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Extending the Lifetime of Die Casting Tools with Cryogenic Heat Treatment

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Abstract

In our work, we aimed to increase the lifespan of tools used in pressure die casting. We conducted experiments on test specimens made from two types of base materials, which were subjected to various heat treatments, followed by material testing on the specimens. In parallel, the final tools were also produced, and parts were manufactured using these tools. Based on the results of the experiments and production, considering both quality and economic aspects, the most suitable base material proved to be the electroslag remelted tool steel, for which we applied cryogenic heat treatment. To enhance the tool lifespan, we performed additional heat treatments on the optimal material, as well as optical microscopy examinations and hardness measurements.

Keywords: *tool steel, die, lifetime, cryogenic treatment.*

1. Introduction

Pressure die casting is used for the production of precise castings with complex geometries, primarily for automotive parts. To achieve the required cleanliness, homogeneity, and optimal microstructure of the product, it is essential to carefully select the raw materials and design an appropriate manufacturing process [1, 2]. The quality of the die-casting tool material also depends on the steel manufacturing process, which can include conventionally produced, remelted, or powder metallurgy-produced materials [3]. In our experiments, we conducted tests on two material grades: a conventionally cast and an electroslag remelted material. Electroslag remelted steel differs from conventionally produced steel in that it is cleaner, free from contaminants, almost inclusion-free, and structurally more homogeneous. Other characteristics of electroslag remelting include the absence of macro-segregation, minimal micro-segregation, and excellent material properties [4].

The selected materials belong to the family of hot-work tool steels, which are characterized by three primary properties: hot strength, hot toughness, and hot wear resistance. These properties can be achieved through their chemical composition and appropriate heat treatment. The conventional heat treatment process for hot-work tool steels consists of stress relief, hardening, and tempering. An alternative process is cryogenic heat treatment, which was applied along with conventional heat treatment in our study. Among these, cryogenic heat treatment proved to be the most effective, as evidenced by the achieved hardness values and the favorable microstructure. In the microstructure following cryogenic treatment, the amount of retained austenite is minimal.

The lifespan of die-casting tools is characterized by the so-called shot count, which indicates the number of shots the tool can withstand under optimal operating conditions without intervention. According to the literature, this number ranges between 75,000 and 150,000 shots for aluminum castings [1, 2].

2. Materials, Equipment, Devices, Methods

2.1. Material Selection

In our study, we experimented with a pressure die-casting tool for an aluminum car seal housing. This tool has a complex shape with varying wall thicknesses, making it sensitive to heat, pressure, and different types of stresses. When selecting the tool material, we need to consider properties that affect its lifespan. The objective is to minimize wear processes and prevent cracking and tool breakage. For hot-work tool steels, resistance to thermal fatigue – essential to preventing crack formation – is a key factor in addition to handling various stresses [5].

The most important alloying element in tool steels is carbon, which significantly impacts the properties of the alloy. Increasing carbon content enhances strength and hardenability but decreases ductility, formability, weldability, and machinability. Silicon primarily acts as a deoxidizer and also increases strength, wear resistance, and heat resistance. Manganese acts as a deoxidizer and, by forming manganese sulfide with sulfur, prevents red brittleness, reduces the critical cooling rate, and improves hardenability. Chromium is a carbide-forming alloying element that, like manganese, lowers the critical cooling rate, thereby enhancing hardenability and through-hardening capability, as well as improving hot strength and scale resistance. Molybdenum, another carbide-forming alloying element, also serves to reduce the critical cooling rate, thus improving hardenability and through-hardening capability. It promotes fine grain formation and increases strength and wear resistance. Vanadium is a very strong carbide former that enhances toughness, hot strength, and temper resistance [6].

Initially, we used Böhler W302-grade tool steel, a hot-work tool steel produced by conventional casting. A tool made from this material, when conventionally heat-treated, was able to perform 6,000 defect-free shots during operation. At that point, micro-cracks appeared in the critical cross-section of the tool, which were repaired by overlay welding, but this only marginally extended its lifespan [7]. We then experimented with Uddeholm Unimax, an electroslag remelted tool steel. The chemical compositions of these steels are shown in Table 1.

Table 1. *Chemical Composition of the Tool Steels Used*

	C (%)	Si (%)	Mn (%)	Cr (%)	Mo (%)	V (%)
W302	0.39	1.0	0.40	5.20	1.40	0.95
UNIMAX	0.50	0.20	0.50	5.00	2.30	0.50

2.2. Tools and Equipment

2.2.1. The Heat Treatment Furnace

The tools were heat-treated in a Schmetz-type vacuum furnace (Figure 1). The electric vacuum furnace operates by heating in a vacuum, cooling with nitrogen gas, and cryogenically cooling through the spraying and injection of liquid nitrogen.

2.2.2. Microscopic Microstructure Examination

The optical microscopic microstructure examination was conducted using a Neophot 2 light microscope, and the images were taken at a magnification of 1000×.

2.2.3. Heat Treatment of Böhler W302 Tool Steel

The heat treatment is generally followed by a final sizing process, which is why the planning of the heat treatment technology is very important, as it determines the tool's final properties. The heat treatments consist of heating, holding at temperature, and cooling. In the case of a pressure die-casting tool, stress relief, hardening, and tempering are applied.

Fig. 1. *The Heat Treatment Furnace.*

2.2.3.1. Stress Relief Annealing

Stress relief is necessary to eliminate the residual stresses formed during the manufacturing of the tool. Thermal internal stresses can also form after hardening, which may combine with the residual stresses created during manufacturing. The total of these stresses can lead to micro-cracks and fractures. Therefore, stress relief before manufacturing and heat treatment is crucial. During the stress relief process, the tool was slowly heated to 650 °C in a 2 bar nitrogen protective gas environment, held at that temperature for 2 hours, and then slowly cooled to room temperature (Fi-gure 2).

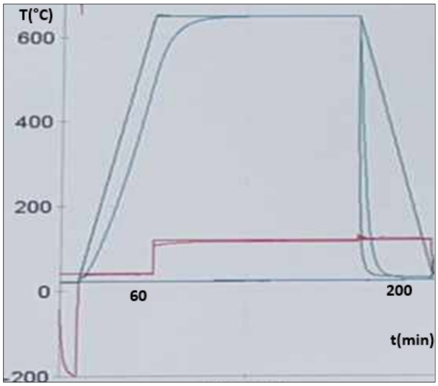

Fig. 2. *Stress Relief Annealing*

2.2.3.2. Hardening

Stress relief was followed by hardening, during which a three-step heating process was used in a vacuum to equalize the temperature between the surface and the core before structural transformations, with the goal of preventing stresses caused by phase changes. The hardening temperature for the tool made from Böhler W302 material was set at 1020 °C. After reaching this temperature, a 15-minute holding period followed to allow the formation of homogeneous austenite (Figure 3).

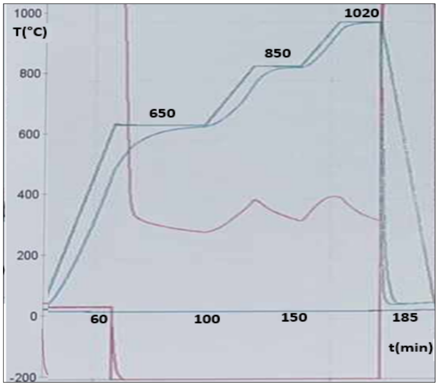

Fig. 3. *Hardening*

2.2.3.3. Tempering

The purpose of tempering is to adjust the hardness-toughness ratio, reduce stresses, and decrease the amount of retained austenite. For the tool made from Böhler W302 material, we applied three high-temperature tempering cycles (Fi-gure 4) [8, 9, 10].

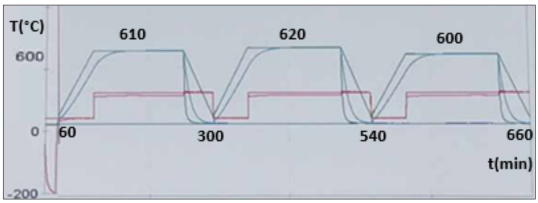

Fig. 4. *Tempering*

2.3. Heat Treatment of Uddeholm UNIMAX Tool Steel

The purpose of cryogenic heat treatment is to reduce the amount of retained austenite, which leads to improved homogeneity, structural stability, increased hardness, and toughness. By improving these factors, the tool's lifespan is also extended. There are several possible methods for cryogenic treatment, and we used the evaporation and injection of liquid nitrogen. The key principle is that the cooling of the furnace chamber is achieved by spraying and injecting nitrogen, allowing the tool to be cooled to –150 °C. For Uddeholm UNIMAX tool steel, the hardening temperature was set at 1050 °C, and the tool was held at this temperature for 20 minutes [8, 11]. After the holding period, the tool was cooled to 50 °C with 8 bar nitrogen gas, followed by cryogenic

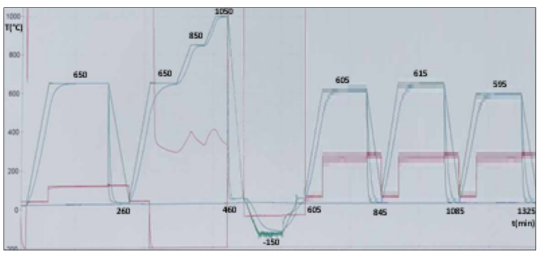

Fig. 5. *Heat Treatment Diagram of the Uddeholm UNIMAX Tool Steel.*

treatment using liquid nitrogen. The high-temperature tempering cycles were performed in 2 bar nitrogen gas (**Figure 5**).

3. Measurement Results

3.1. Hardness Measurement

The hardness of the tool made from Böhler W302 after heat treatment is 45 HRC, while the tool made from Uddeholm UNIMAX steel has a hardness of 48 HRC after heat treatment. These results are shown in **Table 2.**

Table. 2. *Hardness Values in Tabular Form*

Tool Material	Average hardness (HRC)
Böhler W302	45
Uddeholm UNIMAX	48

3.2. Microscopic Microstructure Examination

The microstructure examination was performed after specimen preparation using an optical microscope, as illustrated in **Figures 6.** and **7.** The microscopic images show that in the case of the re-melted and cryogenically treated steel quality, the amount of retained austenite was minimized, and the quantity of secondary carbides increased.

4. Conclusion

The lifespan of pressure die-casting tools can be increased by selecting the appropriate raw material made with the correct manufacturing technology, such as electroslag remelted steel. The cryogenic treatment applied during the tool's heat treatment reduces the amount of retained austenite and achieves the optimal microstructure, which also leads to an increase in tool lifespan. The lifespan of the car sealing housing die-casting tool in question, with the well-chosen raw material and proper heat treatments, demonstrates excellent results in terms of cost-effectiveness. Thus, the tool's lifespan was successfully increased by nearly 47 times (**Table 3.**).

Table. 3. *Lifespans in Tabular Form*

Tool Material	**Lifespan** (number of shots)
Böhler W302	6000
Avverage	75 000–150 000
Uddeholm UNIMAX	280 000

A further opportunity for increased durability is seen in surface treatment. By applying a suitable PVD coating, the surface hardness and wear resistance can be further increased, thus increasing the tool life. **[12, 13]**.

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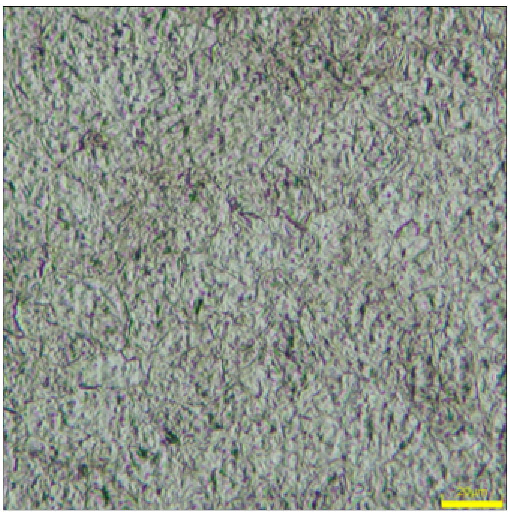

Fig. 6. *Microstructure of Böhler W302 Tool Steel, Traditionally Heat Treated*

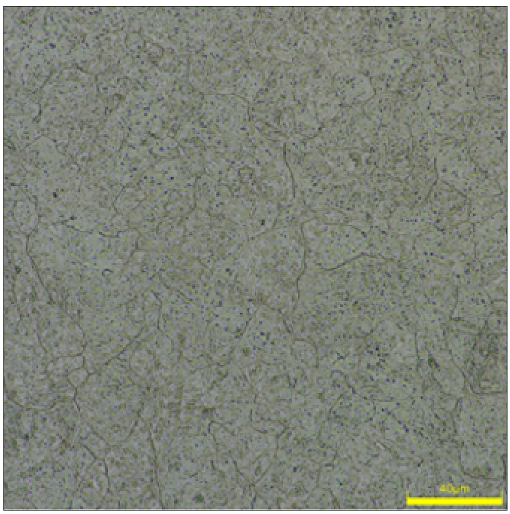

Fig. 7. *Microstructure of Uddeholm UNIMAX Tool Steel with Cryogenic Heat Treatment.*

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