INFLUENCE OF SELECTED MATERIALS AND SURFACE TREATMENTS ON THE DURABILITY OF TOOLS FOR THE EXTRUSION OF CERAMIC ROOFING TILES

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Abstract

This study presents the results of a comprehensive evaluation of selected methods for enhancing the tribological wear resistance of forming tools made from wear-resistant steels, used in the extrusion of ceramic roof tiles. The research addressed both the selection of tool materials and surface engineering techniques. Microscopic analyses (XRD combined with SEM-EDS) were performed on the plastic mass, composed mainly of clay and sand. Comparative wear tests were conducted using a laboratory-scale “rotating bowl” method, where the ceramic mass served as the abrasive medium. Four material variants were selected for testing: Hardox 600, hardened NC11LV, nitrided NC11LV, and C45 with a hardfaced EuTroLoy 16006A layer.Microstructural analysis of the plastic mass allowed identification of hard fractions responsible for accelerated tool wear. Results of the rotating bowl test showed that the C45 hardfaced sample exhibited the highest wear resistance, based on 3D-scanned geometric material loss perpendicular to the surface. For final verification, forming tools made from all analyzed materials were tested under industrial production conditions. Each tool operated for 170 hours and was then analyzed for material loss using 3D scanning. The results indicate that under operational conditions, the tool made from NC11LV with an additional nitrided layer exhibited the best performance, with critical areas showing material loss below 0.50 mm. The outcomes of this comprehensive study enable a more informed selection of materials and surface treatment technologies, contributing to the optimization of operational parameters of forming tools and improving their durability in ceramic tile production.

Keywords: Forming tools, abrasive wear resistance, surface engineering techniques

1. INTRODUCTION

Contemporary research conducted across numerous industrial sectors focuses on minimizing the effects of friction, which is one of the key factors responsible for the wear of machine components. Among the most common negative consequences of friction is tribological wear. This is particularly pronounced in the ceramic industry, for example during the forming of roof tiles. In this process, a ceramic mass with abrasive properties is processed, which primarily results from its composition: it contains plastic components (clay), tempering additives (quartz sand, basalt, and ceramic waste), as well as fluxes (feldspars) [1, 2]. The appropriate plasticity of this mass is ensured by water added during the process [3]. It is primarily the hard particles (fractions) that cause intense abrasive friction and, consequently, tribological wear, leading to a reduction in the service life of forming tools.

To reduce the wear of the most highly stressed machine components, various methods are employed to enhance durability. Research focuses on improving the material, the surface layer, and the operating conditions [4]. A fundamental solution is the use of wear-resistant steels (e.g., Hardox), supplied in the quenched condition without the need for additional heat treatment [5]. Cold-work tool steels (including

X165CrV12, X210Cr12, and X153CrMoV12) are also increasingly used; after heat treatment, they develop a martensitic microstructure with M_7C_3 carbides, which ensures high hardness and abrasion resistance [6]. An alternative approach involves surface layer modification methods, particularly nitriding. Although this technique is gaining popularity in metal forming processes, it is still rarely used in the ceramic industry. Welding, beam-based, and hybrid techniques are also widely employed, when combined with appropriate finishing treatments, they can significantly extend the service life of forming tools [7].

This study focuses on a detailed analysis of the wear of forming tools used in the extrusion of ceramic roof tiles. The implemented research program included selected laboratory tests and operational trials, which enabled the identification of the main causes of intensive tool wear. The obtained results also allowed for the verification and selection of an effective method to reduce wear and enhance the durability of the forming tools.

2. MATERIALS AND METHODS

As part of the conducted research, various materials and methods for improving the durability of forming tools were verified, as summarized in **Table 1**. The selection of the analyzed material variants was based on the authors' previous studies, which confirmed their development potential in enhancing the service life of forming tools.

Table 1 Tested materials and methods for protecting the working surface

Materials and protecting methods
Wear-resistant steel – Hardox 600
Heat Treatment of NC11LV Cold Work Tool Steel
Thermochemical treatment (nitriding) NC11LV Cold Work Tool Steel
Hardfacing – C45 steel with EuTroLoy 16006A wear-resistant weld

The study was divided into three stages, within which a detailed analysis of the formed material was carried out, along with the verification of selected material solutions. In the first stage, SEM–EDS analysis was employed to provide a comprehensive characterization of the formed material, including the identification of hard fractions responsible for intensive abrasive wear.

In the second stage, the analyzed tool materials were subjected to abrasion resistance testing using a "rotating bowl" test rig, as shown in **Figure 1**. In this test, the actual mass used in the ceramic roof tile production process served as the abrasive medium, enabling the evaluation of the tested tool materials under conditions that closely approximate real operating environments.



Figure 1 Test stand a) station diagram: 1 – swing, 2 – sample holder, 3 – rotating bowl, 4 – abrasive mass, 5 – sample load, 6 – sample, b) general view of the station [4]

The wear of the materials during the tests was determined based on mass loss, which was calculated according to the following formula:

$$W_m = m_0 - m_x[g] \quad (1)$$

where:

W_m - mass loss (g)

m_0 - initial sample mass (g)

m_x - sample mass along the fraction distance x (g)

The tests were carried out under the following parameters:

- Fraction distance – 10000 m,
- Fraction velocity – 1.56-1.70 m*s^{-1},
- Sample load – 63 N,
- Sample angle attack – 4°.

In the subsequent, third stage, forming tools for the production of ceramic roof tiles were manufactured from the selected material variants. They were then tested under real operating conditions, where they operated for 170 hours in an environment characterized by typical wear mechanisms, enabling a comparative assessment of their durability. After completion of the tests, wear analysis was carried out using 3D scanning, allowing for a precise evaluation of geometric changes and the degree of degradation of the working surfaces. For this purpose, a GOM ATOS Core 135a 3D scanner was used.

3. RESULTS OF THE MASS ANALYSIS FOR THE PRODUCTION OF CERAMIC ROOF TILES – STAGE

The composition of the mass used in production is complex and comprises three main groups of components: plastic constituents, lean (non-plastic) materials, and fluxes. Their properties cause the material to exhibit abrasive behavior. As part of the research conducted by the authors, analyses were performed on a typical ceramic mass [4], the summary results of which are shown in the **Figure 2**.

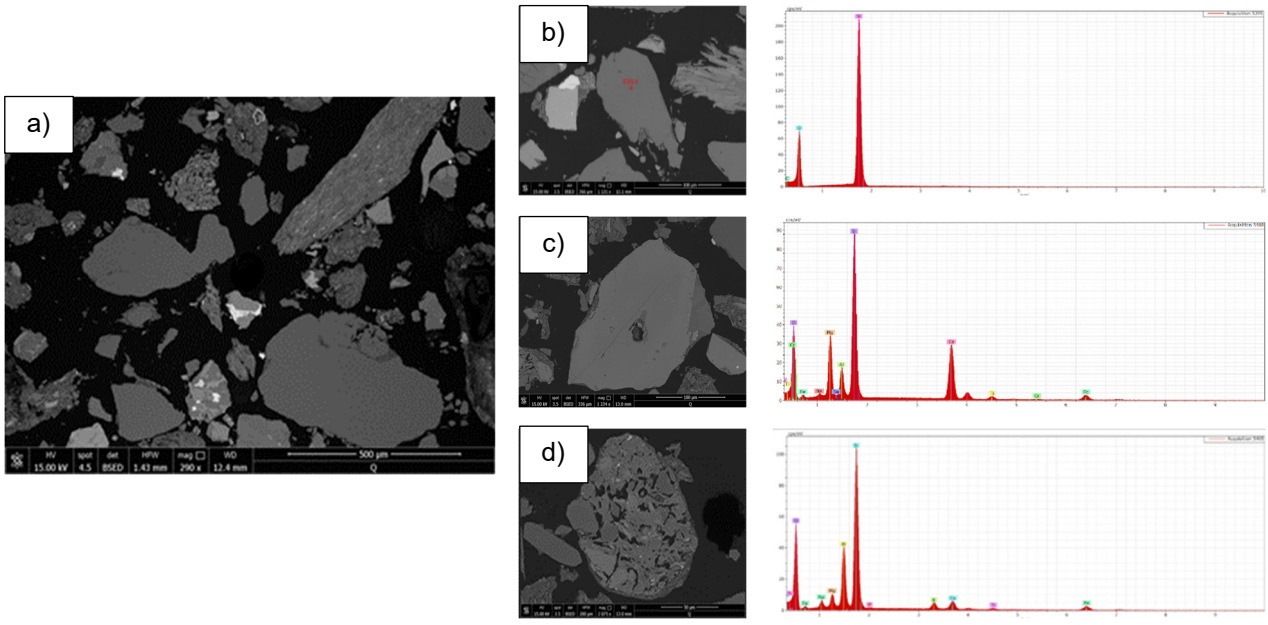

Figure 2 SEM images and EDS spectrum of the mass for the production of ceramic roof tiles: a) general view, b) quartz, c) pyrope (garnet), d) ceramic fragment [4]

The SEM micrograph of the ceramic body at low magnification (**Figure 2**) indicates a distinctly heterogeneous and complex character. The analyzed material consists of numerous fractions of natural origin, differing in their properties, which may result in varied interactions with forming tools during the technological process. In the examined sample, the presence of grains, mineral aggregates, ceramic fragments, and rock debris was identified. In accordance with the guidelines for the production of ceramic roof tiles, fractions larger than 40 μm accounted for approximately 35%.

A significant contribution to the abrasive wear of forming tools is primarily attributed to the hard constituents present in the mass. During the course of the study, several minerals with high hardness on the Mohs hardness scale were identified. The most important of these include the quantitatively dominant quartz (**Figure 2a**), with a hardness of 7, as well as garnet (**Figure 2b**), whose hardness ranges from 7 to 7.5 on the Mohs scale.

4. RESULTS OF THE "ROTATING BOWL" ABRASION RESISTANCE TEST – STAGE II

For the abrasion resistance tests using the “rotating bowl” test rig, samples were prepared from all selected materials. The specimens had dimensions of 25 × 30 × 10 mm. The total sliding distance was 10,000 m. The mass of each sample was measured every 2,000 m after cleaning in an ultrasonic bath and drying in a stream of warm air. Mass measurements were carried out using a Radwag AS 160 R2 analytical balance with an accuracy of 0.0001 g. The results of the abrasion resistance tests are presented in **Table 2** and illustrated in the graph in **Figure 3**.

Table 2 Mass loss results of the tested samples in the "rotating bowl" test

Mass loss [g]						
Material	**Fraction distance [m]**					
	0	**2000**	**4000**	**6000**	**8000**	**10000**
Hardox 600	0.0000	0.0540	0.1154	0.1946	0.2216	0.2785
NC11LV hardned	0.0000	0.0244	0.0492	0.0693	0.0870	0.1017
NC11LV nitrided	0.0000	0.0293	0.0613	0.0852	0.1095	0.1329
C45 surfaced	0.0000	0.0210	0.0440	0.0631	0.0764	0.0879

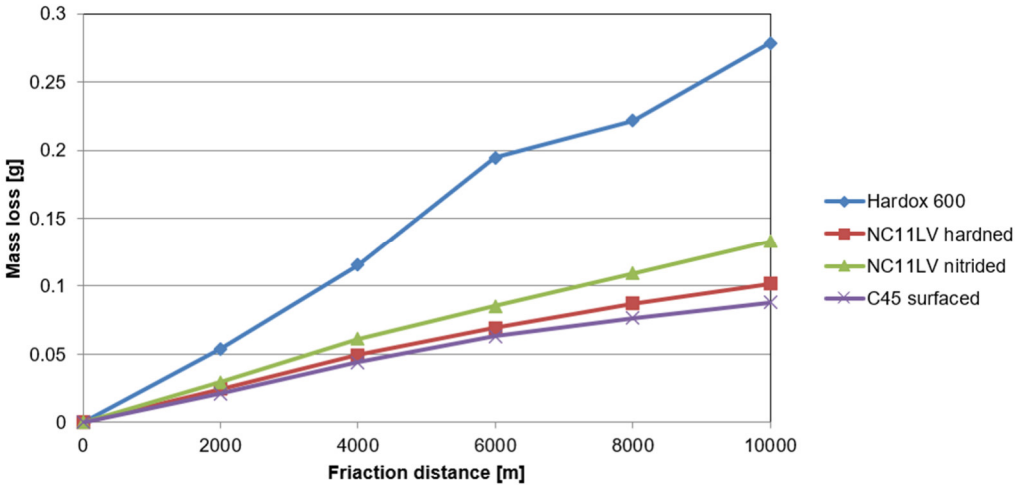

Figure 3 Curve of changes in mass loss of sample

Each selected material shows good abrasion resistance; however, for this study the key is its behavior under the intense friction occurring during extrusion of ceramic roof tiles. The results obtained from the “rotating bowl” test rig indicate the influence of friction conditions and the properties of the abrasive medium on the analyzed

wear-resistant materials. Among the tested materials, the specimen made of Hardox 600 steel exhibited the highest wear, with an average mass loss of 0.2785 g after a sliding distance of 10,000 m. Additionally, in the case of Hardox 600 steel, variations in the slope of the wear curve may indicate changes in contact conditions at the friction interface, such as progressive degradation of the surface layer or intensification of wear mechanisms. Better results were obtained for NC11LV cold-work tool steel. Depending on the applied surface treatment, this material exhibited a differentiated, yet still relatively low level of wear. The mass loss of the hardened sample was 0.1017 g, whereas for the nitrided specimen it was 0.1329 g. An analysis of the wear curves for these materials indicates that they follow a similar trend without abrupt changes, which suggests stable wear intensity throughout the duration of the experiment. The most beneficial results were recorded for C45 steel coated with a hardfaced layer, which demonstrated the lowest mass loss among all tested samples. The average mass loss was only 0.0879 g. The wear curve of this specimen also shows the most uniform progression. Such behavior suggests a stabilized wear mechanism, in which the hardfaced layer effectively limits the development of surface damage during the friction process.

5. OPERATING TEST RESULTS – STAGE III

After 170 hours of operation, the forming tools were subjected to geometric analysis using a 3D scanner. The obtained scan was compared with the baseline CAD model or with a reference scan performed prior to the commencement of the operational tests. The results are presented in **Figure 4**.

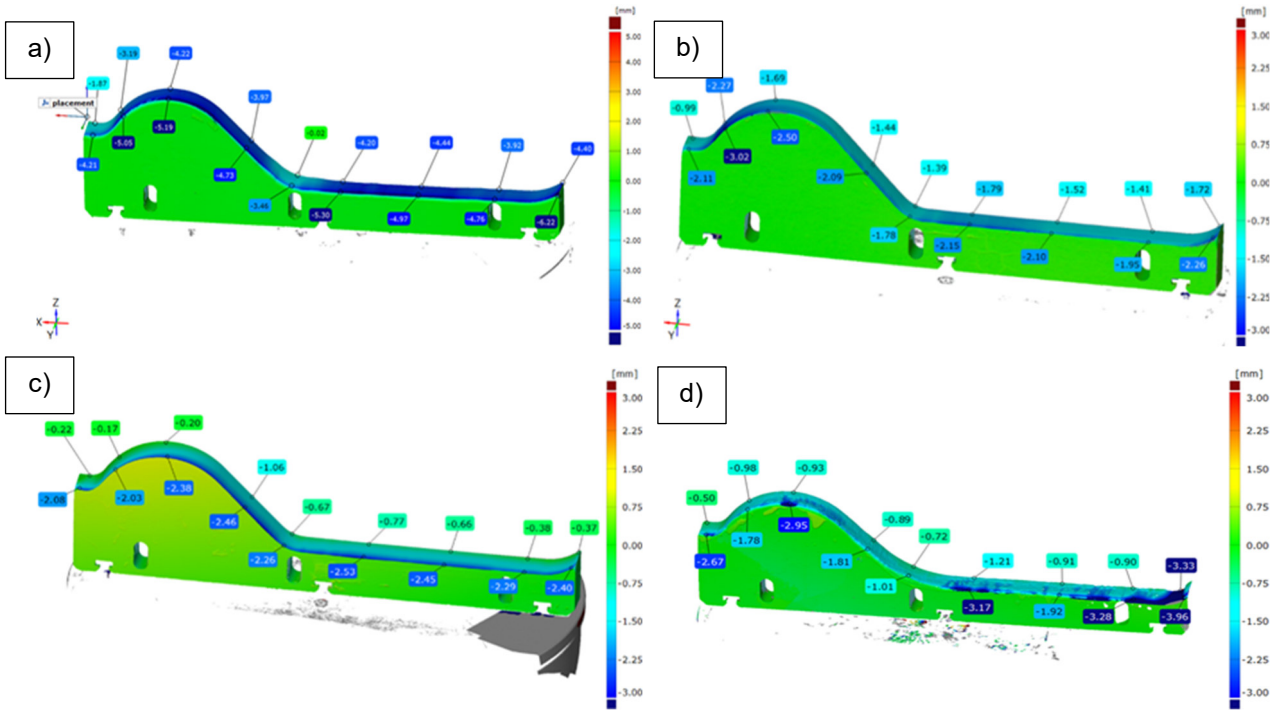

Figure 4 Scanning results of forming tools after 170 hours of operation: a) Hardox 600, b) NC11LV, c) NC11LV nitrided, d) C45 hardfacing

Based on the analysis of the obtained scans, it was found that the highest wear occurred in the tool made of Hardox 600 steel, which is consistent with the results of the laboratory tests. Local material losses reached up to 6.22 mm. Among the other solutions, the highest wear of the working surface was observed for the welded (cladded) tool (**Figure 4d**), where it locally reached 3.96 mm. These areas correspond to zones of complete wear of the hardfacing layer and exposure of the substrate material (C45 steel). Where the hardfacing layer remained continuous, a significant reduction in wear was observed, down to approximately 0.50 mm. The differences observed for these hardfaced tools after operation, compared to laboratory test results, can be explained by a

somewhat different and more complex loading state in real conditions (higher unit pressures). This further emphasizes the necessity of final validation of the selected solutions under industrial conditions. The tool made of hardened NC11LV steel exhibited the most uniform wear pattern, ranging from 1.39 to 3.02 mm. The highest wear resistance, however, was observed for the nitrided NC11LV steel tool, for which local wear was limited to approximately 0.17 mm. In areas of highest operational loads, the nitrided layer gradually wore away, which led to an increase in wear, locally exceeding 2.50 mm.

6. CONCLUSION

This paper presents a comprehensive analysis of wear in tools used for the forming of ceramic roof tiles. In the first stage, SEM–EDS results of the ceramic body were presented, confirming its complex composition. It was demonstrated that hard fractions such as quartz and garnet, as well as the addition of ground ceramic, have a key influence on abrasive wear. Abrasion resistance tests were carried out using a “rotating bowl” test rig, with the ceramic mass serving as the abrasive medium. Under laboratory conditions, the best performance was achieved by C45 steel with a EuTroLoy 16006A hardfacing layer. In contrast, industrial trials revealed differentiated tool wear at the material inlet and outlet zones. The most favorable results were obtained for nitrided NC11LV steel, where the average wear at the outlet region was 0.50 mm. The obtained results show that, in addition to the abrasive medium itself, different friction mechanisms as well as the nature and level of loading occurring in laboratory methods and industrial tests also have a significant influence on wear behavior. On this basis, it can be concluded that the combination of laboratory and operational studies enables a more comprehensive assessment and supports the selection of tool materials in the ceramic industry.

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