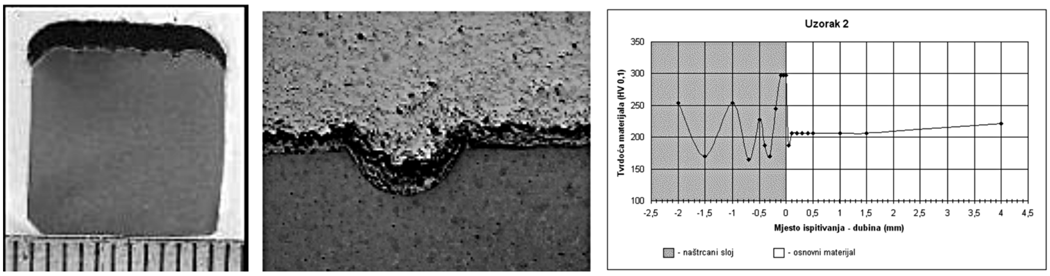
**Table 2**. Thickness of sprayed coatings alongside reference lines

**Tablica 2.** Debljine naštrcanog sloja po referentnim pravcima

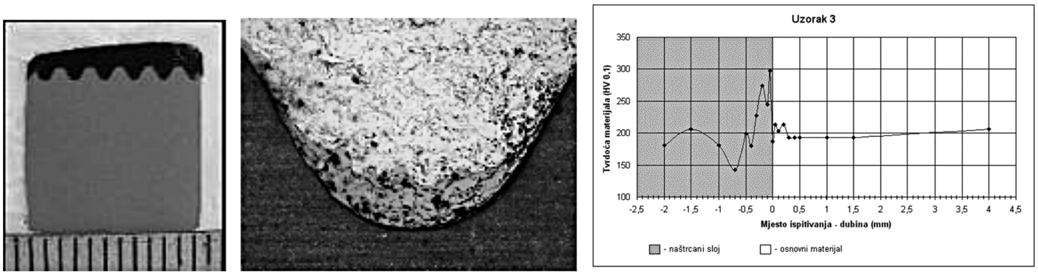
| Position of ref. line / Položaj referentnog pravca | Reference line No. / Referentni pravac br. | Thickness of layer / Debljina sloja, mm | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|  | 1 | 2.05 | 2.09 | 2.48 | 2.30 | 1.26 | 1.02 | 0.30 |
| | 2 | 1.47 | 2.25 | 2.04 | 2.47 | 1.68 | 1.20 | 0.38 |
| | 3 | 1.05 | 2.09 | 2.42 | 2.50 | 1.53 | 1.12 | 0.39 |
| | 4 | 1.21 | 2.08 | 2.31 | 2.39 | 1.15 | 0.96 | 0.32 |
| | 5 | 1.40 | 2.05 | 1.32 | 2.41 | 1.08 | 0.84 | 0.29 |



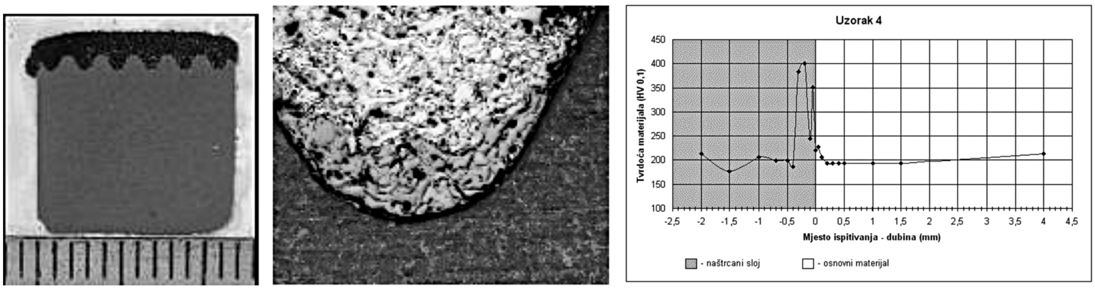

a) Specimen Type 1, a=0.25 mm (radial) / Uzorak Tip 1, a=0.25 mm (radijalno)



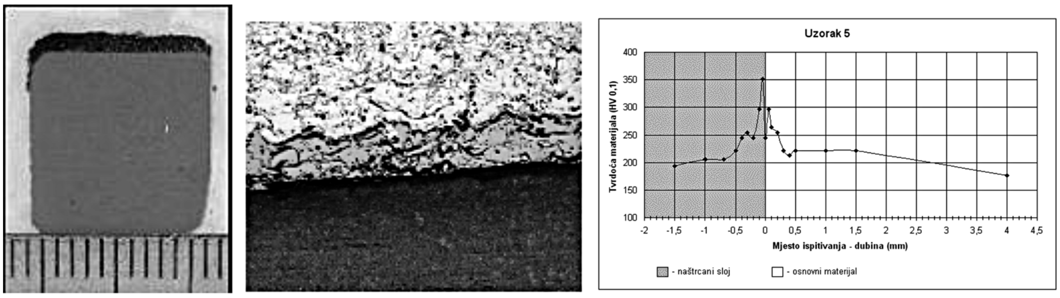

b) Specimen Type 2, a=0.50 mm (radial) / Uzorak Tip 2, a=0.50 mm (radijalno)



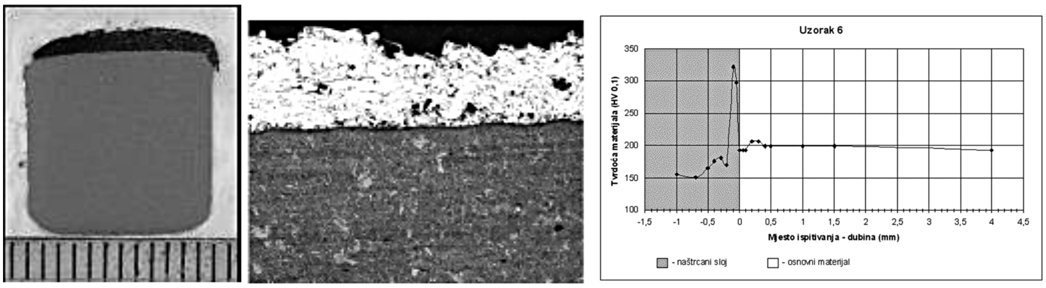

c) Specimen Type 3, a=1.00 mm (radial) / Uzorak Tip 3, a=1.00 mm (radijalno)



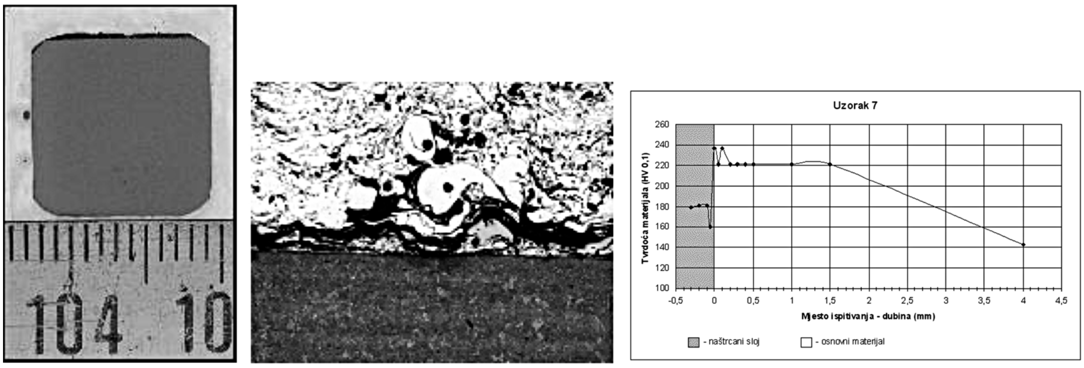

d) Specimen Type 4, a=1.50 mm (radial) / Uzorak Tip 4, a=1.50 mm (radijalno)




e) Specimen Type 5, a=1.00 mm (axial) / Uzorak Tip 5, a=1.00 mm (aksijalno)




f) Specimen Type 6 (smooth, degreased), a=0 / Uzorak Tip 6 (glatko, odmašćeno), a=0




g) Specimen Type 7 (smooth, emulsion-coated), a=0 / Uzorak Tip 7 (glatko, emulzija), a=0

**Figure 3**. Specimen microstructures and hardness distribution HV 0,1 from surface to core
**Slika 3.** Mikrostruktura uzoraka i tok tvrdoće HV 0,1 od površine prema jezgri

In addition to a variation of coating thickness around the edges, metallographic examination and hardness control further showed that these coatings were locally very thin for specimens Type 7 (emulsion-coated prior to spraying) and Type 6 (machine-turned and degreased). Consequently, it was decided to exclude these two types from shear testing.

During machine-turning, the respective first throughout measures were established as:

Ø39,20 mm for specimens of Type 1

Ø40,00 mm for specimens of Type 2, 3, 4 and 5.

Following the Experiment Plan, six specimens of each Type were selected randomly – three to test torque, three to test shear:

## 3.2. Torque testing

Out of each Type, three specimens were randomly selected and marked, i.e. 1.1, 1.2, 1.3; … ; 5.2, 5.3. Figure 4 shows all specimens prepared for torque testing.

Consequently, a rectangular hole OK 19 was machined in each of these specimens in order to allow for the use of a torque wrench type ART 263 UNIOR.

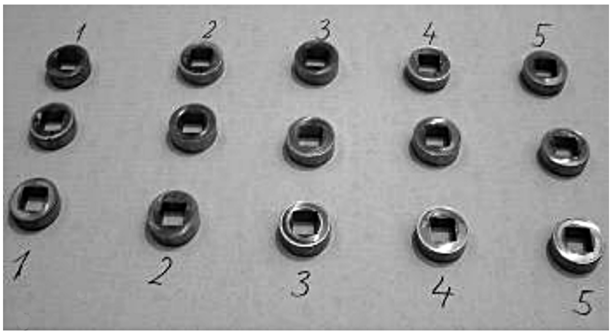



**Figure 4.** Torque testing samples
**Slika 4.** Uzorci za ispitivanje na zakretanje

For each group of specimens (diameter Ø39.20 mm and Ø40.0 mm) one matching ring was machined to dimension:

- Ø39.20$^{-0,037; -0,020}$, for specimens Type 1
- 4 rings Ø40.00$^{-0,037; -0,20}$ for specimens Type 2, 3, 4 and 5.

Components of the torque testing tool were fabricated from 42CrMo4 steel, quenched and tempered. Contact surfaces to the specimens were additionally induction-tempered to ~ 58 HRC up to a depth of 1 mm. Correct measures and tolerances were secured by final sanding.

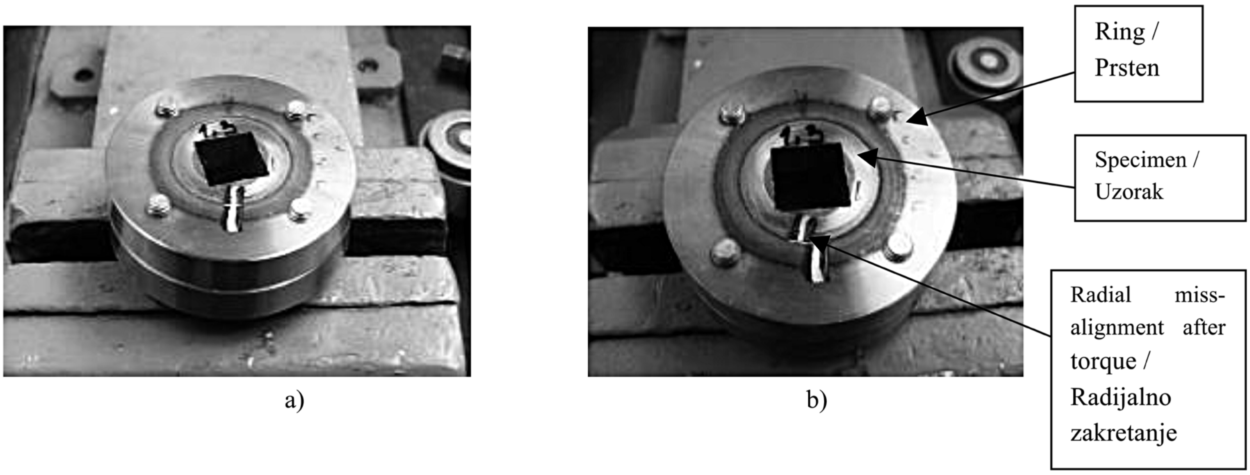



**Figure 5.** Typical positioning of the specimen during torque testing of the sprayed coating: a) Prior to torque application, b) after torque application

**Slika 5.** Karakteristični položaj uzorka kod ispitivanja zakretanjem naštrcanog sloja: a) prije zakretanja, b) nakon zakretanja moment ključem

The inner diameter of the ring were selected to allow for a shrink connection overlap of 0.02 mm [5] with the specimen – a measure typical for a common joint between shaft and color (M6/h6). Before joining, the ring had been heated to ~140 °C in an oven, allowing for sufficient clearance of the temporarily widened component to fit the specimen dimension. Upon cooling to ambient temperature, the joint was fixed in a bench wise by a fixture with screws, before torque was exhibited using a torque wrench, Figure 5a. Figure 5b shows typical miss-alignment after torque application. Experiment results are given in Table 3.

**Table 3.** Torque momentum onto the sprayed coating

**Tablica 3.** Moment zakretanje naštrcanog sloja

| Spec. No. | Ring heating temperatur / Temp. predgijanja prstena ° C | Torque / Moment zakretanja $M_Z$, Nm | | Specimen diameter / Promjer uzorka, mm |
|---|---|---|---|---|
| | | Single results | Average value | |
| 1.1 | $\upsilon_p$=140 | 230 | 217 | Ø39.20$^{-0,037; -0,020}$ |
| 1.2 | $\upsilon_p$=140 | 210 | | |
| 1.3 | $\upsilon_p$=140 | 210 | | |
| 2.1 | $\upsilon_p$=140 | 200 | 195 | Ø40.00$^{-0,037; -0,20}$ |
| 2.2 | $\upsilon_p$=140 | 195 | | |
| 2.3 | $\upsilon_p$=140 | 190 | | |
| 3.1 | $\upsilon_p$=135 | 180 | 180 | Ø40.00$^{-0,037; -0,20}$ |
| 3.2 | $\upsilon_p$=135 | 190 | | |
| 3.3 | $\upsilon_p$=135 | 170 | | |
| 4.1 | $\upsilon_p$=135 | 200 | 190 | Ø40.00$^{-0,037; -0,20}$ |
| 4.2 | $\upsilon_p$=135 | 190 | | |
| 4.3 | $\upsilon_p$=140 | 230 | | |
| 5.1 | $\upsilon_p$=135 | 320 | 292 | Ø40.00$^{-0,037; -0,20}$ |
| 5.2 | $\upsilon_p$=140 | 325 | | |
| 5.3 | $\upsilon_p$=140 | 250 | | |

### 3.3. Shear testing of the sprayed coating

For the axial shear test, testing tool components were fabricated from cold forming tool steel X210Cr12 tempered and annealed to ~62 HRC. Figure 6 shows the tool.

It consists of a hammer die and two matrix dies, whose respective diameter is adjusted to the outer dimension of sprayed specimens:

- Matrix I: Ø$38.20^{+0,20}$ mm,
- Matrix II: Ø$40.0^{+0,20}$ mm,
- Outer hammer die diameter: Ø$38.20^{+0,15/+0,20}$ mm,
- Inner diameter of the specimen sanded to Ø$16^{+0,011/+0,000}$.

The experiment was conducted on a calibrated tear tester. The force was recorded at the moment of axial movement of the coating. The time elapse between force build-up and axial movement was measured by means of a chronograph.

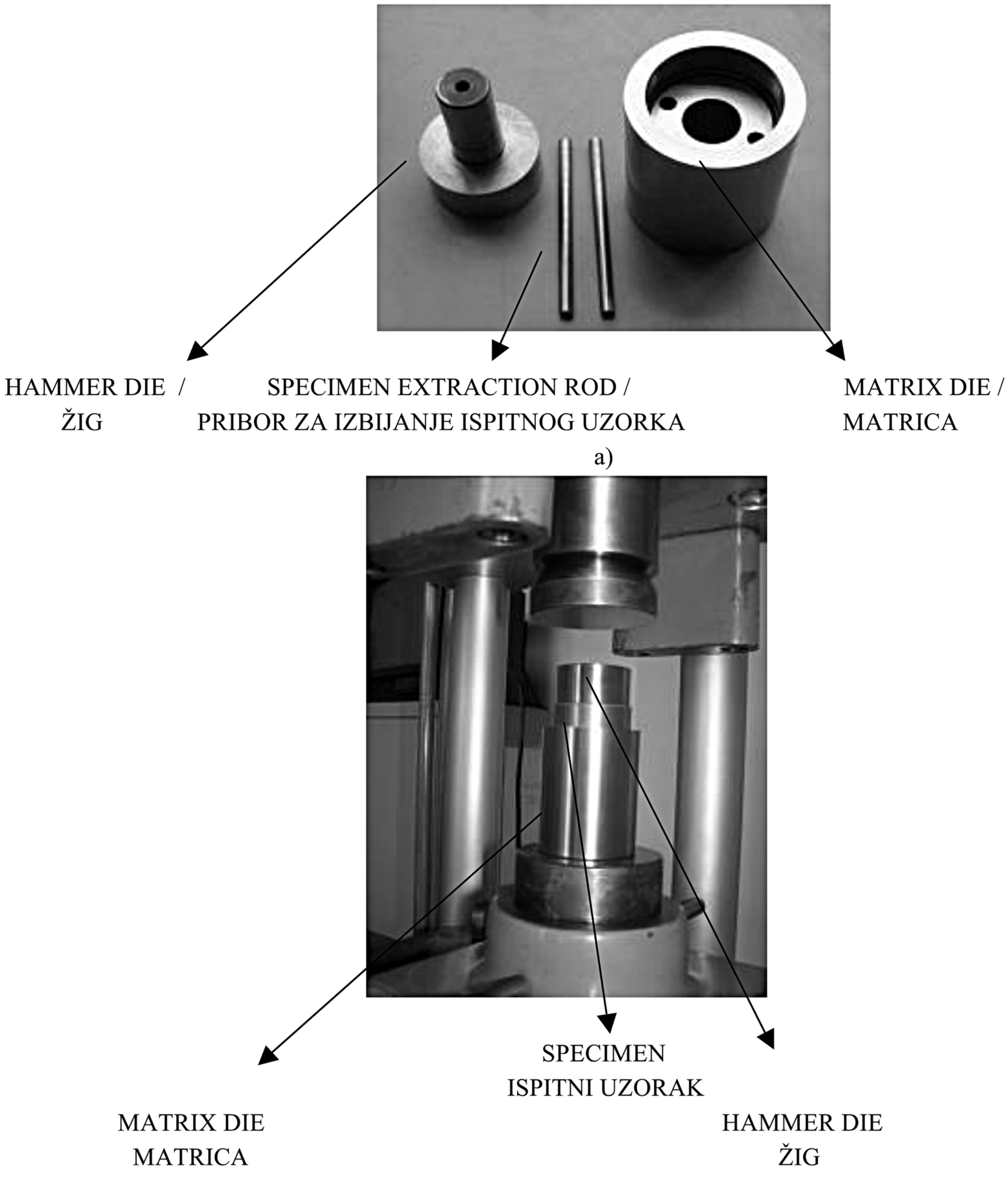



**Figure 6.** Shear testing of the sprayed coating: a) Support components, b) support and specimen on the tester

**Slika 6.** Ispitivanje naštrcanih slojeva na "odrez": a) dijelovi pristroja, b) položaj pristroja i uzorka na kidalici

Typical appearance of the specimens after axial damage is shown in Figure 7.

**Figure 7.** Typical appearance of the specimens after shear testing
**Slika 7.** Karakteristični izgled uzoraka nakon ispitivanja na "odrez"

Table 4 shows the values as obtained for loads causing axial shear of the coating.

**Table 4.** Shear force values for axially loaded coatings
**Tablica 4.** Sila odreza aksijalno opterećenog naštrcanog sloja

| Type / Tip | Shearforce / Sila odreza $F$, kN<br>Time elapse to damage / Vrijeme do oštećenja $t$, s<br>Specimen No. / Uzorak broj | | | Average value of force $F_S$, / Srednja vrijednost sile odreza $F_S$, kN | Remark.visual observation of the coating upon loading / Vizualna opažanja o oštećivanju sloja |
|---|---|---|---|---|---|
| | 1. | 2. | 3. | | |
| 1. | $F_{S1}$=39.9<br>$t$=5.6 s | $F_{S2}$=27<br>$t$=3.5 s | $F_{S3}$=45.4<br>$t$=8.3 s | $F_S$=37 | 1.1) coating completely stripped off<br>1.2) initial damage at 27000 N, complete tear off at 28200 N<br>1.3) coating cracked and broke apart instantly and completely |
| 2. | $F_{S1}$=73.4<br>$t$=13 s | $F_{S2}$=79<br>$t$=10.5 s | $F_{S3}$=60.4<br>$t$=12.3 s | $F_S$=71 | 2.1) coating cracked completely, but broke apart partly<br>2.2) partial break-up (~1/6)<br>2.3) complete break-up |
| 3. | $F_{S1}$=87.8<br>$t$=13.2 s | $F_{S2}$=80.2<br>$t$=13.1 s | $F_{S3}$=87.8<br>$t$=14.3 s | $F_S$=85.3 | 3.1) on half completely cracked, the second half exhibited partial shear-off<br>3.2) coating only partly broke into fragments<br>3.3) coating totally peeled off and broke apart |
| 4. | $F_{S1}$=65.4<br>$t$=11.4 s | $F_{S2}$=90<br>$t$=15.4 s | $F_{S3}$=72<br>$t$=10.4 s | $F_S$=75.8 | 4.1) coating cracked alongside entire surface<br>4.2) broken fragments mostly imprinted into matrix<br>4.3) coating broke up completely |
| 5. | $F_{S1}$=52<br>$t$=11.2 s | $F_{S2}$=47.5<br>$t$=9.5 s | $F_{S3}$=54,8<br>$t$=11.3 s | $F_S$=51.5 | 5.1) coating fully stripped off<br>5.2) axial stripping after break-up<br>5.3) complete stripping |

## 4. Results analysis

Metallographic structure and cross-cut hardness distribution analysis expose a variation of coating thickness in relation to the Type of base material surface preparation. Maximal layer thickness corresponds with radially notched surfaces while the thickness of the coating decreases for axial notches. For smooth surfaces, thickness is even lower – on the degreased surface around 1 mm and on the surface treated with an emulsion only between 0.3 and 0.4 mm. Here, thickness values are scattered with respect to reference lines; most obviously for specimens of Type 1 (between 2.05 and 1.05 mm) and those of Type 5 (between 1.68 and 1.15 mm). For all other types of surface specimens, the scattering of thickness of the coating varies within some 10 % (specimens Type 2, 3 and 4) at established thickness above 2 mm.

Within Type 7, scatter is not as distinguished as with other Types, however the thickness of the sprayed layer is lower, only around 1 mm. Hardness is nearly equal for all specimen Types. In contrast to others, for Type 7 the cross-cut metallographic exposes variations of thickness of the intermediate layer. In addition, thinner surface layers appear on specimens of thinner intermediate layers. The variations of layer thickness are as follows:

- For Type 6 specimens (emulsion coated), the intermediate layer barely exists. It is very thin for turned and degreased Type 7 specimens (Figure 3.f and 3.g).
- On specimens with radial notches, a difference in intermediate layer thickness relates to the width of the respective notch: For wider notches (a=1.25 and a=1,00 mm) the intermediate layer is visible at the notch root only, but not on its flanks (Figures 3.d and 3.c).
- Knurled specimens (Type 5) exhibit an even thickness of the intermediate layer across the entire cross-section of the axial notches (Figure 3.e).

It is noteworthy that HV 0,1 hardness values, as measured along reference lines away from the sprayed coating, are also scattered, as the diagram in Figure 3 shows.

Specimens of both Type 6 and Type 7 exhibited only very thin coatings and were thus discharged from further examination. The remaining specimens were then sanded to the first possible throughout measure – for Type 1 Ø 39.20 mm, for Types 2, 3, 4 and 5 Ø 40.00 mm.

Torque testing (results given in Table 3) exhibited that:

- Maximal torque, $M_z$=292 Nm, was established with Type 5 specimens, knurled; axial notch.
- Among specimens with radial notches, maximal torque ($M_z$=217 Nm) was recorded for Type 1 (a=0.25 mm). For Type 2 and Type 4 torque was roughly equal ($M_z$=190 Nm) with respective notch depths a=0.5 and a=1.25 mm. The lowest torque ($M_z$=180 Nm) was established for Type 3 specimens with a notch depth a=1.00 mm.
- Shear testing (as presented in Table 4) exhibited that:
- The lowest shear force needed to shear off the sprayed coating was recorded for Type 5 specimens with axially knurled notches ($F_S$=37 kN).
- Maximal shear force ($F_S$=85.3 kN) was recorded for specimens Type 2, radial notches with a=0,5 mm, followed by those with a=1.00 mm ($F_S$=75.8 kN) and finally by specimens with radial notches a=0.25 mm ($F_S$=71 kN).
- For specimens with radial notches and a=1,25 mm, minimal shear force was recorded with $F_S$=51.5 kN.

## 5. Conclusions

It is of utmost importance that axle and shaft assemblies function reliably under design loads. Their failure implies material cost and losses but it also may be a safety hazard for traffic and operating staff. This paper suggests that properties of sprayed repair coatings of those components can be influenced by adequate choice of parameters during surface preparation, relative to prevailing load type. The durability of such sprayed coatings can be further improved by correct positioning of notches relative to prevailing load direction. Axial notches prove more durable under radial loads than radial ones. For axial loads, radial notches prove more suitable.

A cross-reference of these results with hardness values and micro structural analysis data leads to the following conclusions:

- The notch size significantly affects the thickness of intermediate layers and their even distribution around the notch edge.
- Smaller radial notches do bear higher torque at radial shear, but still optimal results are being achieved with axial notches under radial loads.
- During axial shear testing, the shearforce relates to the depth of radial notches – flat notches exhibit low shear resistance.
- The position of the dents relative to load direction significantly affects the durability of the sprayed layer. Radially loaded axial notches prove more durable than radial notches. Vice versa, radial notches are more suitable than axial ones under axial loads.

## Acknowledgments

The presented results derive from a scientific research project (Advanced joining technology in light mechanical constructions No. 152-1521473-1476) supported by the Croatian Ministry of Science, Education and Sports.

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