The influence of milling-burnishing successive and simultaneous processes on the material hardness

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Abstract. Recent developments in the field of bio-engineering allow the use of magnesium alloys as a substitute for medical implants. The issue with such alloys is the degradation rate which has to be improved in order to provide the necessary support for the entire duration of the bone fraction healing. For improving the bone shielding heat treatment does not represent a solution, but chemical and/or mechanical do. One mechanical process that has excellent result is burnishing, but this process is difficult to be implemented on a milling machine. Therefore, it was necessary that a new tool and tool holder to be developed, that allow the simultaneous process to take place. A high-pressure hydraulic roller burnishing tool with a special tool holder was used on a CNC milling machine. The material used for this study is magnesium alloy AZ31B-F, and one of the main purposes was to improve the material hardness (HV). The milling-burnishing parameters that were varied are the speed and feed, burnishing pressure and depth, type of process (successive or simultaneous), machining direction and the material hardness after milling. The results were analyzed as percentage improvement between the milling and burnishing measured values.

1. Introduction
Magnesium based materials that can degrade in living tissue resulted in researchers interest and also a multitude of medical applications in the last years [1].

A critical problem is the chemical composition of the alloy, as not all magnesium based materials have non-toxic degradation. Recent studies show that Mg-1Al and Mg-1Zn alloys implanted in living tissue have no negative effect on viabilities of blood vessel related cell [2]. Never the less the development of magnesium alloys is a multidisciplinary challenge, as it takes into consideration also the required mechanical properties [3].

In comparison to other implant materials (table 1) magnesium alloys have closer physical and mechanical properties to those of the natural bone [4]. The main issue with magnesium based implants is the low corrosion rate. This problem can be solved by adjusting the degradation kinetics with the improvement of the surface and subsurface properties. This can be achieved by manufacturing process [5]. The material hardness in the case of magnesium alloy orthopedically implants is related to the wear resistance mechanism. Researches in this field leads to advanced chemical and/or mechanical surface treatments to improve the corrosion rate [6].
Table 1. Physical and mechanical properties of implant materials in comparison to the human bone [4]

| Properties                        | Human bone | Mg alloy | Ti alloy | Polylactide |
|-----------------------------------|------------|----------|----------|-------------|
| Density [g/cm³]                   | 1.8-2.1    | 1.74-2.0 | 4.4-4.5  | 1.25-1.29   |
| Compressive yield strength [MPa]  | 3-20       | 41-45    | 110-117  | 45.5-61.4   |
| Elastic modulus [GPa]             | 130-180    | 65-100   | 758-1117 | 3.75        |

2. Material and experimental setup

Simultaneous and even successive burnishing-milling is a difficult operation to be implemented. Therefore, it was necessary to design and machine a new tool and tool holder (figure 1 [7]). The tool facilitates the implementation of the successive and simultaneous milling-burnishing process. The burnishing tool is composed from a tool holder (1), piston housing (2), piston (3), seal (4), hydraulic oil inlet (5), roller support (6), deforming roller (7), roller shaft (8). The distance from the face mill to the roller represents the burnishing depth and can be adjusted.

![Figure 1. Schematic representation of the high pressure roller burnishing tool [7]](image)

2.1. Material

One of the magnesium alloys that meet the requirements necessary to be implemented in the human body is AZ31B-F. The chemical composition of this alloy is given in table 2 [7]. An extruded 400x400x20 [mm] plate was cut using water jet. The samples used where cut to a thickness of 20 [mm], with a length of 102 [mm] and a width of 72 [mm].

| Element | Al  | Ca  | Cu  | Fe  | Mg  | Mn  | Ni  | Si  | Zn  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         | 2.5±3.5 | <0.04 | <0.05 | <0.005 | 97 | >0.2 | >0.005 | <0.1 | 0.6±1.4 |

2.2. Experimental plan

This study was conducted with the milling-burnishing parameters given table 3 [7]. Minimum and maximum values were chosen by taking into account: the maximum burnishing pressure and depth
that the CNC milling machine can handle. The lowest value with which distinct results were noted and using cutting speed that is consistent to the HSM (high speed machining) process. A total number of 162 experiments were carried out. For the simultaneous process 54 samples were machined while for successive process 108 samples, meaning 54 for each machining direction. The material hardness was measured on Vickers scale [HV], using the ultrasound device Innovatest Ultramatic 2.

Table 3. Milling-burnishing input parameters [7]

| Input parameter                      | Min. value | Avg. value | Max. value |
|--------------------------------------|------------|------------|------------|
| Cutting speed [m/min]                | 100        | 350        | 600        |
| Feed per tooth [mm/tooth]            | 0.06       | 0.08       | 0.1        |
| Milling depth of cut [mm]            |            | 0.6        |            |
| Burnishing pressure [bar]            | 30         | 60         | 90         |
| Burnishing depth [mm]                | 0.5        | -          | 0.75       |

2.3. Milling-burnishing experimental setup
The milling-burnishing experimental setup is outlined in figure 2 [7]. A 3 axes Knuth RapiMill 700 milling machine was used for this study. The machine was equipped with a Sandvick Coromant 490 cutting tool, having a diameter of 50 [mm] and CCMT inserts with a tip radius of 0.8[mm]. For the hydraulic component a low pressure and high pressure Ecoroll HGP 3.0 pump was used. The pressure in the tool is indicated by a dial gauge. The AZ31B-F samples were fixed on a vise. The experiment was conducted in successive and simultaneous conditions, for the last the operation being conducted in both machining and reverse machining direction.

Figure 2. Experimental setup of the milling-burnishing process [7]

3. Results
The material hardness measurements were taken after the milled surface was machined, and then on the burnished one. The hardness measurements were taken on the after the milling operation and after the burnishing operation. In the case of the material hardness measured after the milling operation the obtained results where between 48.95 and 70.45 [HV]. The results obtained when measuring the material hardness after the burnishing operation range from 54.65 to 82.45 [HV]. The results where
then compared as percentage improvement, calculated using equation 1, where HV_m is the material hardness measured after the milling operation and HV_b is the material hardness measured after the milling operation. The comparison was made between the simultaneous and successive surfaces.

\[
Percentage\ improvement = \frac{HV_b - HV_m}{HV_b} \times 100
\]  

(1)

3.1. Cutting speed

The results given in figure 3 for the cutting speed influence on the material hardness are for all the processes. In the case of the simultaneous milling-burnishing the material hardness shows significant improvement when cutting with a speed of 350 [m/min]. For this case an improvement of 23.13 [%] was achieved (from 63.15 to 82.15 [HV]). The smallest percentage improvement of 3.43 [%] (from 64.85 to 67.15 [HV]) was obtained when cutting with a speed of 600 [m/min]. Comparable results with the simultaneous machining were obtained when cutting with a speed of 100 [m.min], using the successive process in the reverse machining direction.

![Figure 3](image3.png)

**Figure 3.** The influence of the cutting speed on the material hardness

3.2. Cutting feed

In figure 4 it is highlighted the influence of the cutting feed on the material hardness percentage improvement. The most satisfactory results by means of process stability and percentage improvement were obtained when using a cutting feed of 0.08 [mm/tooth]. The results have shown that the simultaneous and successive (reverse machining direction) offer comparable results. The highest percentage improvement of 23.13 [%] was obtained when a feed of 0.6 [mm/tooth] was used. It was also noted that the simultaneous process offers superior results for all the cutting speeds, compared to the successive ones.

![Figure 4](image4.png)

**Figure 4.** The influence of the feed on the material hardness
3.3. Burnishing pressure

The percentage improvements show higher values as the burnishing pressure is increased (figure 5). In the case of the simultaneous process, this increase in pressure (from 30 to 60 to 90) leads to a rise in the percentage improvement of the material hardness from 18.19 [%] to 19.78 [%] to 23.13 [%]. For the successive (machining direction) process, the average value of the burnishing pressure offers the highest results. In this case, the most significant improvement is of 17.94 [%] (from 48.95 to 59.65 [HV]). Using the successive (reverse machining direction) results in obtaining optimal results when using a pressure of 90 [bar]. The material hardness improved from 56.65 to 67.35 [HV], mean 15.89 [%].

![Figure 5. The influence of the burnishing pressure on the material hardness](image)

3.4. Burnishing depth

From figure 6, it can be noted that applying a burnishing depth of 0.75 [mm] offers superior results. The highest percentage improvement obtained is of 23.13 [%], from 63.15 to 82.15 [HV]. When using a burnishing depth of 0.5 [mm], the successive (machining direction) process offers the higher percentage improvement in material hardness. Once the burnishing depth increases, the material hardness percentage improvement presents slight variations for the successive (machining direction) process. The opposite occurs for the simultaneous and successive (reverse machining direction). The percentage improvement in the material hardness increases from 13.83 to 23.13 [%], for the simultaneous process, and from 15.36 to 15.89 [%] for the successive milling burnishing in reverse machining direction process.

![Figure 6. The influence of the burnishing depth on the material hardness](image)
4. Conclusions
The experimental study highlights the material hardness percentage improvements obtained when simultaneous and successive milling-burnishing process are used on a magnesium alloy AZ31B-F.

The parameters of the milling-burnishing process (cutting speed and feed, burnishing pressure and depth) where changed in order to see into what extend the material hardness improves.

The most satisfying results were obtained while using a cutting speed of 350 [m/min]. For the simultaneous and successive (machining direction) the highest stability processes take place when cutting with a speed of 100 [m/min]. As the speed increases the material hardness percentage improvement and the process stability decrease.

The average value of the feed offers the highest results for the simultaneous process, while the lowest value leads to a higher process stability. The successive processes machining with a feed of 0.1 [mm/tooth] offer superior results.

A higher burnishing pressure results in higher percentage improvements in the material hardness. When using a pressure of 30 [bar] all the process types present a higher process stability.

In the case of the burnishing depth it was recorded that the 0.5 [mm] depth leads to better percentage improvements for the successive (machining direction) process. The simultaneous process has excellent results when applying a burnishing depth of 0.75 [mm]. The stability of the processes is improved when using a depth of burnishing of 0.5 [mm].

It can be concluded from this study that in the case of milling-burnishing magnesium alloy AZ31B-F the material hardness can be improved when using the simultaneous processes. The successive process also offers good results in comparison to those obtained after the milling process.

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