Machining of Warm Compacted P/M-parts in Green State

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ABSTRACT

Powder metallurgy (P/M) is known for producing complex parts to very close tolerances.
Due to technical limitations some parts are too complex to obtain, with regard to the final shape, merely with applying P/M technique. When P/M-technique is inadequate a secondary operation is a possible way to achieve the desired shape. Machining of sintered parts is comparatively well known but nevertheless, in some cases, a demanding operation due to sintered properties. However, machining of green parts often fails due to poor properties of the compacts (e.g. strength). Warm compaction is one way to achieve the necessary strength, without the disadvantage due to sintering. The following report summarise the experience of green drilling when using two warm compacted powder materials, D. AE + 0.5%C and Astaloy CrM + 0.5%C.

1. INTRODUCTION

Green machining, i.e. machining of as-compacted P/M parts, is a conceivable way to produce a desired shape or, more correctly, modification of a compact form, when the powder compaction method alone is insufficient or, when machining of sintered parts are difficult or even impossible. Cutting and chip removing operations, like turning, milling and drilling, are operations within the field ”Green machining”.

2. THE MAIN FEATURE OF THE INVESTIGATION

The primary purpose of the investigation is to find, if they exists, correlations between the quality of through holes and a number of input parameters as well as investigate the endurance of drills. The parameters that are considered are type of powder material, the green density of the compacted specimens, cutting parameters and drill type. The hole quality is defined by the surface finish as well as by the edge integrity.

Powder materials and warm compaction

The two metal powders that are used in the tests are D. AE and Astaloy CrM (Table I). D. AE consist of very pure iron powder to which finely divided alloying elements have been diffusion bonded. By adding graphite, a very high strength is obtained with D. AE after sintering. Astaloy CrM is a water atomized iron powder, pre-alloyed with chromium and molybdenum. Astaloy CrM is also added with graphite which results in a very high strength and hardness after sintering. Both powders are made as Densmixes, a mixing-technique for warm compaction powder to which 0.6% lube is added.

Table I. Contents of alloying elements

Material	Cr [%]	Ni [%]	Cu [%]	Mo [%]
D. AE + 0.5%C	-	4.0	1.5	0.5
Astaloy CrM + 0.5%C	3.0	-	-	0.5

Two types of geometries are warm compacted. Specimens with a geometry Ø80 mm (discs) and pressed height of 12 mm are used in drilling experiments and bar specimens 90x12x6 mm (LxWxH), also in green state, are used to evaluate green strength (three point bending test). During warm compaction the temperature of powder, filling devices and tools are kept at 130ºC. Specimens are made with two different densities per each powder. Test name are used in the study to characterise both types of powder and the respective density levels (**Table II**).

Table II.

Internal test name	Material	Compaction pressure [MPa / Tsi]	Density [g/cm³]	Green strength [N/mm² / Psi]
D +	D. AE + 0.5%C	700 / 50.4	7.30	27 / 3915
D -	D. AE + 0.5%C	540 / 38.9	7.15	25 / 3625
A +	Astaloy CrM + 0.5%C	800 / 57.6	7.15	30 / 4350
A -	Astaloy CrM + 0.5%C	650 / 46.8	7.00	27 / 3915

Drills

All test drills are Ø5 mm. By choosing drills (Table III) with different geometry and substrates, the influence of these differences can be observed in the drilling results. The drills have been recommended by their suppliers who, of course, have been informed about the material to be machined.

Table III.

Internal test name	Manufacturer	Code	Standardisation	Point angle	Material	Surface treatment
Dss130	Dormer	PFX A927	DIN 1897 R	130º	HSCo	Brightened
Djs130*	Dormer	PFX A907	DIN 338 R	130°	HSCo	Brightened
Tjs118**	Titex	A 1211	DIN 338, Type N	118º	HSS	Steam oxided
Tsc118	Titex	A 1163	DIN 6539, Type N	118º	HM (K10)	None
Tsc130***	Titex	A 1163	DIN 6539, Type N	130º	HM (K10)	None

*) Only used in endurance test (wear test)

**) Only used in the test with D + (D. AE with density 7.30 g/cm³)

***) Originally a Titex A 1163 with point angle 118º. Special grinded to achieve point angle 130º

The drill Tjs118 is an ordinary standard high speed steel drill. It was only used in the experiments with the material D +. The drills Dss130 and Djs 130 are also high speed steel drills, yet with some more complex, sharpened point geometry compared to the basic standard. These two drills have the same geometry apart from the 24 mm longer overall length of the Djs130. The two solid carbide drills, Tsc118 and Tsc130, are based on the same drill model, the drill Tsc118. The drill Tsc130 is produced with an additional grinding step to achieve a point angle of 130º. Both solid carbide drills are fabricated with a sharp point geometry. The exact shapes of all drills can be seen in the producer catalogues.

Test equipment and cutting parameters

All drilling tests were executed with a CNC milling machine (MAHO MH 500 W). With a separate high speed spindle, connected to the mill, the cutting speeds of 80 and 120 m/min could be reached.
The cutting parameters are chosen according to an earlier test [1]. Table IV shows the cutting speeds and feeds. Three cutting speeds and four feeds results in a total of twelve different combinations of cutting parameters.

Table IV.

Cutting speed, v_c [m/min]	Feed, f [mm/rev]
40	0.025
80	0.05
	0.1
120	0.2

During the tests, the axial force (Fz), and torque (Tz), in drill feed direction, were measured with a 2-component dynamometer (Kistler, type 9271A). In the following some of the results are presented.

3. QUALITY TEST

In the quality test the edge integrity and surface finish were investigated. A number of 16 through holes, distributed as a 4 x 4 matrix, were drilled on each Ø80 mm disc. With each feed rate eight holes were drilled. Therefore, when using four different feed rates, two discs were used with the same drill type and the same cutting speed. The drilling operation started with the lowest feed rate and ended with the highest. Figure 1 shows the order, from the first hole to the last, per disc. The force and torque measuring took place when hole #6, #7, #10 and #11 were drilled into the discs. For each new combination of material and density that was tested, a brand new drill was used. All materials (D +, D -, A – and A +) were tested with the drills Dss130, Tsc118 and Tsc130 with a sharp point geometry and a short overall length. In additional reference test the performance of a standard 118º high speed steel drill Tjs118 was investigated with material D+. This gives an overall number of 156 experimental combinations of materials, drills and cutting parameters tested in the quality tests

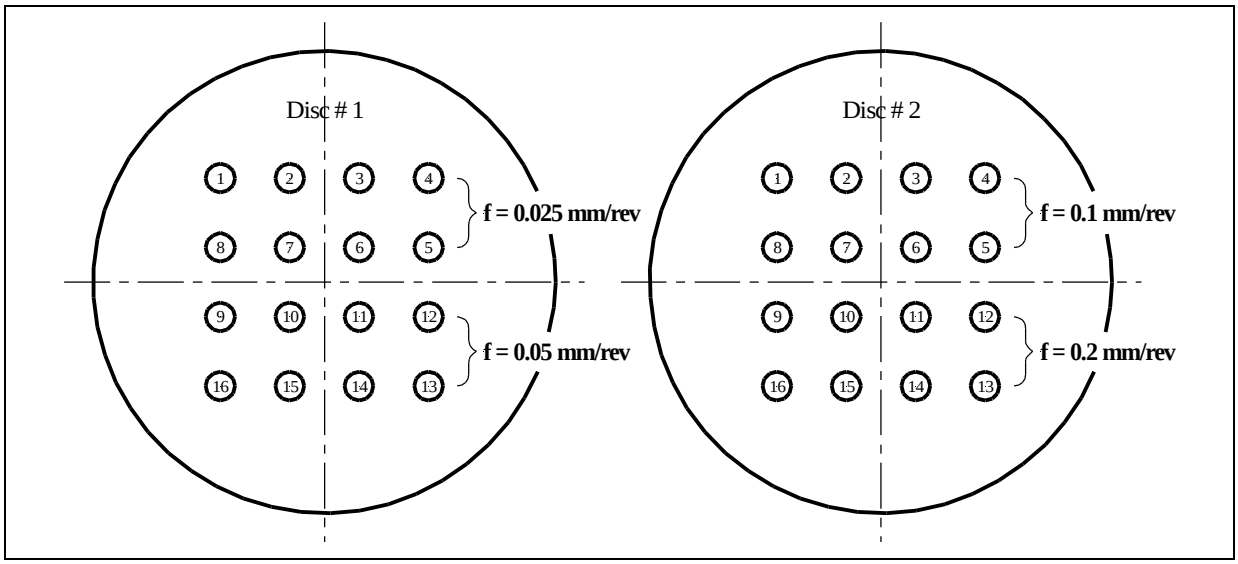


Figure 1: Drilling layout. Numbers 1 to 16 describe the numerical order of the drilling operations.

Force and torque

The diagrams in figure 2 shows the increase of the axial force and torque as depending on the feed rate, with the four different feed levels between 0.025 and 0.2 mm/rev. Both, the axial force and the torque, increase steadily with increasing feed level. Thus, the highest output values correspond with the highest feed rate.

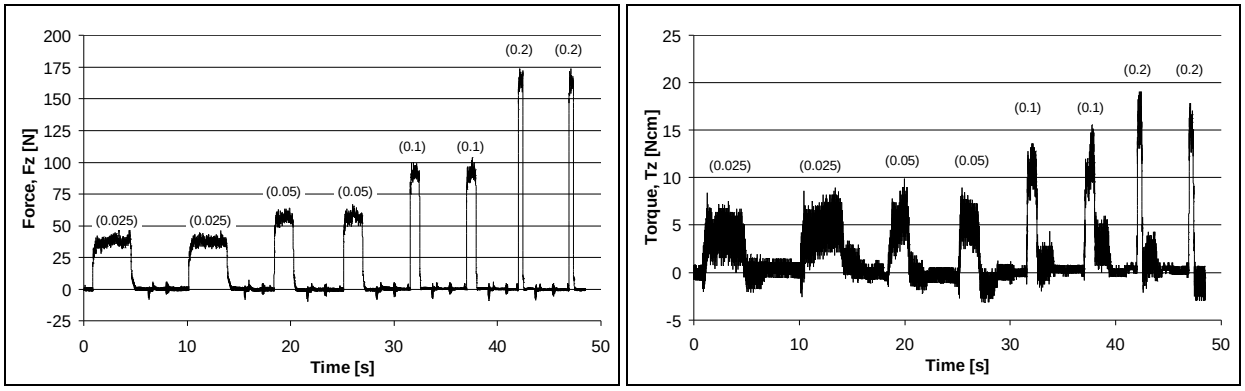


Figure 2: Measured force (left) and torque (right). Tsc118, v_c = 120 m/min, f = 0.025 – 0.1 mm/rev. Powder material D +.

In figure 3 the results of the force and torque measurements of all 156 different input parameter combinations are plotted vs. the feed rate. A clear correlation is found between feed rate and force as well as between feed rate and torque, no other influence regarded. Yet, at all feed levels the data points scatter in a wide range. A position at the lower end means that force and torque are comparatively low. In this case a good drill performance can be expected. In low positions the results of the two solid carbide drills dominate.

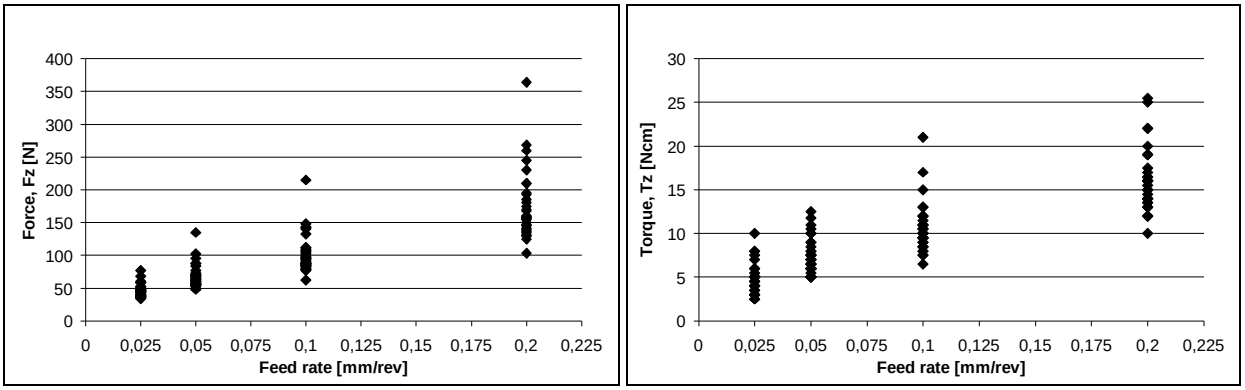


Figure 3: Correlations between feed rate and force (left) and feed rate and torque (right)

Edge integrity

In a through hole drilling operation there are two particular critical moments. The first one is when the drill tip is entering (creating an inlet edge) into the material. The second one is when the drill tip is leaving (creating an outlet edge) the material, on the other side of the disc. Both, the entering and the leaving, produce more or less damaged edges. To estimate the defect dimensions at the edges, the holes are scanned with a contour measurement machine (Mahr Contouroscop C4P). The measuring can be done without cutting the disc apart. Figure 4 shows, as an example, a contour found during a scanning.

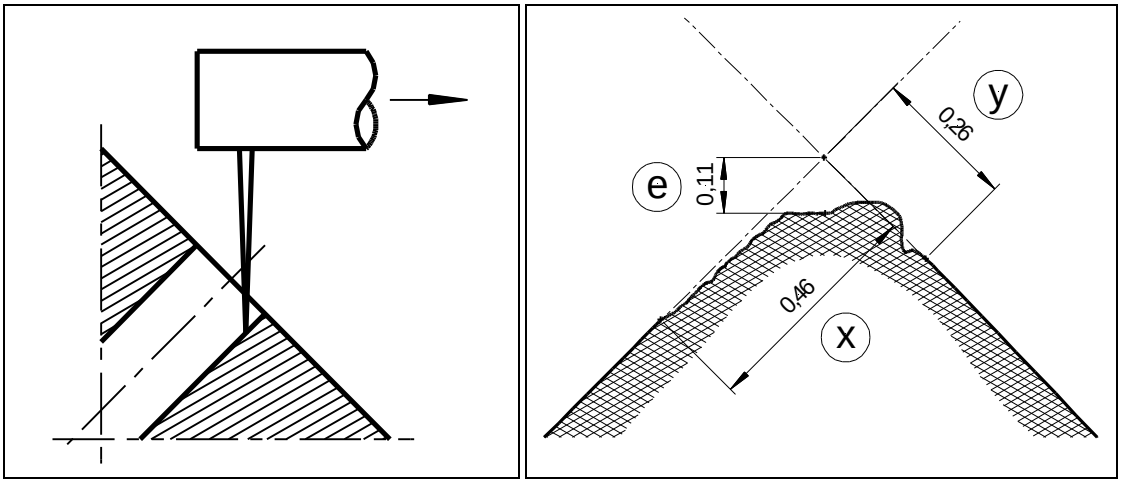


Figure 4: Left picture: Schematic principle of scanning edge integrity with probe (needle).
Right picture: Breakout values of an inlet edge (D +, Tsc118, v_c = 120, f = 0.025)

As this example proves , the appearance of the occurring damages shows a very irregular contour that in most cases consists of a combination of breakouts and burrs. Since it is impossible to describe such defects by considering just one axis, three values were measured for their characterisation; the length of breakout on the face ”y”, the length of breakout inside hole ”x”, and the depth of breakout in the edge direction ”e”. While the depth of the breakout can be measured easily, a rule had to be established for the determination of the lengths of breakout. Both lengths of breakout were measured at the first intersection between the scanned contour and the unaffected shape of the surface. At each of the eight holes, drilled with a specific combination of material, drill type, and cutting parameters, the three defect dimensions were measured at the positions with the largest length of breakout on the face. The result were summarised to averages. The mean values calculated in this way are actually averages maxima.

In figure 5 the breakout dimensions ”y” and ”e” are plotted, for both, the inlet and the outlet edges, vs. the breakout dimension ”x” for all 156 different combinations of the input parameters. Especially between ”x” and ”e” a close correlation is visible, whereas some of the "y" values deviate significantly from a close correlation. Most of the "y" values far beyond a imaginary correlation line were measured in the experiments with the drill Tjs118. These results prove that, generally, the breakouts can be described in a qualitative way by considering just one axis.
In most cases the corresponding ”inlet x” and ”outlet x” are of the same size, while both the ”inlet y” and ”inlet e”, in majority, are smaller than the corresponding values on the outlet side.

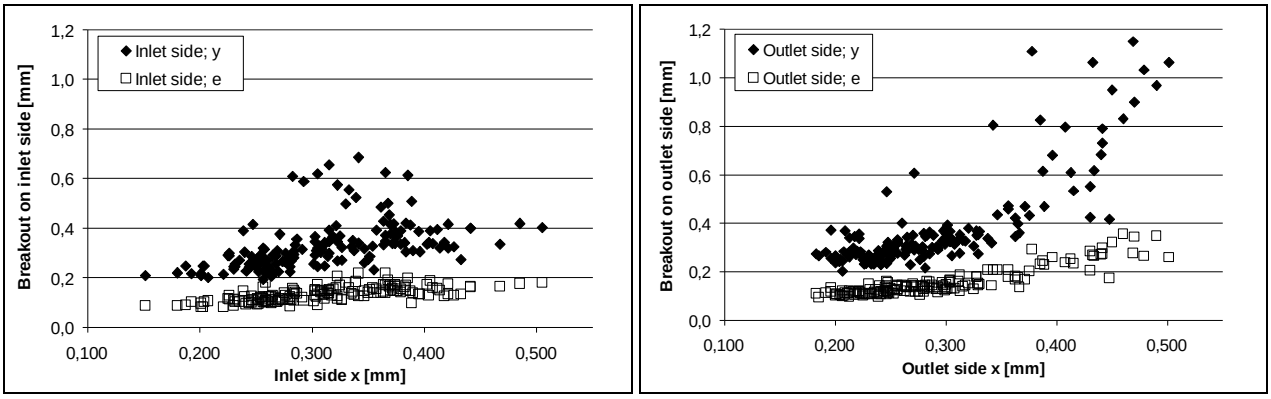
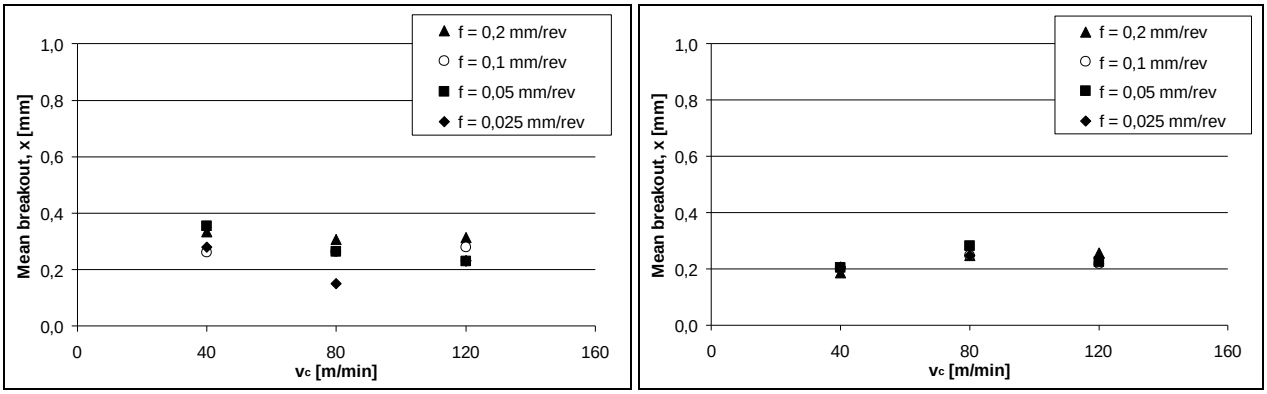


Figure 5: Correlation between x-values vs. y- and e-values for inlet side (left) and ditto outlet (right).



Inlet side Outlet side

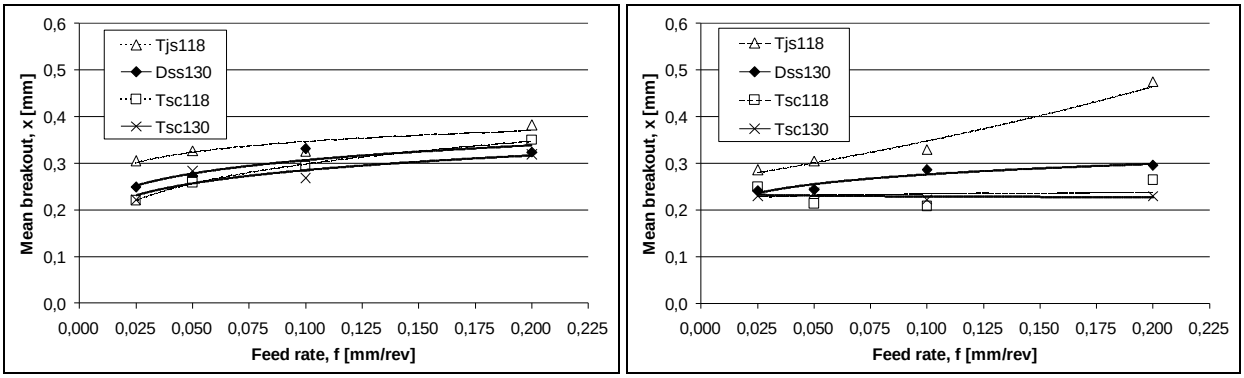
Figure 6:Breakouts at the in- and outlet edge "x" vs. cutting speed at different feed rates when using Tsc130 and the material D +.

Figure 6 shows the results of the breakout measurements at the inlet and outlet edges (only for the x-value) as depending on the cutting speed and the feed rate for the material D+ and the drill Tsc130. The influence of the cutting speed is unspecific. At all cutting speed levels the results scatter more or less over the range of standard deviation. The cutting speed itself seems to have no influence on the breakouts.

For all the other combinations (not shown in this report) of material, densities, drills and cutting parameters the patterns are similar, yet with some exceptions. Especially with the high speed steel drills, the results at different cutting speeds sometimes deviate significantly from each other. One imaginable reason is the order in which the cutting speeds were investigated during the tests with the same drill. The later on presented results of the endurance tests make clear that the performance of high speed steel drills deteriorates rapidly right from the drilling of the first holes.

In contrast to the cutting speed, the feed level has an significant influence on the breakout sizes with some of the drills. When the feed rate is increased a tendency towards increased breakouts can be observed with these drills. To point this out more clearly the mean values calculated as described before were summarized once again to cutting speed independent general mean values for each combination of material and drill type. In figure 7, the average x-values calculated in this way are plotted for the four drill types Dss130, Tjs118, Tsc118 and Tsc130 and the material D + vs. the feed.

With regard to the correlation lines in the diagrams in figure 7 and to the results of the other materials (not shown in this report) the two most influencing input parameters can be identified. These are the drill type, characterised by the material and the geometry, and the feed. On both, the inlet and the outlet sides, best edge integrity is obtained with the two solid carbide drills. Both high speed steel drills produce significantly larger breakouts, with the worst results achieved by the standard drill Tjs118. The influence of the feed rate differs in dependence on the drill type. With both high speed steel drills the breakout sizes increase at both edges with increasing feed level. When the solid carbide drills are used only the inlet edge integrity deteriorates with increasing feed level, whereas no feed influence is observed at the outlet edges. Regarding the results of all materials no significant difference was found between the two solid carbide drills.



Inlet side Outlet side

Figure 7: Breakouts at the in- and outlet edges "x" vs. feed rate with regard to the drill type. Powder material D +.

For getting an impression of the influence of the material, it was evaluated how many of the 10 (20, 30, 40) smallest breakouts occurred with D. AE and with Astaloy CrM, respectively, without differentiating between densities and independent of the drill type used. Table V gives an overview of the values arranging the breakout results according to the breakout dimensions formerly introduced. The test results with the drill Tjs118 have been left out of this evaluation so that the number of experiments is equal for both materials, 72 tests each. As the values show the material type appears to have some influence. There are more small breakouts with D. AE than with Astaloy CrM.

The same kind of evaluation with an additional differentiation of the results according to the density levels did not show any differences between the density levels investigated, neither for type D.AE nor for type Astaloy CrM.

Table V. Number of smallest breakouts with D. AE

D. AE	Number of breakouts up to N			
Breakout place	N = 10	N = 20	N = 30	N = 40
Inlet side, x	7	14	20	27
Inlet side, y	7	17	20	28
Inlet side, e	8	14	20	25
Outlet side, x	7	14	22	28
Outlet side , y	7	15	22	29
Outlets side, e	9	18	22	28

Surface finish

To measure the surface finish inside the holes, the test specimens Ø80 were sawed through. Mean roughness (R_a), roughness depth (R_z), peak height (R_p) and waviness height (W_t) were measured. The surface finish was measured for every tested combination (material, density, drill and cutting parameters). The cutoff, the sampling length and the evaluation length were chosen as to comply with the specifications of DIN EN ISO 4288; the values used are listed in table VI.

Table VI.

Definition	Value
Cut-off, λ_c [mm]	0.8
Sampling length, l_r [mm]	0.8
Evaluation length, l_n [mm]	4

The correlation between the surface finish parameters, shown in figure 8, is close, especially between R_a, R_z and R_p. All parameters are equally well suited to describe the surface finish quality.

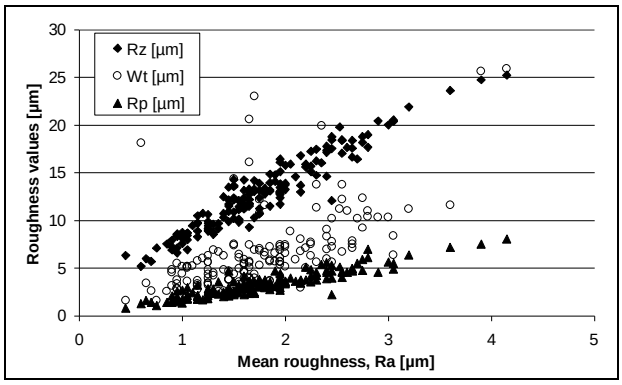


Figure 8: Correlations between R_a vs. R_z, R_p and W_t.

The same kind of evaluation that was carried out for interpreting the influence of material on the breakout size (see Table V), was used for the interpretation of the surface finish results. The output value Ra (and the other surface finish values for that matter) was taken as reference parameter. The result obtained by this procedures of counting smallest values is that the feed rate is the most influential input parameter. The cutting speed, on the other hand, does not seem to have any effect.

In figure 9 the surface finish parameters are plotted for the four drill types Dss130, Tjs118, Tsc118 and Tsc130 and the material D+ vs. the feed. The data points in the diagrams are cutting speed independent general mean values, calculated in the same way as the general mean values in the breakout vs. cutting speed diagrams.

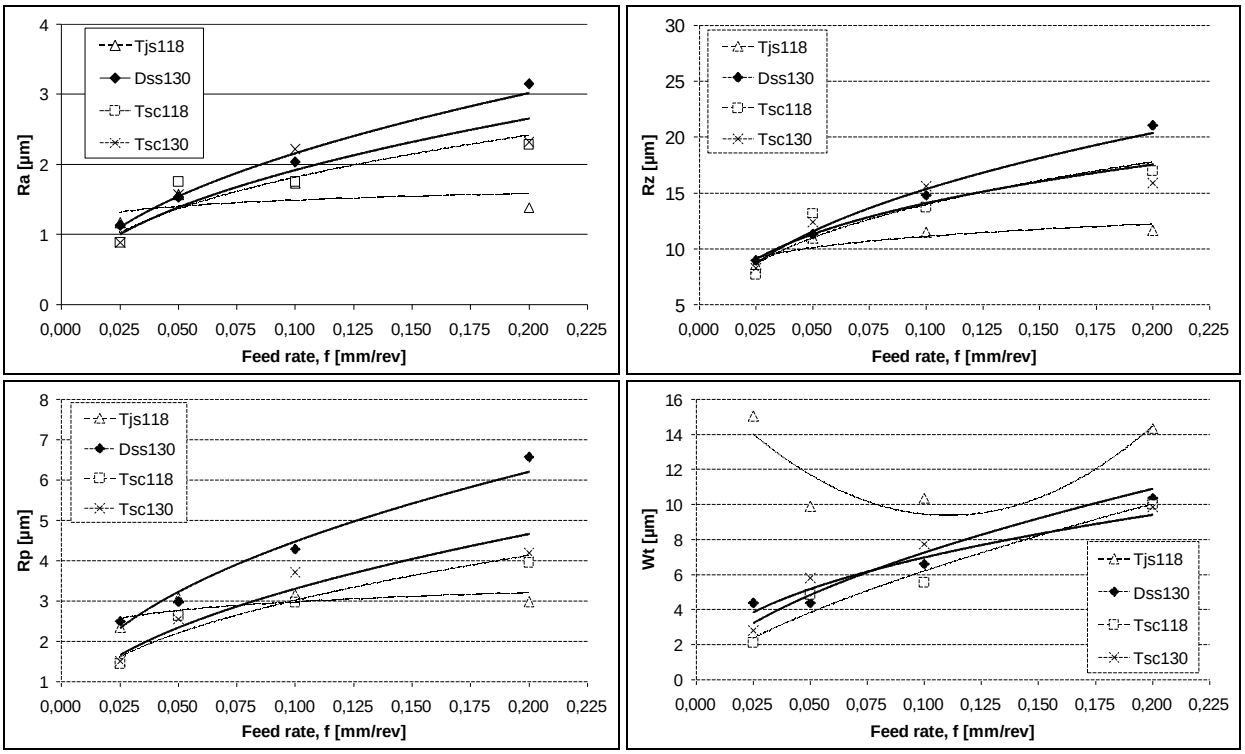


Figure 9: Surface finish inside hole vs. feed rate and drill type. Powder material D + .

As explained before, the feed rate is the most influential input parameter. With all drill types the surface finish results decrease with increasing feed level. Yet, this effect is, considering the roughness parameters, less pronounced with the standard high speed steel drill Tjs118 than with the other drill types. The better performance of this drill at high feed levels is only apparently so. Considering the waviness parameter, it becomes clear that the smooth roughness profile is overlaid by a clearly worse waviness profile. The surfaces produced with this drill type often show extensive breakouts caused by pull-out of particle agglomerates. These breakouts first of all affect the waviness parameter Wt. The low roughness values with this drill type are obtained at the cost of an unacceptable waviness.
With the three other drills the waviness parameter Wt correlates much better with the roughness parameters. At all feed levels the best surface finish is obtained with the two solid carbide drills, Tsc118 and Tsc130. Best overall results are produced with these drills at the lowest feed level of 0.025mm/rev. Considering the results of all materials, there are no effects of the material or the density on the surface quality.

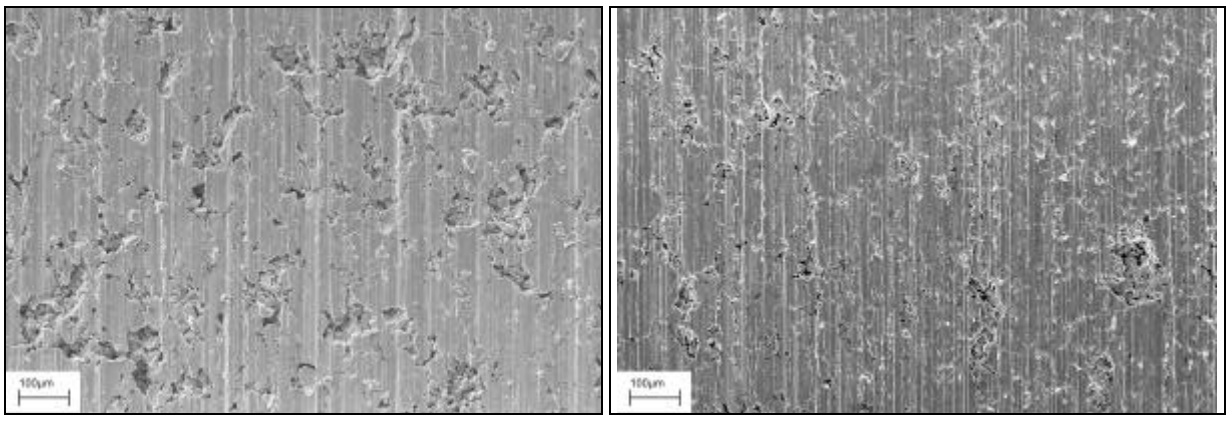


Figure 10: Surface finish inside hole (photo with SEM). Drill Dss130. Feed rate f = 0.2 (left) and f = 0.025 (right). Cutting speed v_c = 80 m/min. Powder material D +.

For getting some additional information about the characteristics of green drilled surfaces the holes were inspected by SEM (Scanning Electron Microscope). Figure 10 gives, as examples, the SEM-photos of surfaces produced at the lowest and at the highest feed level. All surfaces produced by green drilling show pittings due to pull-out of particles or particle agglomerates. The number and the size of these pittings increases with increasing feed level. One reason for this effect could be that the low feed rates produce low axial force and torque (Figure 2). It can be assumed that with these conditions, the risk of particle breakouts inside the hole during the drilling operation is minimized.
A second reason could be that the low feed rates may support a smearing effect that takes place between the periphery of the drill and the surface of the hole. In this case the loose chips and the pulled out particles may have the function of a smearing and grinding material. This could of course also explain the sensitivity of wear observed in the endurance tests when using high speed steel drills.

4. WEAR TEST - ENDURANCE OF DRILL

During the quality tests some observations were made that could be associated with tool wear. It were in particular some of the results with the high speed steel drills that lead to this conclusion. A new and unused drill was used with each combination of powder material and density, but no exchange of drill was made when the cutting parameters were altered. The wear must consequently be regarded as an influencing factor, which may have affected the quality results. A drill with a good performance, for instance, that produces low and stable cutting forces during its lifetime, cuts probably for a long time with satisfactory results, whereas the results obtained with a drill with a lower wear resistance deteriorate much faster.

The endurance of a drill can be evaluated by a continuous drilling test, in which the drills are used with constant cutting parameters. It can be expected that the cutting forces and torques change during the time as a sign of tool wear. The correlation between feed rate vs. axial force and torque has been shown previously (Figures 2 and 3) and the effects of the feed rate on the quality criteria were described in detail in the first part of this study.

Especially for green machining operations, wear tests are very time and material consuming. Thus the tool life behavior could only be tested in a spot check with one of the materials, Astaloy CrM with the density 7.15 g/cm³. Two different drills were chosen; a high speed steel drill Djs130, which is a 24 mm longer version of drill Dss130, and the solid carbide drill Tsc118. A low feed rate (0.05 mm/rev) and a medium cutting speed (80 m/min) were tested.

Forces and torques

In figure 11 the axial forces and torques are plotted for the two drill types Tsc118 and Djs130 vs. the tool life in number of holes drilled. The data points in the diagrams are mean values, each calculated from at least four measurements.

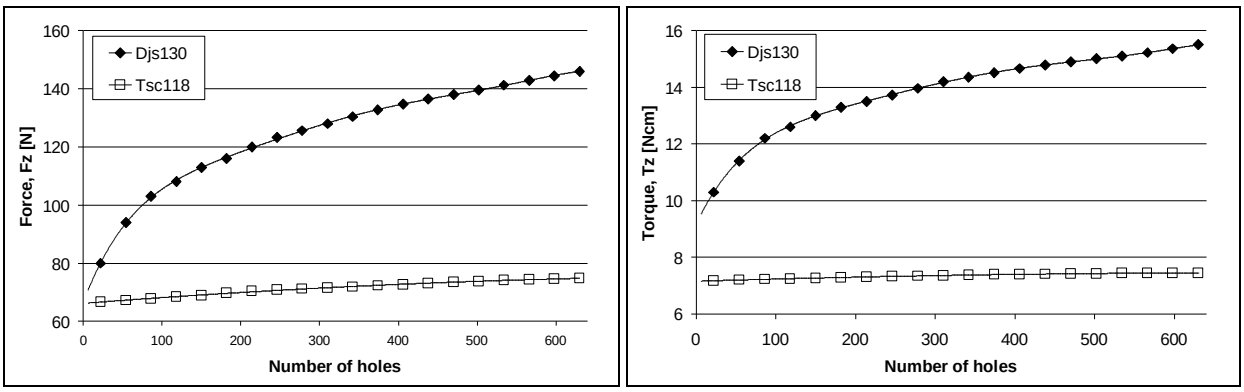


Figure 11: Forces (left) and torques (right) vs. number of drilled holes
Feed rate f = 0.05 mm/rev, cutting speed v_c = 80 m/min. Powder material A+

The axial cutting force and the torque increase rapidly with the high speed steel drill right from the beginning. This behavior implies that damage has occurred in the region near the cutting edges. The corresponding values with the solid carbide drill after the same time of drill engagement, on the other hand, are quite stable and low during the production of all 640 holes.

Surface of drills – the cutting edges

Both drills were examined on several occasions during the wear tests. A number of SEM-photos have been taken from the first drilling operation to the last. Figure 12 gives overviews of the drills Djs130 and Tsc118. In addition, the primary cutting edges of both drills are shown as close-ups in figures 13, 14 and 15, in the condition as delivered, and after the drilling of 320 holes and 640 holes, respectively.

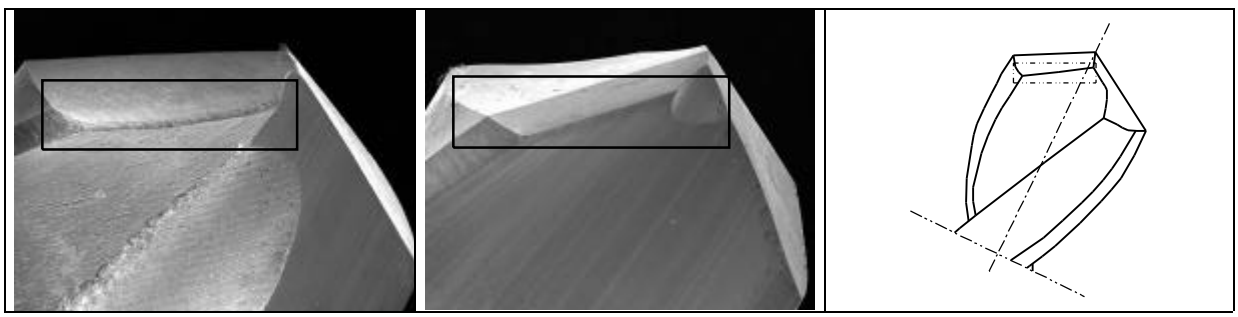


Figure 12:Djs130 (left), Tsc118 (middle) and sketch of drill
with marked position of the close-ups in figures 13 to 15 (right)

On the new Djs130 drill (Figure 13, left) the primary cutting edge looks slightly unsharp, in contrast to the distinct edge on the solid carbide drill Tsc118.

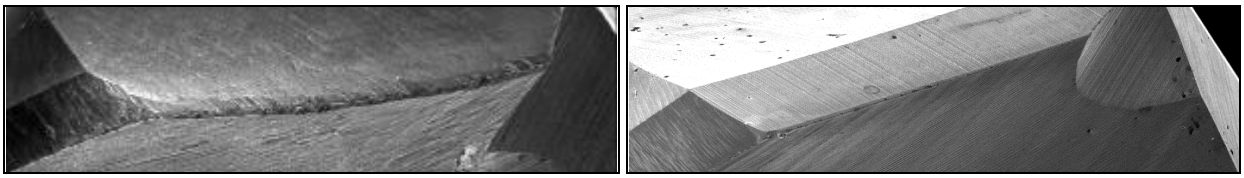


Figure 13: Unused drills. High speed steel Djs 130 (left) and solid carbide Tsc118 (right)

After the drilling of 320 holes (Figure 14) the edge of the high speed steel drill is obviously worn, while no changes occur on the solid carbide drill.

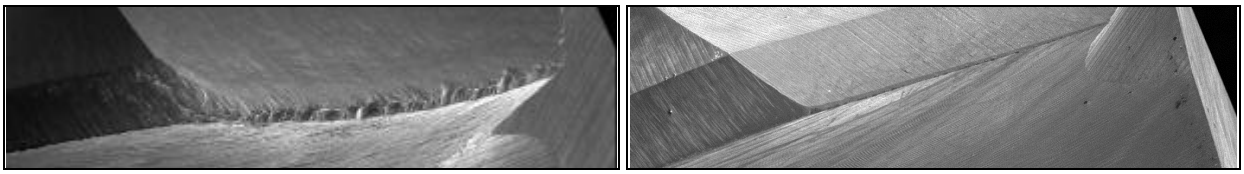


Figure 14: After 320 holes. High speed steel Djs 130 (left) and solid carbide Tsc118 (right)

Finally, after the drilling of 640 holes (Figure 15) when the wear tests are finished, severe chamfer wear and large breakouts can bee seen at the edge of the high speed steel drill (left). Even the periphery is affected. The solid carbide drill shows almost no signs of wear. Probably, small differences could be found, when examining the solid carbide edge with a higher magnification.

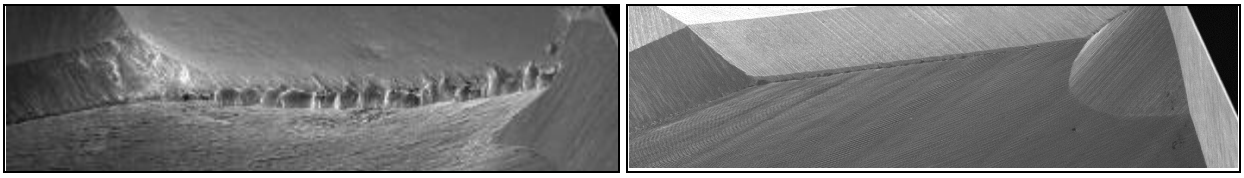
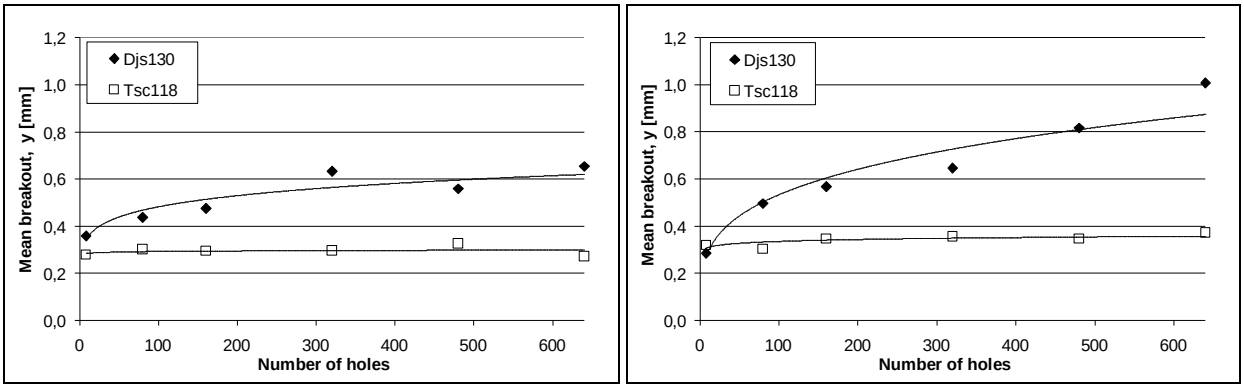


Figure 15: After 640 drilled holes. High speed steel Djs 130 (left) and solid carbide Tsc118 (right)

Edge integrity -surface finish

In a final step the breakout sizes and the surface finish produced at the beginning of the wear tests and after the drilling of 80, 160, 320, 480 and 640 holes were measured.

The results are shown for "inlet y" and "outlet y" in figure 16. The breakout size curves correlate very well with the results of the force and torque measurements. The solid carbide drill produces almost constant edge integrity over the complete length of the test, whereas the breakout sizes increase parallel to the increasing forces and torques with the high speed steel drill.



Inlet side Outlet side

Figure 16: Breakouts, produced by Djs130 and Tsc118, at the in- and outlet edges ”y” vs. drilled holes. Powder material A+

The surface finish (the roughness value Ra), produced during wear test, are shown in figure 17. Surprisingly, the surface finish seems not to be influenced by an increase of wear at the primary cutting edges. Right from the beginning the results are mostly constant with both drill types and even seem to improve at the end of the wear tests. One explanation for this behavior could be that the surfaces inside the holes are much more affected by the condition of the minor cutting edges than by the wear at the primary cutting edges.

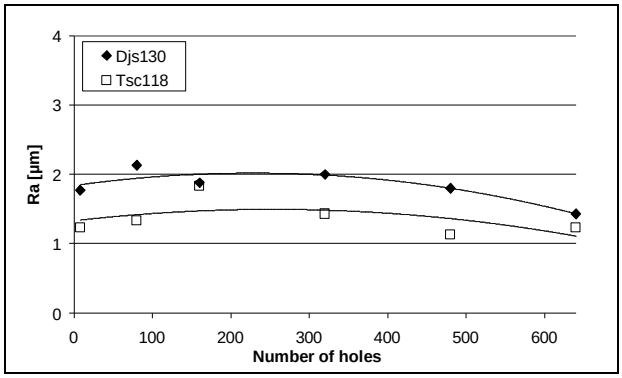


Figure 17. Surface finish, Ra, inside hole, produced by Djs130 and Tsc118. Powder material A +.

5. CONCLUSIONS

The quality and endurance tests showed that the two most dominating parameters are the feed rate and the type of drill substrate. The smallest breakouts and the lowest surface finish values were generated when solid carbide drills were used at a low feed rate.

The powder material seems to have an influence on the edge integrity, both on the in- and the outlet side. The smallest breakout values were achieved with D. AE.

No visible effects on the edge integrity and the surface finish could be seen by varying the density in the range that was used in the investigation.

The choice of cutting speed had an influence on the breakout result, but only when high speed steel drills were used. In the endurance test it was found that the performance of high speed steel drills rapidly deteriorated, already after the first holes were drilled. Since the same drill was used in the quality test during all combinations of cutting parameters, this proves the observed cutting speed influence.

Regarding its performance compared with solid carbide drills, there is no reason why high speed steel drills should be used in a drilling operation, like the one stated in the investigation. The solid carbide drill is superior in every way, except the cost price.

Depending on the demands on the edge integrity and the surface finish the solid carbide drill can be used with either low or high feed rates and always with a high cutting speed, since this parameter has no influence at all on the quality. In cases where a high hole quality is required a lower feed rate should be selected. No drill point angle influence can be detected by using either Tsc118 or Tsc130, wherefore the two solid carbide drills can be chosen freely.

REFERENCES

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