Characterization of behaviour of new segment diamond tools sintered by microwave technology

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Abstract

This research work addresses the cutting performance of microwave-sintered diamond-impregnated segment discs used for stone cutting. Comparative studies among two different production routes were carried out namely microwave sintering (MW) and hot pressing (HP). The case study was based on the circular sawing process of granite pieces of Pink Porriño, with a constant water flow of 2,2 l /min and variating the machine parameters, i.e feed speeds of 22, 30 and 38 mm/s; rotation speed of 20, 30 and 40 m/s and depth of cut of 9 and 18 mm. Data of the resulting force (generated by the contact between the tool and the stone slab) were used to monitor the performance of the tool. Microwave-sintered segment tools displayed higher resulting forces than hot-pressing ones (the maximum difference was 32%). The tool wear (weight loss) was also investigated. On average, HP segments wears out more than MW ones. The difference in tools mass loss ranged from 1 % to 20 %. During this work the characterization of the stone was also carried out. The results obtained for MW segments show quite similiar cutting behaviour compared with their HP counter-parts, sugesting that microwave sintering is a promising technology. The data from this study points to this method being able to compete with the currently used manufacturing process.

Keyword: Diamond Impregnated Tools, Tool Wear, Stone Cutting, Cutting Performance, Microwave Sintering

1. Introduction

Diamond impregnated metal matrix segments are used in the cutting of ornamental stones, a market worth billions of euros in Europe alone.[1]

The only way to maintain market leadership is to invest in the development of new technologies and production concepts.

Improving the production of diamond segments for stone cutting tools involves increasing cutting efficiency, lowering energy / production cost and decreasing tool wear (increasing tool lifetime). To this end, it is important to explore different technological options, particularly those with the greatest potential.

The present study aims at investigating wheter microwave sintering is able to compete with currently used diamond impregnated tools production tecnologies. Microwave sintering of materials is fundamentally different from conventional sintering. Conventional sintering involves heat generated by external sources that is transferred via conduction from to the inside of the workpiece through thermal conductivity mechanisms. On the other hand, in the case of microwave sintering, the heating takes place via absorption the electro-magnetic waves and conversion of the electromagnetic energy into thermal energy. The heat is generated internally within the material followed by volumetric heating (inside-out heating profile) [2].

The economic interest of this new technology is associated to advantages, when compared to conventional processes, such as reduced energy consumption and production costs associated with high heating rates, reduced processing times and decreased sintering temperatures, among others [3].

The present experimental work is a follow up study dedicated to this subject [4]. In that work, segments sintered by MW used in the tools of this study, were produced and characterized. It has been concluded that the microwave segments have lower hardness and greater adhesion of diamonds to the matrix than the hot-pressed ones.

This experimental work addresses the cutting behaviour of diamond segments discs in order to evaluate their performance under different working conditions by monitoring the performance of the disc along the cutting operation.

The cutting behaviour is linked to the stone Porriño Granite used in the process of monitoring the performance of the disc. For this reason the stone was also characterized in this study.

2. Background

In the context of this study, it is useful to understand the wear mechanisms in diamonds during stone cutting using saws with diamond impregnated segments.

According to Wang et al. [5] and Luo [6] while the diamonds remain on the surface of the segment they can exhibit one of seven states: 1) fresh (protrudes above the matrix, but may not immediately contribute to the cut due to shielding-effect) ; 2) sharp (is active in the cut) ; 3) micro-fractured (presenting micro-cracks, crushes, or fragments on the grit surface); 4) macro-fractured (further damaged compared to 3)); 5) polished (worn out presents a flat face and less efficient cutting ability) and 6) pull-out (the earlier the diamond is removed, the deeper is the crater).

The different stages of wear of the diamonds is shown in Fig. 1.

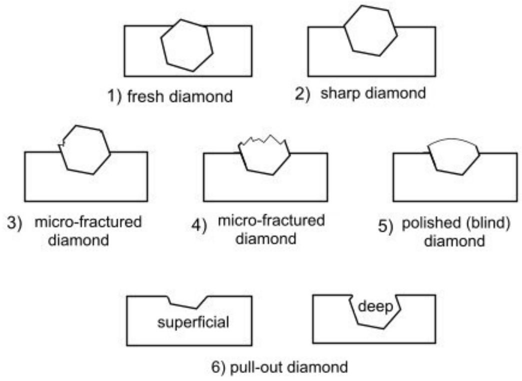

Figure 1: Diamond wear classification

Liao e Luo [7] concluded that increased force acting on the blade is largely associated with diamonds with polished (blind) surfaces. Since polished diamonds do not contribute to the cutting action, they appear as a wear-resistant surface. An increase in force was observed for segments whose surface had more than 1/3 of diamonds in this state.

3. Experimental

3.1. Materials

In order to assess the segments cutting behaviour, experiments were performed under a given set of conditions: peripherical speed (vp), feed rate (vc) and depth of cut (hc). The tests were performed with discs with an external diameter of 400 mm on 100 mm x 60 mm x 2 mm Pink Porriño Granite slabs. Each test reference comprises the working parameters “vc-vp-hc” (mm/s - m/s - mm). Discs contained 28 segments brazed to the steel rim. Each segment of the cutting blade initially had the following dimensions: thickness (equivalent to the width of the cuts) = 3.8 mm; length = 34 mm and height = 8 mm.

Two discs of each type of segments were produced. The surface of the segments was analized using the Dino-Lite Edge Digital Microscope AM7515MZT digital camera and their mass was measured with the RADWAG balance, model PS 10100.R2 scale.

The testing facility (cutting machine including data aquisition software) allowed full control of the working parameters while all the necessary outputs were monitored and stored by a software developed at I.S.T (Fig. 2).

Figure 2: General view of the equipment used to perform the cutting tests.

During the tests the following outputs were analysed: the resulting force (F_r) generated by the contact between the tool and stone slab and the weight loss resulting from wear of the cutting tools.

3.2. Cutting Test Procedure

Experiment Design [DoE] was used to obtain a representative basis of comparison between the cutting behavior of the segments. In this regard, it was important to vary the process inputs to create different test conditions in order to assert that the results were not only valid in a controlled situation, but in a range of tested values.

The parameters used in the cutting tests for the 4 discs are presented in table 1. The $HP1$ and $MW1$ tool segments were produced by hot pressing and microwave, respectively. The direct comparison of the results obtained enable comparing the 2 production processes. The second tools of each process ($HP2$ and $MW2$), when compared to the first, allowed to have a sense of the variation of each process.

Table 1: DoE for the tools $HP1$, $MW1$, $HP2$ e $MW2$

vc [m/s]	vp [mm/min]	hc [mm]
30	30	18
38	30	18
22	30	18
30	20	18
30	40	18
30	30	9

A simplified formula for calculating the equivalent chip thickness removed by a diamond particle is:

$$h_{eq} = \frac{h_c * v_c}{v_p} \quad (1)$$

where (h_{eq}) is the equivalent chip thickness, hc is the depth of cut, vc is the feed rate and vp is the pheripherical speed.

4. Results & Discussion

4.1. Stone Characterization

During the course of this study, the characterization of the stone used took place and the values obtained were: density (2,625 g/cm^3), Young's modulus (E=59,34±13,38 GPa) and fracture toughness (K_{IC} at 0,015 mm/min = 0,77±0,11 MPa$\sqrt{m}$ e K_{IC} at 15 mm/min = 0,74±0,19 MPa$\sqrt{m}$).

4.2. Mass loss

The tools were weighed before and after 33 or 66 cuts (depending on the test). Then the average mass loss was calculated according to the equation:

$$\Delta m = |mi - mf| \quad (2)$$

Where $\triangle_m$ is variation of mass; mi inicial mass (before the cutting test) and, mf final mass (after the cutting test).

It seems that the wear of HP tools is slightly higher than that of their MW counterparts (Table 2).

Table 2: Average and standard deviation mass loss values obtained for HP and MW tools after 66 cuts

Test	Tool	mean [g]	stand.dev. [g]
30-30-18	HP	7,95	0,78
	MW	8,05	0,64
38-30-18	HP	8,45	0,78
	MW	7,95	0,35
22-30-18	HP	5,05	0,92
	MW	4,05	0,21
30-20-18	HP	6,30 •	1,70
	MW	6,05 •	0,78
30-40-18	HP	3,40 •	0,42
	MW	2,90 •	0,00
30-30-09	HP	2,60	0,28
	MW	2,20	0,14

• for 33 cuts instead

4.3. Resultant Force

4.3.1 Variation of feed rate

In this research work the performance of each disc was observed along the cutting operation involving a area of cut up to 329 linear meters, which using an average cutting depth of 18 mm, is equivalent to 5,922 m^2.

As a result, data was collected and treated in order to obtain a graphic of the resultant force (Fr) as a function of the cutting area, as shown in figure 3.

In the first square meter of cutting area, there is a constant increase in the Fr with increasing area of cut. This first phase was observed for all discs, showing an almost linear relationship between Fr and the cutting area. However, this initial behavior is not repeated over the remaining cuts for the same tool, so it does not properly reflect the performance of the cutting discs. This is why the resulting force values are not represented in Fig. 3.

When tool production is complete, the segments are polished so that they all have the same dimensions. Due to this operation, the first layer of the segments, which come into contact with the rock, do not have sharp diamonds.

Since the matrix is not protected by protruding diamonds, it worns off more easily, requiring less resultant force. The constant increase in force is due to the appearance of diamonds at the cutting surface (figure 4).

Data in Fig. 3 (vc=30mm/s, vp=30m/min and hc=18 mm) shows the range of resulting force variation for each disc under investigation. Microwave

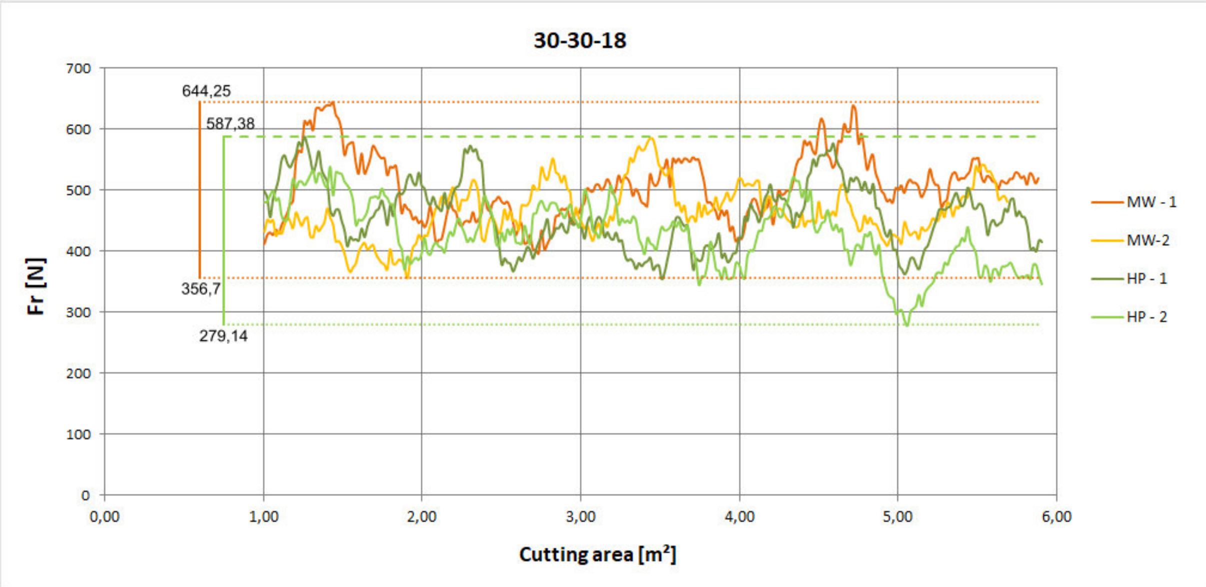

Figure 3: Resulting force as a function of cutting area in test vc=30mm/s, vp=30m/min and hc=18 mm for all tools

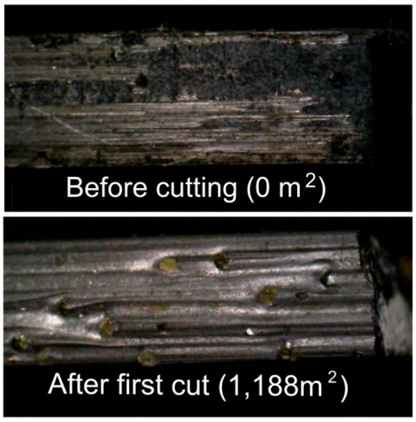

Figure 4: MW1, segment 2' tool contact surface, before and after first cut, in test 30-30-18

tools showed a resultant force value 8% higher than that obtained for hot pressed tools. Higher resultant force values translate to lower cutting efficiency.

This was the only test that presented higher MW tool wear over HP.

When the cutting parameters were vc=38mm/s, vp=30m/min and hc=18 mm (Fig. 5), MW tools showed a resultant force value 19% higher than hot pressed ones. The highest and lowest values of resultant force, respectively, were 538,1 N and 334,7 N for HP tools and 612,9 N and 386,5 N for MW tools.

For the test with vc=22mm/s, vp=30m/min and hc=18 mm (Fig. 6), MW tools have a resultant force value 29% higher than HP tools. The highest and lowest values of resultant force, were 640,3 N and 293,95 N for HP tools and 931,35 N and 475,82 N for MW tools, respectively.

The use of a higher feed rate resulted in faster layer renewal, thereby a higher tool mass wear was observed. The active diamonds were not used to their full potential because their life in the tool surface was shorter than at lower speeds. Diamonds detached faster from the matrix, never displaying polished crystals, thus, reducing oscillation of the resulting force values. For lower feed rates a greater oscillation of resulting force values was observed. Therefore a lower tool mass wear was observed. Since the process was less severe, the diamond goes from a free-cutting to a less efficient cutting action, because it is worn until the crystal shows a flattened (polished) surface.

Nevertheless, for all feed rates investigated, on average, MW tools had higher resulting force than HP ones.

4.3.2 Variation of peripherical speed

In tests with a feed rate of 30 mm/s and a depth of cut of 18 mm for, peripheral speeds of 20 (figure 7),30 and 40 (figure 8) m/s, respectively, the resulting force for the MW tools was 32%, 8% and 7% higher than the values obtained for the proproduced by hot-pressing.

Hot-pressed tools have the lowest resulting force values and highest mass loss. These two observations can be related. Since MW tools have diamonds with greater bonding to the matrix, those can remain on the surface of segments longer, becoming polished and contributing to the increase of resulting force while protecting the matrix from wear.

The behavior observed at the beginning of the graph presented in figure 8 is related to the change

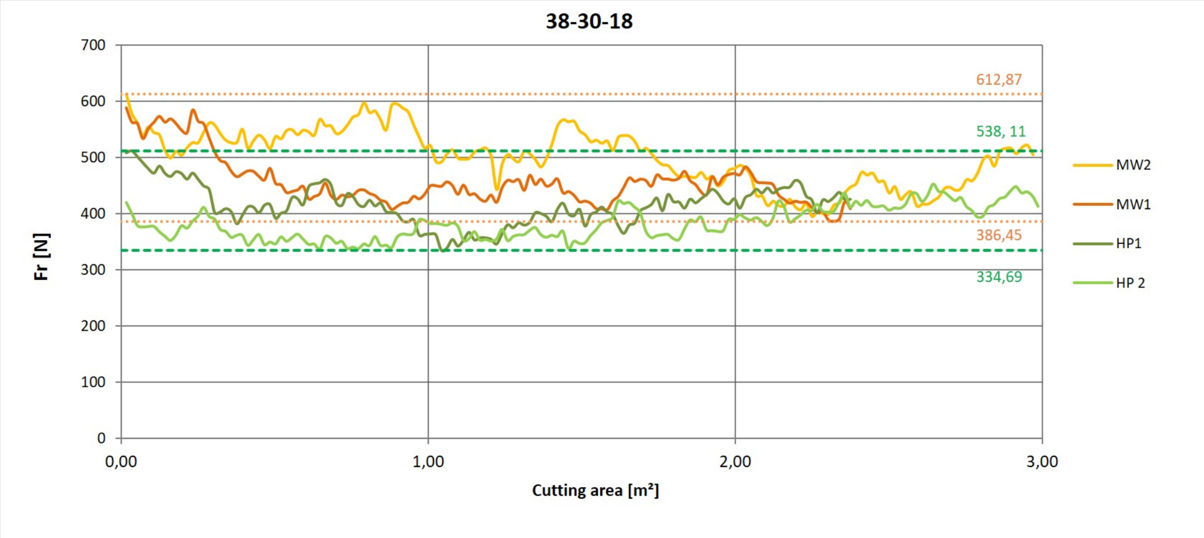

Figure 5: Resulting force as a function of cutting area in test vc=38mm/s, vp=30m/min and hc=18 mm for all tools

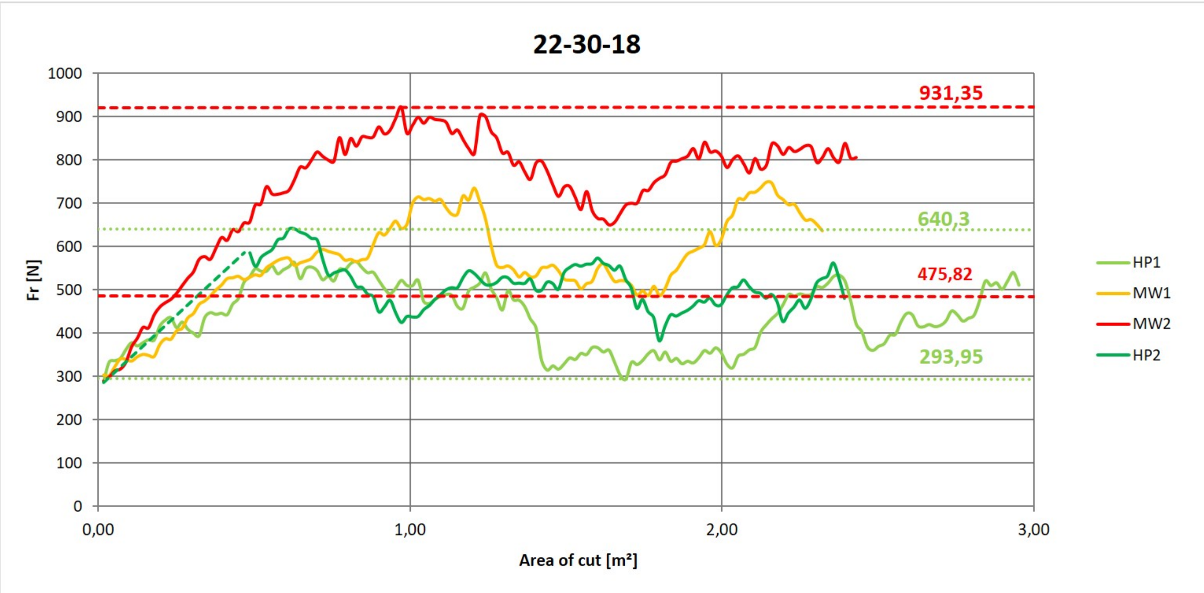

Figure 6: Resulting force as a function of cutting area in test vc=22mm/s, vp=30m/min and hc=18 mm for all tools

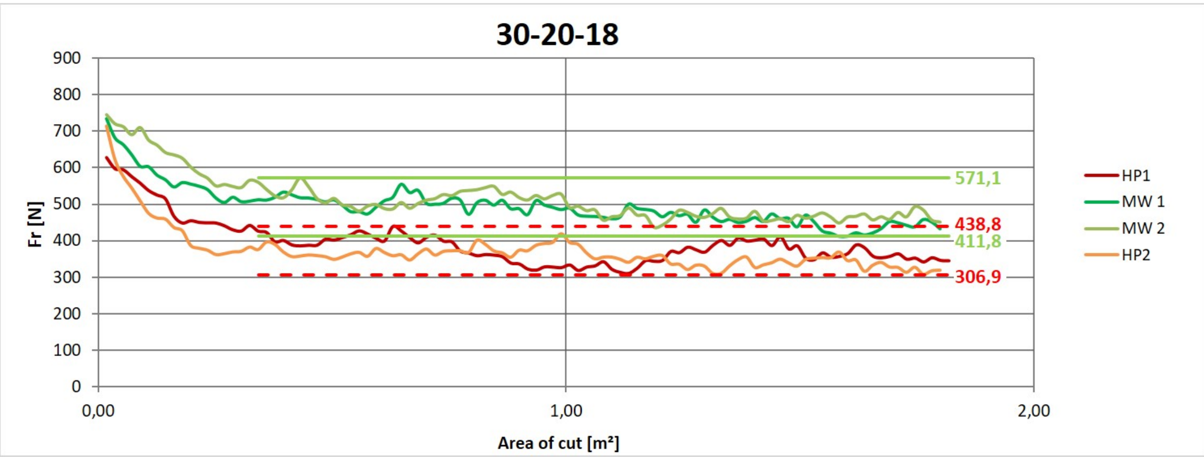

Figure 7: Resulting force as a function of cutting area in test vc=30mm/s, vp=20m/min and hc=18 mm for all tools

in cut severity.

When there is a change in working conditions that results in a increase in the cutting severity (e.g. increase of feed rate or decrease of peripheral speed), the resulting force values at the beginning of the new test show higher values followed by a downward trend until reaching a steady behaviour. In contrast, the decrease in severity (decrease of feed speed, increase of peripheral speed and decrease of depth of cut) initially presents a resulting increase in Fr.

Therefore, the initial behaviour of the tool is related to the wear of the remaining layer that was subjected to the previous test conditions. Only after this initial state can the performance be affected by the new parameters being used.

The decrease in peripheral speed resulted in increased cutting severity. Therefore a higher tool mass wear was observed, which also resulted in a greater dissonance between the results of different manufacturing processes. That is, for the peripheral speed of 20 m/s there was a clear trend of resulting average force values for HP tools lower than that recorded for MW tools.

4.3.3 Variation of depth of cut

The use of smaller depth of cut induces less material removal and requires less resulting force for cutting work. Since work is less severe, less tool wear occurs.

Also, when using smaller depths of cut values, less material is removed and it is necessary to cut more granite slabs in order to achieve renewal of the surface layer of the segment. As a consequence, the rate of fresh diamond appearance is lower. The diamonds already present in the surface of the segment reach polished surface state. That is why when observing the graph shown in Fig. 9, it is clear a resulting force increase with increasing of cutting area.

When the worned diamond detach from the matrix, the resulting force decreases, because the matrix is exposed to wear.

The average resulting force of the microwave tools recorded at feed rate 30 mm/s, peripheral speed 30 m/min and depths of cut 18 and 9 (figure 9) mm, respectively, was 8% and 17% higher than those produced by hot pressing.

4.3.4 Variation of parameters

It seems that the resultant force of MW tools is slightly higher the HP ones (Table 3).

Table 3: Average and standard deviation resultant force values obtained for HP and MW tools after 66 cuts

Test	Tool	mean [N]	stand.dev. [N]	$\triangle_{\mathrm{Fr}}$
30-30-18	HP	444,7	74	
	MW	480,0	68	8%
38-30-18	HP	399,1	36	
	MW	478,8	51	19%
22-30-18	HP	474,7	76	
	MW	707,1	81	29%
30-20-18	HP	365,7	39	
	MW	484,1	35	32%
30-40-18	HP	390,5	49	
	MW	416,5	76	7%
30-30-09	HP	311,2	40	
	MW	365,5	78	17%

were $\triangle_{\mathrm{Fr}} = \frac{MW-HP}{HP}$x100

5. Conclusions

Using a higher feed rate resulted in faster layer renewal, which lead to reduced oscillation of the resulting force values and an increase of tool wear.

The decrease in peripheral velocity resulted in increased cutting severity, which lead to increased tool wear. Also, the dissonance between the results of different manufacturing processes was more easily observed.

The use of smaller depth of cut induced less material removal and requires less resulting force for cutting work. Since work is less severe, less tool wear occurs.

Hot-pressed tools have the lowest resulting force values and highest mass loss. These two facts can be related. Since microwave tools have diamonds with greater bonding to the matrix, those can remain on the surface of segments longer, becoming polished and contributing to the increase of resulting force while protecting the matrix from wear.

Although it is at an early stage of scientific study, this technique already demonstrates, by means of this study, a small difference of results relative to the segments made by hot pressing regarding the performance of cutting ornamental stones.

Under conditions vc = 30 mm / s, vp = 40 mm / min and hc = 18 mm, the smallest difference in force values between 2 tools (MW 7 % higher than HP) was recorded. In the greatest force difference attained (vc = 30 mm / s, vp = 20 mm / min and hc = 18 mm) MW has values 32 % higher than HP.

On average, HP tools worn out more than MW ones. The difference in tools mass loss ranges from 1 % to 20 %.

Considering also its economic advantages, the data from this study point to this method being able to compete with the currently used manufacturing processes.

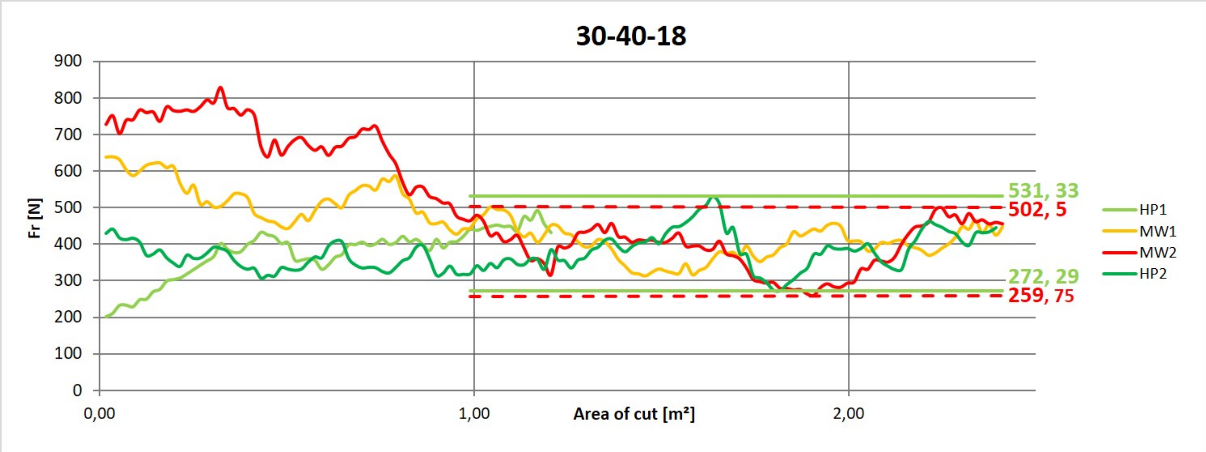

Figure 8: Resulting force as a function of cutting area in test vc=30mm/s, vp=40m/min and hc=18 mm for all tools

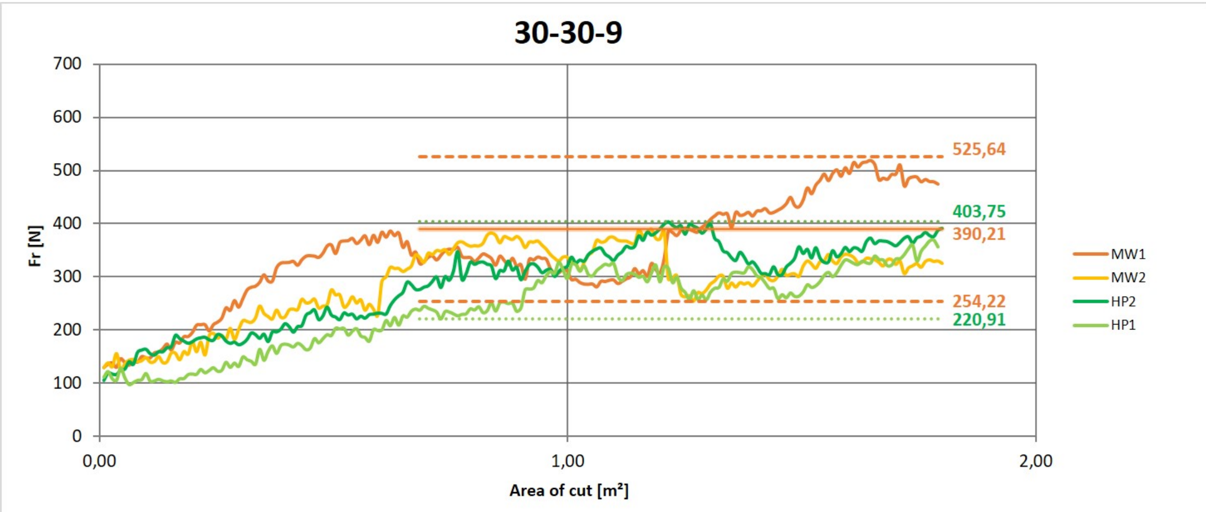

Figure 9: Resulting force as a function of cutting area in test vc=30mm/s, vp=30m/min and hc=9 mm for all tools

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