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AN EXAMINATION OF THE EFFECTIVENESS OF TUMBLING ON SAND-CAST PARTS

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Abstract

The purpose of this study is to examine the effectiveness of the tumbling method on sand-cast metal parts. The first phase of the research was to design and construct a laboratory-scale tumbling mill, make samples for the measuring instruments available and to construct a coal-powered furnace that can be used in the making of the metal samples. After the design and construction of the necessary hardware, we conducted the experiment, took the necessary measurements and processed our data: this consisted of measuring the surface roughness of the metal samples before, during and after a complete tumbling cycle, then processing the resulting data. The experiment allows us to determine the optimal tumbling parameters such as the ideal tumbling medial size, the optimal speed of revolution of the tumbling drum and the smallest surface roughness achievable via the tumbling method. The experiment also allows us to find a correlation between the tumbling time and the change in surface roughness, which makes it possible to determine the optimal time frame in which the method is the most effective.

Keywords*: surface roughness, tumbling mill, sand-cast parts, tumbling, sand casting, tumbling media.*

1. Introduction

1.1. Surface Roughness

Tolerances are the permissible limits of certain properties on a part or an assembly, and they can refer to various aspects of the part: geometric tolerances like parallelism, roundness, perpendicularity or deviations in certain dimensions. Parts must also be manufactured to meet other criteria such as structural properties (hardness, elasticity, density and isotropy of the crystal matrix), optical (transparency, reflectivity) and others. One of these properties is surface roughness.

Surface roughness refers to the micro-irregularities of a surface usually created in the machining process. These can be feed marks or other irregularities in the measured area. [1] Surface roughness tolerances determine the acceptable roughness of a given surface of a part or a lower and upper limit, which the roughness cannot exceed.

One of the most widely used roughness index is the average surface roughness index, which, according to the ISO 21920-2:2021 standard, corresponds to the numerical average of y-ordinates of the peaks and valleys along a continuous profile.

1.2. Measuring Surface Roughness

In order to determine whether the surface roughness of a part is within tolerance, it must be measured via various methods. These methods can be categorized as contact-based and contactless methods. [1]

Contact-based measuring instruments are the most common as they are widely available due to their relatively simple construction. They are reliable and easier to use than the more precise and more complex optical measuring instruments. Before the beginning of the 20th century, surface roughness was determined either through observation or by dragging one's fingernail on the surface. However, as the resolution of the average human eye is around 400 μm, more precise instruments were needed. [2]

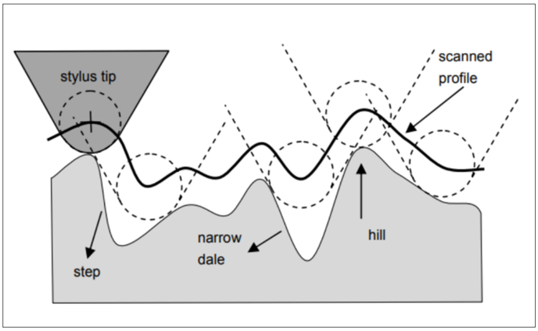

Fig. 1. *The profile created by the stylus tip.* [1]

The first contact-type stylus profilometer (from here on referred to as "SP") was invented in 1929 by G. Schmaltz. The way portable SPs work is by dragging a diamond or ruby stylus along the surface of the part via the use of an electric motor. The accuracy of the resulting profile curve (in the case of analogue devices) or cloud of points (in the case of digital devices) ranges between 0.1 and 4 µm (Ra). The radius of the stylus tip is usually 5 µm and the length of the profile varies between 5 and 8 mm. [2] Thus it follows that the accuracy of the measurement depends greatly on the stylus tip radius, since the stylus cannot enter valleys narrower than the tip diameter (see Fig. 1).

1.3. Tumbling Mills and their Operation

The construction of a tumbling mill is simple, it consists of three main parts: a revolving drum, tumbling media and the drive mechanism.

The drum is usually a tube with a circular or polygonal cross-section, and depending on the size of the machine, can be closed, half-open or open on both ends. The tumbling or grinding media is placed in the drum, and it is usually a small granulate of some hard material (sand, ceramics, hard composites or metal). Larger metal or ceramic media is used for grinding powders. The grinding effect is a result of the continuous contact and friction between the media and the surfaces of the workpiece, small particles of the surface are abraded.

It has been proven that the shape of the media affects its behaviour and effectiveness in both grinding and tumbling. The research of Shi shows that cylpeb-shaped (conical cylinder with rounded points) media are more effective than spherical media with the same mass, since they have a larger surface. [3] Nanda P. et al used prism-shaped and pyramidal media in order to ensure contact between the media and the entire surface of the sample. [4, 5] Spherical and cylindrical media have a smaller chance of coming into contact with inner corners on the sample due to their rounded shape, while the tips of prism-shaped and pyramidal media have a better chance of coming into contact with these areas.

2. Methodology

2.1. The Measuring Instrument and the Samples

The goal of this study is to build a device that can be used to determine the effectiveness of tumbling and to examine how low of a surface roughness we can achieve with the method. The first phase consisted of designing and building a small tumbling mill and a fixture for the Insize ISR-C002 Surface Tester, along with metal samples. The fixture is necessary for holding the surface tester in place relative to the metal sample, thus ensuring that all measurements are taken on the same profile. Since the surface roughness of sand-cast metal parts is not only high but very uneven, this step was crucial in order for us to be able to examine the change in surface roughness between tumbling cycles, since even a deviation of a few millimetres would result in a drastic change in the roughness profile. Since the radius of the ruby stylus is very small and the technology at our disposal cannot provide such accuracy, each measurement was repeated multiple times and the final data was compiled from the numerical averages of these measurements.

The samples were sand-cast using fine mesh greensand. The blank for the samples was made using a Creality K1C 3D printer. Their dimensions can be seen in Fig. 2.

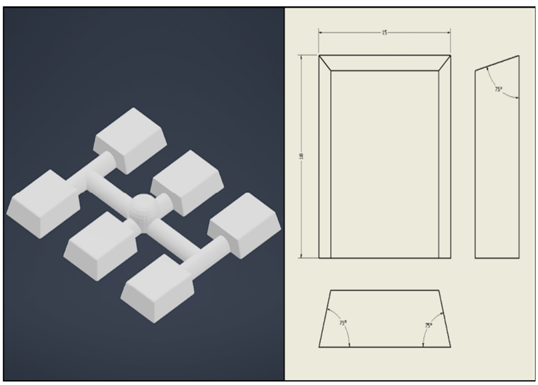

Fig. 2. *CAD model and dimensions of the samples.*

Using the CAD model of the sample, we generated a casting blank for six samples. We used cast samples from two metals, lead and aluminium.

2.2. Design and Construction of the Tumbling Mill

The second phase consisted of building the tumbling mill. During the design phase, we had to keep in mind multiple criteria: small size, low cost, reliability and simple assembly. The tumbling mill is shown in **Fig. 3.**

The drive chain is used to create the friction drive for the tumbling mill. The diameters of the drum and the rollers are known, therefore, in order to achieve the correct rotational speed for the drum, we had to calculate the appropriate pulley diameters.

In his book titled *Ball Milling Theory and Practice for the Amateur Pyrotechnician*, L.E. Sponenburg explains why the optimal rotational speed is crucial. Under a certain rotational speed, the friction between the inside wall of the drum and the media is less than it is required for the rotating drum to move the media, thus the media simply slides along the bottom of the drum, and the relative motion between the media particles is zero. Beyond the so-called critical speed, the media travels so fast in the drum that centrifugal forces push it into the wall, thus the media once again behaves like a solid body with no relative movement between its particles. Critical speed is the highest rotational speed the drum can spin without this phenomenon occurring. **[6]**

Given that the inside diameter of the drum is $ØD_{inner} = 110\,\text{mm}$, and the size of the media varies between 3 and 5 mm, we can calculate the critical speed using the following formula:

$$N_{crit}[RPM] = \frac{423}{\sqrt{D_{Drum_{inner}} - \bar{d}_{media}}} = \frac{423}{\sqrt{110 - 4}} = 41{,}08\ RPM$$

where the $\bar{d}_{media}$ value indicates the average diameter of media particles (considering spherical media).

The optimal speed of rotation is 80% of the critical speed **[6]**, which, in this case is 32.86 RPM. This rotational speed is achieved by using appropriate diameters for the pulleys for the transfer ratio.

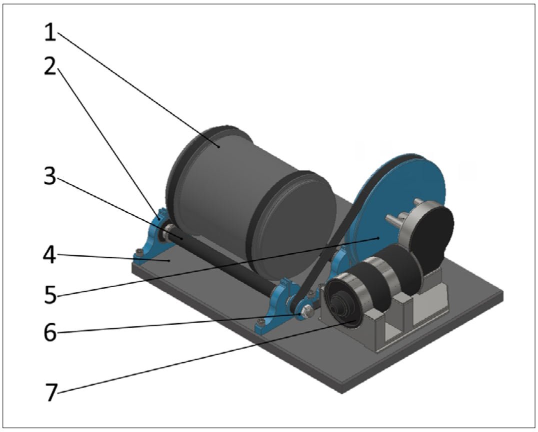

Fig. 3. *CAD model of the tumbling mill (1 – Drum; 2 – Bearings; 3 – Driven Shaft; 4 – Baseplate; 5 – Ø90 mm pulley; 6 – Ø16 mm pulley; 7 – Motor)*

2.3. Experiment Parameters

The goal of the experiment is to determine how tumbling time affects surface roughness. We started from the assumption that some change in surface roughness was guaranteed to occur, however, we aimed to examine the following in particular:

We used 3-5 mm grain bentonite-clay tumbling media for the experiment. In order to have a reference for our measurements, we measured the initial roughness of the raw-cast, unpolished surfaces (Rainitial). We took three measurements from each sample and calculated the numerical average of the results. It is possible to increase the accuracy of the results by increasing the number of measurements per cycle, however, considering that both lead and aluminium are soft metals and the ruby stylus has a much higher hardness, we ran the risk of smoothing over the micro-deviations in the surface.

Tumbling time per sample was 4.5 (four and a half) hours. During the four and a half hours of tumbling, the samples were taken out of the drum regularly for measurements in order to track the changes in surface roughness. Thus, the total tumbling time was divided into smaller tumbling cycles. We determined the cycle time to be 30 minutes: this is long enough for detectable change to occur in surface roughness and provides a sufficient amount of data with a total of 10 cycles.

The samples were numbered from 1 to 6 in order to track their individual changes in surface roughness.

3. Results

We used Microsoft Excel for processing the data and all calculations (like numerical averages, for example) were done using the built-in functions of Excel.

The samples were given IDs based on their metal composition and number, such as Pb1, Pb2, ..., Pb6 for the lead samples and Alu1, Alu2, ..., Alu6 for the aluminium ones. The samples will be referred to by their IDs from here on. Both the surface tester and the sample were tightened down in the fixture in order to ensure that the measurements were taken on the same profile, however, due to the difference in accuracy between the fixture and the stylus, some measurements were still thrown off-profile.

The initial average surface roughness was Ra(Pb_avg1) = 8.785 μm on the lead samples and Ra(Alu_avg1) = 4.816 μm on the aluminium ones. These values show the total numerical average of the surface roughness values from the samples, since the values for individual samples vary (such as: Ra(Pb2) = 12.003 μm, Ra(Pb6) = 6.37 μm; Ra(Alu4) = 6.482 μm and Ra(Alu2) = 3.49 μm).

We used line plots to illustrate the results and compiled graphs for both the surface roughness change on the individual samples and the combined averages. The surface roughness changes for individual samples are shown on **Fig. 4** and **Fig. 5.**

We can observe that for both lead and aluminium samples we have a spike at the 90-minute mark. We suppose that this is either a measurement or fixture error, since had the surfaces of the samples been damaged, this would have shown up in successive measurements as well.

Since the goal of our research was not to examine individual samples but the effectiveness of the tumbling method as a whole, the more relevant graphs are the ones showing the change in the average values of surface roughness. This is shown in **Fig. 6** and **Fig. 7.**

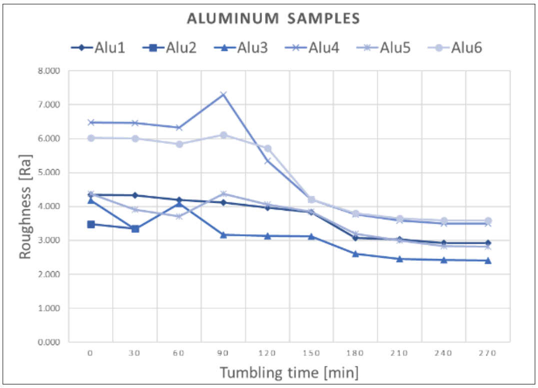

Fig. 4. *Surface Roughness Change in Lead Samples.*

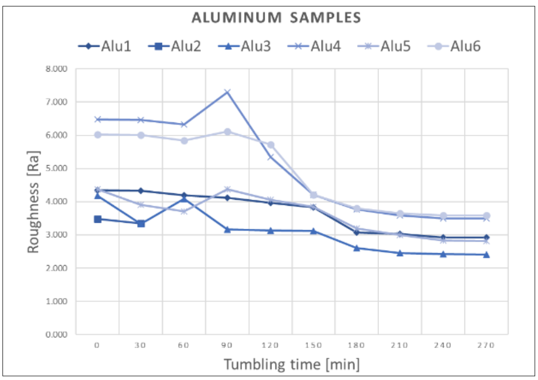

Fig. 5. *Surface Roughness Change in Aluminium Samples.*

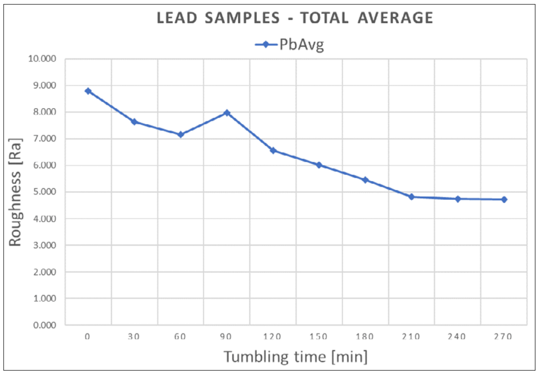

Fig. 6. *Surface Roughness Change in Lead.*

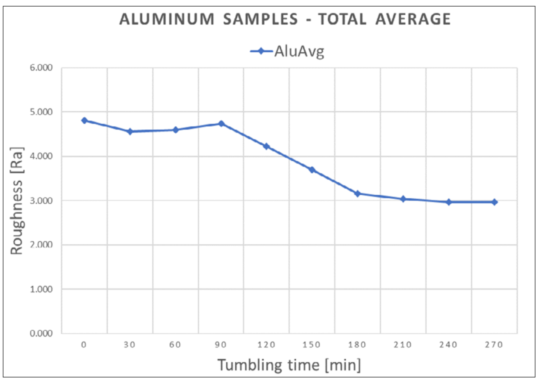

Fig. 7. *Surface Roughness Change in Aluminium Samples.*

The final surface roughness on the lead samples was Ra(Pb_final) = 4.725 µm while on the aluminum samples it was Ra(Alu_final) = 2.962 µm. The difference between the initial and final values of surface roughness gives us the total change in surface roughness, ΔRa, which is 4.059 µm for the lead samples and 1.853 µm for the aluminium sample.

4. Conclusions

When observing the graphs, we notice that the not only are the slopes of the curves similar (despite the difference in material and initial surface roughness) but both slopes show a decrease in steepness and start to flatten out towards the final values.

This led us to believe that the tumbling method is only effective in changing the surface roughness to a certain point, after which it becomes impossible to achieve significant change. This can be explained by the peaks of the roughness profile being sharper in the initial stage, thus require less force to remove than in later phases once the sharp peaks have been abraded to smoother ones. After a certain point, the tumbling media can no longer create enough force on the peaks to remove significant amounts of material, thus the rate of decrease in surface roughness slows down or even stagnates.

The parameters of this phenomenon are dependent on various factors such as the difference in hardness between the samples and the media and the media's grain size (larger grains cannot enter the deeper and narrower valleys of the profile).

We have also noticed an inverse correlation between the change in amount of surface roughness and the hardness of the material (given the same tumbling media): the softer lead samples exhibit a much greater change in surface roughness (ΔRa(Pb) = 4.059 µm) than the harder aluminium ones (ΔRa(Alu) = 1.853 µm).

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