STANISŁAW PŁONKA*, MONIKA PĘPEK**, KONRAD DYBOWSKI***
ROBERT PIETRASIK****

EFFECT OF THERMOCHEMICAL TREATMENT
ON A SELECTED PROPERTIES
OF SURFACE LAYER OF 41CrAlMo7 STEEL

The paper presents results aimed at assessment of an effect of thermochemical treatment type, i.e. sulfonitriding and vacuum nitriding on distribution of hardness and depth of hardening, as well as microstructure of surface layer of 41CrAlMo7 machinery nitriding steel. Moreover, it was discussed an effect of the above thermochemical treatment types and successive operation of grinding with PS20 abrasive aloxite paper having grain size of 600 on geometrical structure of the surface and \( \mu_s \) coefficient of kinetic friction of yarn. To make comparison with up to now state, there were also included investigations concerning the above mentioned properties of surface layer of 50SiCr4 spring steel after hardening and tempering. It has been confirmed that among investigated types of thermochemical treatments the best properties for machinery parts operated in contact with yarn were obtained in result of sulfonitriding.

Key words: sulfonitriding and vacuum nitriding, surface layer, \( \mu_s \) coefficient of kinetic friction of yarn

1. INTRODUCTION

Ring spinning frames incorporate a components operating in direct contact with yarn. Yarn guide of the ring spinning frame belongs to such components. Active surface of the guide should comply, at least, with the following three conditions:
- be characteristic of low coefficient of friction in contact with yarn, what depends on geometrical structure of surface (SGP) mainly, resulted from method of a treatment;
- not generate any electrostatic charges, and „not charge” the yarn electrostatically;
- be sufficiently resistant for wear and random impacts.

---

* Prof. Ph.D., D.Sc. } Department of Manufacturing Technology and Automation, University of Bielsko-Biała, Poland.
** M.Sc., Ph.D. Student } University of Bielsko-Biała, Poland.
*** Ph.D. – Institute of Materials Science and Engineering, Technical University of Lodz, Poland.
Up to now, in order to assure suitable wear resistance and the same sufficient hardness, the yarn guides of ring spinning frames produced by BEFAMA Fabryka Masmyn Włókienniczych (Factory of Textile Machinery) were made from 50SiCr4 steel and were subjected to hardening and tempering treatments. Observations performed within industrial environment have proved that durability of the guides is not satisfactory enough. Therefore, particularly due to fact that value and depth of hardness of surface layer of the guide determines durability, assessment of an effect of thermochemical treatment type, i.e. sulfonitriding and vacuum nitriding of 41CrAlMo7 machinery steel on hardness distribution of surface layer constituted objective of this work.

2. METHODOLOGY AND SCOPE OF THE RESEARCH

Shape and dimensions of the yarn guide of ring spinning frame made from 50SiCr4 spring steel, produced from drawn bars of ø4 mm diameter are shown in the Fig. 1.

Detailed analysis and calculation of maximal transient value of $F_n$ pressure force of the yarn against the guide, in condition as predetermined assumptions, during process of spinning of a mixture composed from 30–55% of polyester fibers and 70–45% of woolen fibers is presented in the work [10].

Stream of fibers being mixture of 30–55% of polyester fibers and 70–45% of woolen fibers, very often woolen fibers comprising dead molecules (grass, tree bark, straw) and not rarely contaminated with grains of dust, which relocates with velocity of $v_\text{a} \approx 30 \text{ m/min.}$ (at spindles’ rotational speed of about 9500 rpm) and maximal tension of about 30 cN, and variable amplitude of the tension force, results in intensive wear of eye of the guide.

Eye of the guide manufactured from 50SiCr4 spring steel, hardened and tempered to hardness of about 400 HB prior installation on the spinning frame and after time of operation of about 8000 hour, in contact with yarn (stream of fibers) being mixture of: 30–55% of polyester fibers and 70–45% of woolen fibers is presented in the Fig. 2 [10].

![Fig. 1. Shape and dimensions of the yarn guide of ring spinning frame made from 50SiCr4 spring steel](image.png)
In this study one made assessment of an effect of thermochemical treatment, i.e. sulfonitriding and vacuum nitriding of 41CrAlMo7 machinery steel on distribution of hardness and depth of hardness of surface layer, as well as made comparison of technological solutions implemented up to now, i.e. heat treated 50SiCr4 spring steel to hardness of 400 HB. Moreover, one performed a complex assessment of geometric structure of surface (SGP) and coefficient of kinetic friction of yarn (μk). The tests were performed on a samples produced from the above grades of steel in as-rolled condition having dimensions of: ø22±0,10 x 40 mm, turned and grinded to roughness of Rₜ ≈ 0.20 μm. The samples prepared in such way from 41CrAlMo7 steel were subjected to thermochemical treatment: sulfonitriding or vacuum nitriding, whereas specimens made from 50SiCr4 steel were heat treated, and next subjected to operation of grinding with PS20 abrasive aloxite paper having grain size of 600 made, produced by Klingspor. Measurements of the hardness were performed on oblique microsections which were cut under angle of 1°30’ (0.026 rad), with use of Leitz Wetzlar (Germany) hardness tester, under microtender load of 0.49 N. Photos of microstructure of the surface layer were made using Nikon Eclipse MA200 microscope.

Recording and measurements of geometrical structure parameters of the surface: Rₚ, Rₛ, Rₚₛ, Rₛₛ, Rₛₚₛ, Rₛₚₛₛ, Rₛₚₛₛₛ, Rₛₚₛₛₛₛ, Rₛₚₛₛₛₛₛ, λₛ, λₛₛ, Rₛₛₛₛₛₛₛₛₛₛ, and fillet radius of peaks, r, were made with use of Talyurf 6 profile measurement gauge made by Rank Taylor Hobson [4, 5, 8, 11]. Whereby, average fillet radius of peaks, r, was determined on base of parabolic approximation of representative peaks of the profile. Among all local elevations of the profile to the assessment were selected, according to indications of [4, 9], ten elevations with typical shape for a given profile, making use of possibility of graphic assessment of approximation quality of selected fragments of the profile.
Determination of $F_0$ tension force of the yarn at inlet of cylindrical sample with dimensions of $\phi 22^{0.10}\times 40$ mm, and $F_1$ tension of yarn at outlet, and $\mu_s$ coefficient of kinetic friction of yarn was performed with use of F-metr type R-1182 device made by Rotschild, at the following conditions: rewinding speed of 30 m/min, wrapping angle of 180°, initial load of 50 cN, measurement duration of 60 s, size of measuring head of 100 G (0.98 N) [1, 6]. During the measurements one used a yarn being a blend of: 30% of polyester fibers and 70% of woolen fibers, causing very intensive wear of the guides in manufacturing environment. The yarn was characteristic of the following parameters (in parentheses are written coefficients of variation): linear mass of 96 tex, twist $T_s = 372$ l/m (5.46%), pull out force $F = 792$ cN (8.77%), elongation $\lambda = 21.84\%$, number of shoulders determined by organoleptic method on length of 2000 mm – 2, and number of neckings on length of 2000 mm – 1.

Gaseous sulfonitriding treatment was performed in retort furnace, in NH$_3$ ammonia and sulphur vapours, in temperature of 570°C during 3 h. Whereas, vacuum nitriding (Nitrovac’79 technology) [2] was performed in retort furnaces in two stages: in the first one – it was performed momentary sulfonitriding in order to decompose passive oxide layer, while in the second one – nitriding at reduced pressure, effected in buildup of diffusion layers with controllable concentration of nitrogen. The essence of vacuum nitriding consists in a possibility of smooth control of nitrogen volume delivered to surface of machined parts, though adjustment of partially dissociated ammonia’s pressure in range of $1.33\times 10^{-4}$ to $1.01\times 10^{-1}$MPa. Change of delivered nitrogen volume results from a compromise between growing nitrogen potential and decreasing adsorption of ammonia particles on the surface as the pressure decreases [2, 3].

3. RESULTS AND ANALYSIS OF THE TESTS

Effect of the thermochemical treatment, i.e. sulfonitriding and vacuum nitriding of 41CrAlMo7 machinery nitriding steel on hardening of surface layer of this steel and comparison of the results with hardness of 50SiCr4 steel hardened and tempered is presented in the Fig. 3.

Hardness on depth of surface layer, $HV_{0.49} = f(h)$, after hardening and tempering of 50SiCr4 spring steel was contained within interval of $HV_{0.49} \approx 549\pm 410$. Maximal hardness on surface layer of 41CrAlMo7 machinery nitriding steel occurred after sulfonitriding on depth of about 20 µm and amounted to $HV_{0.49} = 1253$, while after vacuum nitriding, maximal hardness had value of $HV_{0.49} = 1145$ and occurred at face of the surface layer.

Depth of the surface layer (with criterion of 150 above hardness of core – [7]), in case of sulfonitriding treatment slightly exceeds 50 µm, while in case of vacuum nitriding – 70 µm. Exemplary microstructures of surface layer after sulfoni-
triding and vacuum nitriding of 41CrAlMo7 steel are presented in the Fig. 4. After sulfnitriding (Fig. 4a), a thin subsurface zone of external sulfuridation in form of ferrous sulfides, FeS is visible. Next, from this zone into inside of the material following layers are seen: diffusion zone of internal nitriding (white layer) in form of fine dispersion inclusions of FeS in phase ε (Fe3N), nitride compounds ε (Fe2,N), and compounds γ′ (Fe,N). Going further, a dark diffusion zone of internal nitriding is visible. In case of samples nitried in vacuum (Fig. 4b) – is seen about threefold thinner white layer in form of nitride compound γ′ (Fe,N), and next dark diffusion layer of internal nitriding [2, 3]. Layer of phase ε is advantageous in machinery components requiring resistance for wear and fatigue, and simultaneously being free from impact loads and high contact loads [3], and hence particularly in all textile machinery components being in contact with yarn or thread. Effect of thermochemical treatment of 41CrAlMo7 steel and heat treatment of 50SiCr4 steel on geometrical structure of surface and μk coefficient of kinetic friction of yarn is shown in the Table 1.

Fig. 3. Hardness distribution in function of distance from surface after various thermochemical treatments for 41CrAlMo7 machinery nitriding steel, and after heat treatment of 50SiCr4 spring steel

Rys. 3. Rozkład twardości w funkcji odległości od powierzchni po różnych rodzajach obróbki cieplno-chemicznej stali konstrukcyjnej 41CrAlMo7 oraz po obróbce cieplnej stali sprężynowej 50SiCr4
Fig. 4. Microstructure of surface layer of 41CrAlMo7 machinery steel: a) after sulfonitriding, b) after vacuum nitriding
Rys. 4. Mikrostruktura warstwy wierzchniej stali konstrukcyjnej 41CrAlMo7: a) po azotonasierczaniu, b) po azotowaniu próżniowym

Measurement results of geometrical structure of surface 2D and coefficient of kinetic friction of yarn after heat treatment and thermochemical; and grinding with abrasive aloxite PS20 paper with grain size of 600
Wyniki pomiarów parametrów chropowatości 2D powierzchni i kinetycznego współczynnika tarcia przędzy po obróbce cieplnej i ciepło-chemicznej oraz szlifowaniu papierem ściernym elektrokorundowym PS20 o wielkości ziarna 600

<table>
<thead>
<tr>
<th>Type of heat treatment and thermochemical treatment</th>
<th>Hardening and tempering 50SiCr4 to hardness about 400 HB and grinding with abrasive paper</th>
<th>Sulfonitriding of 41CrAlMo7 steel</th>
<th>Sulfonitriding of 41CrAlMo7 steel and grinding with abrasive paper</th>
<th>Vacuum nitriding of 41CrAlMo7 steel</th>
<th>Vacuum nitriding of 41CrAlMo7 steel and grinding with abrasive paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a$ [μm]</td>
<td>0.072</td>
<td>0.262</td>
<td>0.192</td>
<td>0.466</td>
<td>0.082</td>
</tr>
<tr>
<td>$R_z$ [μm]</td>
<td>0.095</td>
<td>0.387</td>
<td>0.288</td>
<td>0.598</td>
<td>0.110</td>
</tr>
<tr>
<td>$R_p$ [μm]</td>
<td>0.341</td>
<td>1.437</td>
<td>0.964</td>
<td>1.841</td>
<td>0.368</td>
</tr>
<tr>
<td>$R_t$ [μm]</td>
<td>0.288</td>
<td>1.248</td>
<td>0.833</td>
<td>1.632</td>
<td>0.389</td>
</tr>
<tr>
<td>$R_{pm}$ [μm]</td>
<td>0.548</td>
<td>2.685</td>
<td>1.797</td>
<td>3.473</td>
<td>0.757</td>
</tr>
<tr>
<td>$R_{Ro}$ [μm]</td>
<td>0.244</td>
<td>0.690</td>
<td>0.541</td>
<td>1.165</td>
<td>0.253</td>
</tr>
<tr>
<td>$R_{Rt}$ [μm]</td>
<td>0.494</td>
<td>1.571</td>
<td>1.237</td>
<td>2.458</td>
<td>0.573</td>
</tr>
<tr>
<td>$R_{Rf}$ [μm]</td>
<td>0.234</td>
<td>1.012</td>
<td>0.506</td>
<td>1.595</td>
<td>0.261</td>
</tr>
<tr>
<td>$R_{Rd}$ [μm]</td>
<td>0.119</td>
<td>0.486</td>
<td>0.321</td>
<td>0.782</td>
<td>0.180</td>
</tr>
<tr>
<td>$R_{Aq}$ [rad]</td>
<td>0.105</td>
<td>0.444</td>
<td>0.307</td>
<td>0.768</td>
<td>0.169</td>
</tr>
<tr>
<td>$\lambda_p$ [μm]</td>
<td>0.029</td>
<td>0.046</td>
<td>0.038</td>
<td>0.071</td>
<td>0.031</td>
</tr>
<tr>
<td>$R_{Sa}$ [μm]</td>
<td>21.27</td>
<td>46.60</td>
<td>45.00</td>
<td>53.84</td>
<td>44.92</td>
</tr>
<tr>
<td>$r$ [μm]</td>
<td>23.46</td>
<td>49.84</td>
<td>44.19</td>
<td>82.40</td>
<td>32.07</td>
</tr>
<tr>
<td>$\mu_k$</td>
<td>-0.150</td>
<td>-0.127</td>
<td>-0.147</td>
<td>-0.110</td>
<td>-0.163</td>
</tr>
<tr>
<td>$\mu_k$</td>
<td>0.176</td>
<td>0.272</td>
<td>0.174</td>
<td>0.276</td>
<td>0.172</td>
</tr>
</tbody>
</table>
Detailed investigations of geometrical structure of surfaces being in contact with thread or yarn, and testing of $\mu_k$ coefficient of kinetic friction of yarn against these surfaces for a selected textile machinery parts, were accomplished in the study [9]. Analysis of these results allows to ascertain that the $\mu_k$ coefficient of kinetic friction of yarn is the best correlated by the following parameters: $R_d$, $R_s$, $R_d$, and $r$. Due to it, in the Fig. 5 an effect of thermochemical treatment’s type of 41CrAlMo7 machinery steel and heat treatment of 50SiCr4 spring steel on such SGP parameters and $\mu_k$ coefficient of kinetic friction of yarn is presented.

![Effect of thermochemical treatment on a selected properties](image)

Fig. 5. Effect of thermochemical treatment type of 41CrAlMo7 steel and heat treatment of 50SiCr4 steel, and next grinding with PS20 abrasive aloxite paper having grain size of 600 on a selected parameters of geometrical structure of the surface 2D and $\mu_k$ coefficient of kinetic friction of yarn

Rys. 5. Wpływ rodzaju obróbki cieplno-chemicznej stali 41CrAlMo7 oraz obróbki cieplnej stali 50SiCr4, a następnie szlifowania papierem ściernym PS20 o wielkości ziarna 600 na wybrane parametry chropowatości powierzchni 2D oraz kinetyczny współczynnik tarcia $\mu_k$ przędzy

Value of quadratic mean of profile ordinates, $R_d$, of surfaces sulfonitrided and next grinded with PS20 abrasive paper having grain size of 600 amounted to $R_d = 0.288 \mu$m, whereas in case of surfaces hardened and tempered up to about 400 HB and subsequently grinded with abrasive paper having the same characteristics, was clearly lower – $R_d = 0.095 \mu$m. Value of quadratic mean of profile ordinates, $R_d$, of surfaces nitrided in vacuum and grinded was slightly higher and amounted to $R_d = 0.110 \mu$m. In general, it can be ascertained that values of such geometrical surface parameters (SGP), as: $R_d$, $R_y$, $R_p$, $R_{y_{max}}$, $R_s$, $R_d$, nitrided in vacuum and subsequently grinded, as well as hardened and tempered and next grinded, are very close. Hence, value of $\mu_k$ coefficient of kinetic friction of yarn
against surface nitrided in vacuum and subsequently grinded was only slightly lower (with 0.004) than value of the same coefficient in case of hardened, tempered and subsequently grinded surfaces. Value of quadratic mean of profile ordinates, $R_q$ of the surfaces sulfonitrided and subsequently grinded amounted to $R_q = 0.288 \ \mu m$, i.e. was about 2.6 times higher than in case of nitrided and grinded surfaces. In spite of it, value of the $\mu_k$ coefficient of kinetic friction of yarn against sulfonitrided and next grinded surface was higher with only 0.002 than value of the same $\mu_k$ friction coefficient against nitrided in vacuum and grinded surface. It can be explained by a specific structure of external surface of subsurface zone in surface layer obtained in result of implemented thermochemical treatment of sulfonitriding.

Analysis of SGP parameters and $\mu_k$ coefficient of kinetic friction between sulfonitrided and vacuum nitrided surfaces, which were subsequently grinded with the PS20 grinding paper having grain size of 600 (Table 1), proves that for nearly all parameters of surface roughness, growth of values of these parameters results in rise of $\mu_k$ coefficient of kinetic friction and vice versa. Only in case of the radius of surface shape irregularities, $r$, a conversed dependency is presented, i.e. rise of this radius value effects in reduction of $\mu_k$ coefficient of kinetic friction.

For surface with the biggest value of the $R_t$ parameter, $R_t = 3.473 \ \mu m$, i.e. vacuum nitrided surface, $\mu_k$ coefficient of kinetic friction features the highest value, $\mu_k = 0.276$. Whereas in case of surface with the smallest value of the $R_t$ parameter, $R_t = 0.548 \ \mu m$, i.e. surface hardened and tempered, and next grinded, $\mu_k$ coefficient of kinetic friction of yarn reached value of $\mu_k = 0.176$.

Average fillet radius of irregularities peaks, $r$, of hardened and tempered, and next grinded surfaces reached the highest value of $r = -0.150 \ \mu m$, while $\mu_k$ coefficient of kinetic friction of yarn for this surface reached one of the smallest values, $\mu_k = 0.76$. The smallest average fillet radius of irregularities peaks, $r$, occurred for nitrided surfaces and amounted to $r = -0.110 \ \mu m$. The $\mu_k$ coefficient of kinetic friction of yarn against this surface reached value of $\mu_k = 0.276$. The biggest average fillet radius of irregularities peaks, $r$, occurred for surfaces nitrided in vacuum, and next grinded, and amounted to $r = -0.163 \ \mu m$, while $\mu_k$ coefficient of kinetic friction of yarn against this surface reached the smallest value of $\mu_k = 0.172$.

Average fillet radii of irregularities peaks, $r$, of surfaces sulfonitrided, and subsequently grinded, are equal to $r = -0.147 \mu m$ and are slightly smaller than average fillet radii of irregularities, $r$, of surfaces nitrided in vacuum, and subsequently grinded, $r = -0.163 \mu m$. Whereas values of $\mu_k$ coefficient of kinetic friction of yarn against these surfaces are slightly bigger and for surfaces sulfonitrided and grinded they have value of $\mu_k = 0.174$, while in case of nitrided in vacuum and grinded surfaces they amount to $\mu_k = 0.172$.

Values of quadratic mean of profile height, $R_d$, for surface made from hardened and tempered 50SiCr4 steel, and subsequently grinded, are the smallest and
amount to $R_d = 0.029$ rad, while for surface made from 41CrAlMo7 steel nitrided in vacuum, $R_d = 0.071$ rad. Significantly lower value of quadratic mean of profile height, $R_d$, took place for sulfonitrided surfaces, $R_d = 0.046$ rad.

Due to fact that after thermochemical treatment of sulfonitriding or nitriding in vacuum one obtains a surface layers with relatively small thickness, generally not exceeding 200 $\mu$m, that is why it is recommended to perform finishing grinding of such surfaces, because grinding operation effects in removal of subsurface zone of surface layer which is characterized by very good tribological properties. Solely in well-grounded cases, one can perform a mechanical-abrasive polishing or finish lapping in order to make rounding of peaks of surface irregularities only.

Taking into account all above specified factors and criteria of technological quality such as: maximal hardness $HV_{0.05}$, and roughness parameters: $R_p$, $R_s$, $R_d$, and $r$, the best properties of surface layer in case of 41CrAlMo7 machinery steel were obtained in result of implemented thermochemical treatment of sulfonitriding.

4. SUMMARY AND CONCLUSIONS

1. The highest hardness in subsurface layer of 41CrAlMo7 machinery steel was confirmed after sulfonitriding on depth of about 20 $\mu$m and this hardness had value of about $HV_{0.05} = 1250$.

2. Somewhat different run of hardness distribution in function of distance from surface occurred after nitriding in vacuum. The biggest value after such type of thermochemical treatment is located on surface and in subsurface zone, and has value of $HV_{0.05} = 1145$.

3. Analysis of parameters of geometrical surface structure and coefficient of kinetic friction, $\mu_k$, of yarn proves that for nearly all surface roughness parameters, growth of values of these parameters has an influence on a rise of $\mu_k$ kinetic coefficient of friction of yarn. Only in case of average fillet radius of irregularities peaks, $r$, generally is present an inverse situation, i.e. increase of fillet radius of surface irregularities, $r$, results in reduction of coefficient of kinetic friction, $\mu_k$, of yarn.

4. Taking into consideration all above specified factors, including not recommended operation of finishing grinding for surface layers sulfonitrided and nitrided, as well as criteria of technological quality such as: maximal hardness and roughness parameters: $R_p$, $R_s$, $R_d$, and $r$, the best properties of surface layer of 41CrAlMo7 machinery steel were obtained in result of implemented thermochemical treatment of sulfonitriding.
REFERENCES

[2] Haś Z., Kula P., The new polish nitriding and nitriding like processes in the modern technolo-
jkiej 2000.
surface: profile method. Terms, definitions and parameters of geometrical structure of sur-
face.
friction force and friction coefficient.
[8] Oczos K. E., Liubimov V., Struktura geometryczna powierzchni, Rzeszów, Oficyna Wy-
dawnicza Politechniki Rzeszowskiej 2003.
[9] Plonka S., Methods of assessment and selection of optimal structure of technological process,

Praca wpłynęła do Redakcji 8.03.2011 Recenzent: dr hab. inż. Aleksandra Pertek-Owsianna

Wpływ obróbki cieplno-chemicznej na wybrane właściwości warstwy wierzchniej stali 41CrAlMo7

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań wpływu rodzaju obróbki cieplno-chemicznej, tj. azo-
tonasiarczania i azotowania próżniowego, na rozkład twardości i głębokość utwardzenia oraz
microstrukturę warstwy wierzchniej stali konstrukcyjnej do azotowania 41CrAlMo7. Ponadto
badano wpływ tych rodzajów obróbki cieplno-chemicznej i szlifowania pierścieniem elek-
trakronowym PS20 o wielkości zimą 600 na chropowatość powierzchni i kinetyczny współ-
czynnik tarcia μs przędzy. Dla porównania ze stanem dotychczasowym zamieszczono również
badania ww. właściwości warstwy wierzchniej stali sprzężynowej 50SiCr4 po hartowaniu i odpuszu-
czaniu. Z przebadanych rodzajów obróbki cieplno-chemicznej najlepsze właściwości części ma-
szyn współpracujących z przędzą uzyskano w wyniku zastosowania azotonasiarczania.

Słowa kluczowe: azetonasiarczanie i azotowanie próżniowe, warstwa wierzchnia, kinetyczny
współczynnik tarcia μs przędzy