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# Improving the Properties of UNIMAX Tool Steel by Surface Coating

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**Abstract**

The aim of this study was to determine the extent to which surface coating can improve the service life and mechanical properties of tools made from UNIMAX steel. Two specimens with identical composition and heat treatment were used, one of which was coated with a CrAlN-based BALINIT FORMERA layer. Microhardness measurements, wear tests, and microscopic analyses were carried out during the investigation. The results clearly demonstrated that the coating significantly increases the tool's lifetime and enhances its mechanical properties.

**Keywords:** *tool steel, tool service life, surface coating, material testing.*

## 1. Introduction

In our previous research, we focused on extending the service life of a pressure die-casting tool. During these studies, we were able to determine an optimal material grade and its corresponding heat treatment. As further opportunities to increase tool life, we identified the investigation of coating technologies [1].

The UNIMAX tool steel, produced by Uddeholm, can be applied in a wide range of tooling, for example:

– plastic forming tools
– hot forming tools
– pressure die-casting tools.

The combination of short cycle times and long service life contributes to cost-effective production. Tools manufactured from this material exhibit high hardness and wear resistance while maintaining toughness [2]. The excellent properties of UNIMAX steel are due to its electroslag remelting process, which results in minimized sulfur content, segregation, and nonmetallic inclusions [3]. The steel is highly pure, with enhanced homogeneity and good hot toughness.

Due to controlled solidification, a fine-grained structure and smaller carbide particles are obtained. This steel is alloyed with chromium, molybdenum, and vanadium, providing excellent hot toughness, temper resistance, and surface treatability (Table 1).

**Table 1.** *Chemical composition of UNIMAX tool steel*

| C | Si | Mn | Cr | Mo | V |
|---|---|---|---|---|---|
| 0.50 | 0.20 | 0.50 | 5.00 | 2.30 | 0.50 |

After heat treatment, it exhibits good dimensional stability and polishability. These favorable properties can be further enhanced through the appropriate heat-treatment technologies, including:

– optimal hardening temperature
– cryogenic treatment
– carefully selected tempering temperatures
– multiple tempering cycles.

It has been proven that cryogenic treatment can significantly increase the lifetime of UNIMAX steel die-casting tools by minimizing the amount of retained austenite [4].

In our study, we investigated how tool life could be further increased and how even more favorable properties could be achieved through the application of suitable surface coating technologies [5].

Surface treatments improve wear resistance, surface hardness, and corrosion resistance. The purpose of coating is to create a thin, high-hardness surface layer with low friction, minimal adhesion, high wear resistance, and corrosion resistance [6].

One of the most widely used methods is PVD coating. In this process, the coating material is evaporated in a vacuum and deposited onto the finished tool surface. The coating forms an approximately 1-micron-thick layer that adheres firmly to the tool. The process is generally carried out below 600 °C, which does not affect the base hardness of the tool.

The coating we used is BALINIT, produced by Oerlikon Balzers, a leading player in the coating industry. BALINIT coatings are multifunctional, have unique properties, and enhance the long-term cost-effectiveness and productivity of manufacturing processes. They provide high surface hardness, protecting the tool against wear and erosion. The coating consists of a ceramic material with a low friction coefficient, preventing adhesive and abrasive wear, molten metal sticking, and improving demolding [7]. It also ensures excellent thermal and chemical stability, resulting in no oxidation and reduced contamination of the tool by the melt. Furthermore, it provides protection against heat checking [8].

Thanks to these properties, BALINIT coatings reduce tooling costs, increase service life, and lower production costs, downtime, losses, and maintenance expenses [9].

The specific coating we selected is BALINIT FORMERA ADVANCED. This coating focuses on solving heat checking, preventing adhesion, and providing corrosion protection. As a result, the tool does not require cleaning or maintenance after casting, thereby reducing downtime.

## 2. Materials, Equipment, and Technologies

### 2.1. Material Selection

The test specimens examined in our study were made from the base material of a hot-forming die, designed for the production of automotive aluminum components. For hot-forming tools, essential properties include wear resistance, resistance to thermal fatigue, high hardness, as well as good hot toughness [10]. The Uddeholm UNIMAX tool steel we selected is a premium-quality material that perfectly meets these requirements.

Its high carbon content increases hardness, while chromium alloying is responsible for the formation of complex carbides. Molybdenum, in addition to contributing to carbide formation, also enhances hot toughness and temper resistance. Vanadium is responsible for grain refinement and ensuring good wear resistance [11].

### 2.2. Equipment and Devices

#### 2.2.1. Heat Treatment Furnace

The heat treatments were carried out at Titán 94 Ltd. in Lőrinci, using a Schmetz-type electric vacuum furnace. In this furnace, tool heating is performed under vacuum, cooling is achieved by nitrogen as protective gas, while cryogenic treatment is carried out by spraying liquid nitrogen into the chamber, reaching –150 °C.

In Fig. 1 the furnace interior shows the graphite heating rods on both sides, the flexible thermocouple in the middle, as well as the fan and injection nozzles located at the back of the furnace through which nitrogen is introduced. The 8 test specimens and the installed Ni-NiCr thermocouples serve for process control and monitoring.

Fig. 2 illustrates the furnace setup. The liquid nitrogen tank is visible, nitrogen inlet valves are highlighted in green, while the blue color represents the water cooling of the double-walled furnace. On the left side, the two vacuum pumps belonging to the furnace can be seen.

#### 2.2.2. Coating Furnace

The coating furnace is an INNOVA-type device (Fig. 3), with an inner chamber size of 700 × 1200 mm, into which tools can be mounted on a carousel element. Prior to coating, the tools undergo both chemical and mechanical cleaning. After loading the workpiece into the chamber, it is evacuated to $10^{-6}$ mbar [12]. The surface treatment process continues with evaporation of the coating source, which generates a plasma cloud inside the furnace chamber. Nitrogen gas is introduced into this plasma. The atoms and ions evaporated from the source disks condense onto the workpiece surface through adhesion. This process continues until the desired coating thickness is achieved.

#### 2.2.3. Preparation for Measurements

For the examinations, test specimens had to be cut out first, which was carried out using the Servocut 302 abrasive cutting machine, shown in Fig. 4.

After cutting, sample preparation followed, consisting of hot mounting, grinding, polishing, and etching. Grinding and polishing were performed with a Forcipol 102 grinding-polishing machine (Fig. 5) while etching was carried out with 4% Nital.

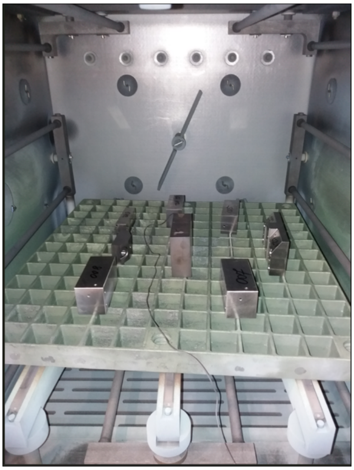

Fig. 1. *Interior of the furnace.*

Fig. 3. *INNOVA coating equipment.*

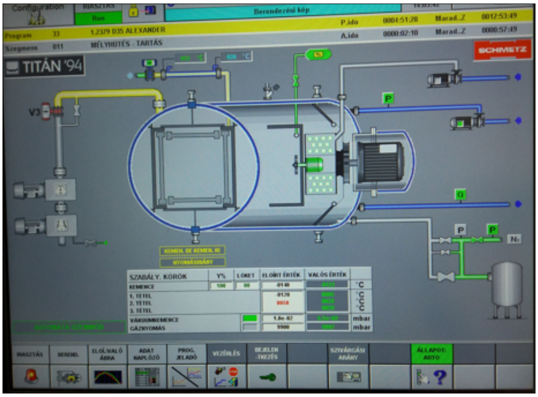


Fig. 2. *Furnace control monitor.*

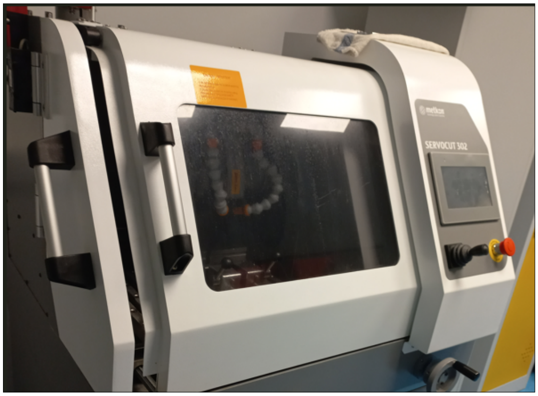


Fig. 4. *Servocut cutting machine.*

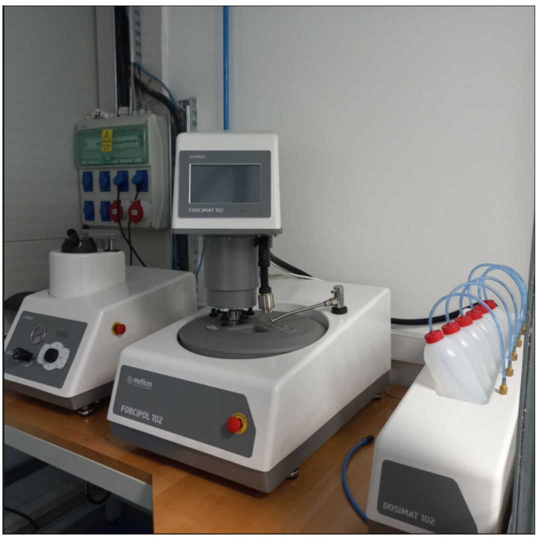


Fig. 5. *Grinding-polishing machine.*

### 2.2.4. Coating Thickness Measurement

The aim of the measurement was to determine the thickness of the deposited coating. Ultrasonic pulses were directed to the surface, which were reflected from the interface between the coating and the tool steel. Using the propagation speed of the reflected wave and the elapsed time, the coating thickness was calculated with the following equationl:

$$D = (v \times t) / 2, \quad (1)$$

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$D$: coating thickness.

$v$: propagation speed.

$t$: time.

### 2.2.5. Microhardness Testing

Microhardness measurements were performed using a KB 30S video hardness tester, illustrated in Fig. 6.


Fig. 6. *Microhardness tester.*

## 2.3. Heat Treatment

### 2.3.1. Stress-Relief Annealing

The first essential step in heat treatment was stress-relief annealing. The tool was slowly heated up to 650 °C in a nitrogen protective atmosphere, held at this temperature for two hours, and then slowly cooled to room temperature.This step is necessary because internal stresses accumulate during tool manufacturing, which promote crack initiation or potential fractures [13]. Annealing reduces this risk, thereby increasing the service life of the tool [14].

### 2.3.2. Hardening

The next heat treatment was hardening, which can be divided into two stages. The first stage was austenitization: the material was heated stepwise up to the hardening temperature and held until homogeneous austenite was formed. The second stage involved cooling in nitrogen gas at a rate faster than the critical cooling speed, down to room temperature, with the goal of producing a martensitic microstructure.

Stepwise heating was applied to equalize temperature differences between the surface and the core of the material and to prevent stresses caused by phase transformations. The hardening of UNIMAX was carried out at 1050 °C.

### 2.3.3. Cryogenic Treatment

For further improvement of tool life, cryogenic treatment was applied to the tool after cooling to room temperature [14]. Following hardening, the test specimens were cooled further to –150 °C using sprayed liquid nitrogen. Cryogenic treatment improves microstructural homogeneity, increases hardness and toughness, and significantly reduces the retained austenite content [15].

### 2.3.4. Tempering

To achieve the proper toughness-to-hardness ratio, tempering is indispensable. For hot-forming tool steels, high-temperature multiple tempering cycles are necessary to form a fine-grained homogeneous spheroidite structure [16], and to reduce stresses caused by heat treatment.

The final hardness was achieved by adjusting the second tempering temperature. In our case, triple high-temperature tempering was applied.

**Table 2.** *Heat treatment parameters* [1]

| Process | Temp. (°C) | Time (min) |
|---|---|---|
| Stress relief | 650 | 260 |
| Hardening | 1050 | 200 |
| Cryogenic treatment | –150 | 145 |
| Tempering 1 | 605 | 240 |
| Tempering 2 | 615 | 240 |
| Tempering 3 | 595 | 240 |
| | | **Total time: 1325 min.** |

## 2.4. Surface Treatment

BALINIT FORMERA differs from conventional PVD coating. In our experiment, the process began with plasma nitriding, followed by PVD coating. As a result, an adhesive layer of 7 μm and a diffusion layer of 80 μm thickness were created. Nitriding is carried out at 480 °C, and the coating temperature does not exceed the tempering temperature of the tool [17]. BALINIT FORMERA produces a multilayer structure, which significantly reduces crack propagation. Its main advantages include heat resistance up to 1000 °C, reduced adhesion of castings, and high resistance to washout, thereby increasing tool lifetime.

# 3. Measurement Results

## 3.1. Microhardness Testing

During the microhardness measurements, care was taken to use only minimal load to avoid exceeding the coating thickness with the indenter. With a load of 0.5 kg, a hardness of 2200 HV was achieved. The uncoated tool had a hardness of 52 HRC, corresponding to approximately 550 HV.

This means that due to surface treatment, surface hardness increased fourfold compared to the uncoated condition.

### 3.2. Coating Thickness Measurement

The coating thickness was determined using a FISCHERSCOPE® X-RAY XDAL® device, which operates on the principle of X-ray fluorescence (XRF). This method enables non-destructive measurement of coating thickness by evaluating the characteristic fluorescent radiation of the elements in the coating and the substrate.

Measurements were carried out on all three coated samples (**Fig. 7**) providing precise data on the thickness of each layer. The coating thickness measurement was repeated on the three test specimens, and the results were averaged. The average coating thickness was 6.94 μm.

## 4. Conclusion

In our investigations, we compared two test specimens subjected to identical heat treatments, with one of them additionally coated with BALINIT FORMERA ADVANCED. Microhardness tests and microscopic microstructural examinations were carried out. After completing the laboratory tests, the coating process was implemented in practice on the tool itself.

With the appropriate heat-treatment technology, the tool was capable of producing 280,000 parts. Thanks to the coating, the new tool could produce an additional 80,000 parts, resulting in a total service life of 360,000 parts.

**Table 3**. *Service life comparison*

| Service life without coating | Service life with coating |
|---|---|
| 280,000 pcs | 360,000 pcs |

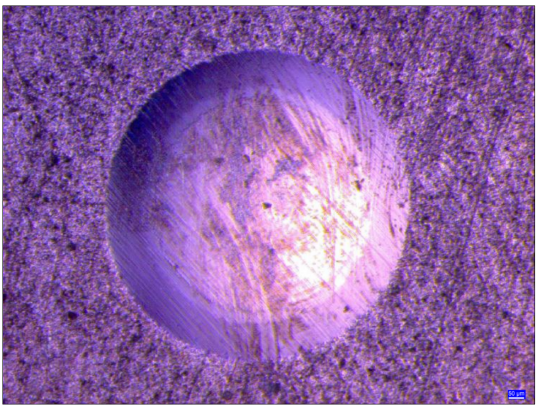

**Fig. 7.** *Image of one test specimen.*

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