Obstruction-Type Chip Breakers for Controllable Chips and Improved Cooling/Lubrication during Drilling – A Feasibility Study

Chandra Nath\textsuperscript{a,}\textsuperscript{*}, Thomas Kurfess\textsuperscript{a}

\textsuperscript{a}School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

nathc2@asme.org, kurfess@gatech.edu

Abstract

During drilling, long stringy chips resulting from ductile plastic deformation of engineering materials cause severe chip clogging within the narrow helical flutes and edge chipping, leading to premature tool wear and breakage, poor tool life, poor hole quality and the productivity. Cutting fluid cannot efficiently access to the cutting edge that plays a vital role for improving machining performance. To address the localized heat and chip control issues during drilling, research was previously performed using conventional flood cooling, modified tool geometry, tool coating materials, and internal coolant via through hole(s). This works focuses on design and insertion of some obstruction-type chip breakers such as ribs and pins on the drill flutes and their influence on chip formation behavior. For feasibility experiments, small round pins made of stainless steel at a diameter of about 0.8-0.85 mm diameter are prepared and attached on the electro-discharge machined (EDM) blind holes on twisted drill flutes. By varying spindle speed and feed rate, drilling experiments are performed on two engineering materials including Al6061 and Inconel 625 superalloys at four cutting conditions. Most chips are found to be broken and some split into two fractions due to the pins. Force and power values with pin-inserted drill bits were found to be reduced from 5-9%. This finding indicates that there is a good potential to implement such obstruction-type chip-breakers on the drill flutes for obtaining controllable chip while also improving coolant flow at the cutting edge through the tiny tool-chip interface.

Keywords: Drilling, Chip-breaker, Engineering materials, Chip formation.

1 Introduction

Drilling is performed on all materials and alloys for applications from automotive parts to aerospace structural and engine components to offshore parts. Drilling is therefore one of the major mechanical machining processes, and accounted to be one-third of all manufacturing operations (H.S. *Corresponding author; Now working at Hitachi America, Ltd. R&D Division, Farmington Hills, MI 48335, USA

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Liu, 2000). During machining, high temperature (500 °C or above) developed in a tiny localized area cannot readily dissipate away from the tool-chip interface (Hong, Markus, & Jeong, 2001; Nandy, Gowrishankar, & Paul, 2009; Ezugwu E. , 2005). The problem becomes more severe when drilling since coolant cannot access the cutting zone within very limited space (drill flutes) due to: i) opposite directional flow of chips in the same path (flute), and ii) limited flute channel size for chips to lift up within the flutes. Combination of these factors results in micro-welding with built-up-edge at the tool-chip interface and edge chipping. Also, long stringy chips resulting from ductile plastic deformation of superalloys cause severe chip clogging within the narrow helical flutes and edge chipping, leading to premature tool breakage and accelerated tool wear, poor hole quality, and therefore the productivity (Chen & Liao, 2003; Sahu, Ozdoganlar, DeVor, & Kapoor, 2003; Ke, Ni, & Stephenson, 2003).

To address the localized heat and chip control issues during drilling of materials, many researches have been performed on conventional flood cooling, modified tool geometry, tool coating materials, and internal coolant via through hole(s). However, fluid penetration at the cutting zone is very poor with the external flood cooling (Degenhardt, DeVor, & Kapoor, 2004; Ke, Ni, & Stephenson, 2003; Sahu, 2003). Modified tool geometries (e.g., point and helix angles, edge shape, flute width, etc.) helps chip breaking (Chen & Liao, 2003; Daniel, 2001). But, this does not help lifting up the chips for effective fluid penetration at the tool-chip interface. Resistive coating materials are also used to prolong tool life (Sharman, Amarasinghe, & Ridqway, 2008; Daniel, 2001), but this limits productivity due to higher tool cost (15-50% as compared to standard drill bits (MSC, 2015). Internal through hole(s) within the drill bit helps immediate cooling of the tool flank face and chip flushing right away (Daniel, 2001). However, coolant interacts with the outer side of the chip and follows it outward, thus limiting the penetration of the interface. Also, such tools are comparatively expensive (30-50% higher (MSC, 2015) and providing coolant through drill holes needs high coolant pressure (for chip flushing) and machine to be retrofitted (Daniel, 2001); which limit productivity.

Some recent studies focus on chip formation phenomenon with chip breakers on drilling tools to obtain manageable broken chips and alleviate wear rate. Studies in (Degenhardt, DeVor, & Kapoor, 2004; Sahu, Ozdoganlar, DeVor, & Kapoor, 2003) demonstrated that a groove on the tool rake with specific geometry and orientation near the cutting edge helps chip breaking and improves tool life. Recently, some tool companies (Chipbreaker Drills, 2008; SOMTA, 2008) also introduce a rib on the backside of each flute to obstacle the chips to be broken after a curl is formed. While these chip breaker techniques are potential for manageable chips with improved tool life, none can ensure fluid penetration at the tool-chip interface. Thus, there is a strong need of technology that enhances machinability with chip breaking functions while also provides improved cooling and lubrication in limited accessible zone during drilling.

This study proposes obstruction-type chip breakers to be inserted or built-in directly on the rake of the flute for effective drilling. The aims are both to obtain the broken chips and to allow the cutting fluid to access the tool-chip cutting interface. In this preliminary study, small round pins are prepared from stainless steel and inserted on EDM-produced blind holes on twisted drill flutes. Drilling experiments are performed on two engineering materials, viz., Al6061 and Inconel 625 superalloys with two drilling parameters including spindle speed and feed rate. In the next, Section 2 proposes the concept of the obstruction-type chip breaker. Tool preparation and experimentation implementation are described in Section 3, followed by drilling results in Section 4 and conclusions in Section5.

2 Machining Chip Formation

2.1 Study Background

During machining, effective fluid penetration at the tool-chip interface highly depends on how chip forms and is controlled or evacuated from the cutting zone. As machining is a chip formation process,
its formation and breaking mechanisms are studied for many years since the beginning of metal cutting research in 1940s (Merchant, 1945). As summarized in (Zhou, 2001), these mechanisms are found to be influenced by a number of parameters: workpiece material, cutting conditions (feed rate, cutting speed, depth of cut), tool insert geometry (nose radius, chip breakers, black wall, rake angle, etc.), cutting fluid and its pressure level with flow coverage zone, tool wear level at the cutting instant, and built-up-edge (BUE), among others (Zhou, 2001). However, most of the studies were mainly focused on turning process, and modified insert geometry has been found to be a popular and comparatively less expensive technique for automatic chip breaking process. Different chip-breakers were accordingly implemented in manufacturing industries, as seen in Figs. 1(a)-(c). As turning is an external machining operation, broken chips with a chip-breaker can easily be controlled (e.g., fall down from the cutting zone due to gravity). Thus, in order to cool and lubricate the cutting zone, cutting fluid could be conveniently delivered from a direction without interfering with the chip breaker.

Study of chip breakers, however, in drilling process is very limited. In 2003, DeVor and Kapoor’s group first introduced a groove-type chip breaker on the rake face (Degenhardt, DeVor, & Kapoor, 2004; Sahu, Ozdoganlar, DeVor, & Kapoor, 2003). Grooves are designed with an orientation angle with respect to the major cutting edge (see Fig. 1(d)) since the drilling chip size varies from smaller at the inner radius to larger values at the outer radius due to the variation of the cutting speed (Li & Shih, 2006). Studies clearly demonstrate that such a groove-based chip breaker on the drill flute functionally works and helps chip breaking, and reducing chip evacuation force, cutting force and torque, thus improving tool life by 45%. However, the chip is not lifted up with a groove. Indirect chip breaking with a rib obstruction on the back side of the other flute (refer Fig. 1(e)) also cannot help chip to lift up. Therefore, penetration of cutting fluid is certainly limited. Also, producing grooves on the flutes is a time consuming process for the production line (may be EDM), which may limit the productivity.

2.2 Proposed Obstruction-Type Chip Breakers

In this study, strategic design and placement of obstruction-type chip-breakers are proposed for achieving effective cooling and lubrication in addition to controllable broken chips during the drilling of engineering materials. Conventional twist drill geometries are considered for the feasibility tests. Three different obstruction-type chip breakers are modeled with rib- and pin-based geometries, as depicted in Figs. 2(a)-(c). Unlike the common obstruction-type chip breakers used for turning operations that entirely interact with the chip width limiting cutting fluid penetration into the tool-chip cutting interface (refer Fig. 1(b)), the proposed chip-breakers are designed such that there are channels or gaps between the tool rake face and the chip. By lifting up the flowing chip, such chip breaker(s) can facilitate cutting fluid to access and penetrate the tool-chip interface for improved cooling and lubrication while also functionally act as a chip breaker at the same time. For instance, Figures 3(a)-(c) depict chip lifting and coolant penetration concept due to an inserted pin on the flute during drilling. Since drilling is an internal cutting process where the cutting fluid and chips flow in opposite directions, such chip breakers could satisfy all these machining functions.
Among the proposed obstruction-type chip breakers, built-in rib geometries (Fig. 2(a) & (b)) on the drill land can be achievable with no or a very little additional effort in current tool manufacturing technologies. For example, a grinding wheel that is used to produce the drill flutes can be adjusted either by axis movement of the wheel in the back and forth direction or by modifying the wheel shape with a pulley geometry if it is moving parallel to the drill center axis. Rather, such modified technology would reduce production cost due to less material removal in each drill. However, built-in pin-based twist drills would be complex to produce in production lines.

2.3 Chip Formation and Breaking Theory

When material shears at the sharp cutting edge, it flows out in a form of chip with a shape either naturally or through contact with obstacles. Chip curling and the sub-sequent chip breaking mechanisms mainly depend on the nature of chip flow and its direction. Three major types of three-dimensional chip flow are as follows: 1) chip up-curl, 2) chip side-curl, and 3) chip lateral-curl (Zhou, 2001). Since this study considers an obstruction away from the cutting edge for chip breaking, chip-up curl (type #1, see Fig. 3) is considered here. The chip up-curl radius, \( R_c \) has a vital influence on up-curl-dominated chip breaking. Based on an analysis of chip and cutting tool geometry, a chip up-curl radius is described as (Li Z., 1990):

\[
R_c = \frac{W_n}{2siny_n} \left(1 - 2 \frac{l_c}{W_n \cos \gamma_n} + \frac{l_c^2}{W_n^2}\right)
\]  

where, \( W_n \) is the chip breaking groove width, \( \gamma_n \) is the insert rake angle in normal direction, \( l_c \) is tool-chip contact width, as seen in Fig. 4. Since the present study is the obstruction-type, the groove can be simulated as the formed by the cutting edge line and the outer radius of the pin at the tip (or where the rib starts). Therefore, the term groove width, \( W_n \) in this study can be considered as the distance between the cutting edge and the pin tip. The chip will fail and break when the developed actual chip fracture strain, \( \varepsilon \) exceeds the breaking or tensile strain, \( \varepsilon_B \) for a particular material being machined (Nakayama, 1962), and this expressed as:
Considering a non-rectangular chip in three dimensional oblique cutting (e.g., turning), the chip fracture strain, $\varepsilon$, is described as (Li Z., 1990):

$$\varepsilon = \alpha h_{ch} \left( \frac{1}{R_c} - \frac{1}{R_L} \right)$$



where $\alpha$ is cross-section coefficient, $h_{ch}$ is the chip thickness, and $R_L$ is the chip breaking radius.

Equations (1)-(3) briefly describe the relationship between the material properties and the chip up-curl radius during 3D cutting. It suggests that if the chip-breaking radius can be influenced by an obstruction like a rib and pin, the chip breakability can be controlled during the machining process. The intention is to enhance smaller chip-breaking radius for achieving a smaller value of the chip fracture strain, $\varepsilon$. Though the height and the location seem to be influencing such chip breaking mechanism in conventional turning process, some other factors such as the size and shape of the rib or pin, and their orientation could also influence both the chip breakability and the cutting fluid penetration. Pin or rib with a larger diameter or length or width that is measured across the flute width can have higher mechanical strength for longer life, but that could proportionately limit the cutting fluid flow toward the interface. The height of the pin or rib can positively influence the chip breaking (smaller in size) by changing the chip curl radius (Zhou, 2001); however, it cannot go until the drill periphery since the chip requires space between the hole periphery and the top of the pin/rib to form curl as to break. Chips from stronger materials like superalloys would be tough to break, otherwise the pin or rib can break in this race. It is also to note that the chip formation mechanism in drilling cannot be properly explained by the chip breaking theory applied in turning process. Drilling chip formation behavior over the cutting rake face (flute) shows that the chip geometry is triangular, unlike a turning process (Li & Shih, 2007). Therefore, chip breaking theory with obstruction-type chip breaker should be considered in future study.

3 Tool Preparation and Experiments

3.1 Tool Preparation with Drilling Chip Breakers

Two obstruction-type chip breakers based on rib that are discussed in Section 2.2 could be ideal for investigating drilling performance - chip breakability, coolant penetration at the interface, and tool life (the end objective). From the manufacturing viability of the tool preparation, these two types should be cost-effective as stated above. However, in order to validate the feasibility of the proposed chip
breakers, drilling tools were prepared with the pin-based chip breaker on the rake face (on both flutes) as seen Fig. 5 (captured by a Dynolite microscope AM413TA). It is easy to prepare in the lab setup for a few holes to be tested chip formation and breakability. Since the pins are not built-in on tool flutes/lands, their mechanical strength on holes is not expected to be high to survive for many holes like the tool life test. Before performing the actual tests for this study, some preliminary tests were also conducted for understanding the required blind hole depth and location. From the tests, it is found that the hole depth must be about 1.5 mm or higher, otherwise the pin slipped out from the hole as soon as chip is found to be formed (at the beginning). Also, the pin location has to be at least 1 mm away from the cutting edge, otherwise the cutting edge chipped and failed in the very beginning due to the chip load. After a couple of such tests, for actual tests, about 2.25 - 2.5 mm deep blind holes on flutes with a diameter of 0.9 mm for 5.95 mm and 8 mm drilling tools, respectively were produced using the EDM (electrical discharge machining) technique. The hole depth was chosen based on the flute web thickness (measured from front to back of the land) so that the pin that to be placed within the blind holes does not slip out due to the lack of mechanical strength, while chip loads and torque on the rake are considerably high in drilling. The pin location (defined by a and b from the tool corner) is kept 1-3 mm away from the cutting edge for all the experiments.

Some paper clips that are made of galvanized steel material with about 0.8 mm diameter were directly cut to prepare the straight pins with a length between 3-3.5 mm for inserting into the holes on both the flutes in each tool. The J-B weld (two parts epoxy) that possesses mechanical strength of about 3800 psi at up to 350 °C temperature was used to insert pins within holes. The tools before and after the pin insertion for 5.95 mm and 8 mm are depicted in Figs. 5(a) and (b), respectively. The pin height, h exposed on the rake face is measured to be about 1-2 mm. The welding glue is also preciously wrapped around the pin in order to secure a good support without interfering with the chip while flow out and break over the pin top point during drilling.

### 3.2 Machine Setup and Procedure

Drilling experiments were performed on a 3-axis CNC vertical milling machine (Okuma Millac 44V). The experimental setup for the tests is shown in Figure 6. As seen in Table 1, with the new tools, four experiments were performed on a 25.4 mm thick Al6061 and a 12.7 mm thick Inconel 625 plates at two levels by varying feed rates using heat resistant cobalt steel jobbers drill bit. Drilling parameters for these two different materials are chosen based on the previous studies (Chen & Liao, 2003; Ezugwu E., 2005). During drilling, cutting fluid at about 10 gallons/min is delivered at the drill periphery from four fluid nozzles. A high performance synthetic cutting fluid Castrol Syntilo 9954 at 7 vol.% concentration with water was used. Broken chips from the machining zone were collected using a net placed in the fluid drain (see Fig. 6). The workpiece plate was placed on a sacrificial supporting plate of aluminum; then these two plates together were fastened on the top of the
Kistler dynamometer 9257B using two bolts at the two ends. The force data were directed to an NI DAQ card via a charge amplifier (type 5010). The machine has a powermeter on its AC motor that runs the spindle. The powermeter line was connected to the same DAQ card. The force and motor AC power (P) data were collected using LabVIEW software in terms of newton (N) and watt (W). To capture drill and chip formation condition on the setup and accumulated chips after each hole (or condition), a conventional camera was used. For comparison of the performance of the new tools, drilling experiments were also performed with the same tools but without the inserted pins.

Table 1: Tool specifications and experimental conditions

| Pin feature    | 5.95 mm | 8 mm  |
|----------------|---------|-------|
| Distance, a (mm) | 1.65-2.0 | 1.8-2.25 |
| Distance, b (mm) | 1.65-2.0 | 1.8-2.25 |
| Hole dia, d (mm) | 2.0-2.25 | 2.0-2.5  |
| Pin height, h (mm) | 1.5–1.5 | 2.0-2.5  |

| Specifications     | Drill type      | Flute geometry |
|--------------------|-----------------|---------------|
| Drill type         | Uncoated cobalt steel | Parabolic     |
| Point angle (mm)   | 135°            |               |
| Drill depth (mm)   | 55.88           | 80.16         |
| Overall length (mm)| 92.08           | 114.0         |

| Workpiece Material | Al6061 | Inconel 625 |
|--------------------|--------|-------------|
| Speed (rpm)        | 2500, 3500 | 375, 500   |
| Feed rate (mm/rev) | 0.05, 0.1 | 0.05, 0.075 |

4 Experimental Results and Analyses

In this section, chip formation behavior in drilling of Al6061 and Inconel 625 is presented as to validate viability of the effectiveness of the proposed obstruction-type chip breakers. As stated in Section 3.1, tool life tests cannot be performed with the tools where pins are inserted because pins are found to survive on the EDM holes for one or two holes only. Experiments without pin were also performed for comparison of the machining performance including chip formation, force and power.

4.1 Al6061 chips

Table 2 depicts collected Al6061 chips that are produced at four different drilling conditions with both the 5.95 mm and 8.0 mm drills. It is observed that most chips are broken at all conditions when a pin-based chip breaker exists on the drill flute. Some chips are still found to be long. It is because either one or both pins are observed to come out from the hole or bend down on the flute. It is assumed that the pin(s) could not survive well on the blind hole with the rigidity and strength offered by the J-B welding. At the end of the cutting, due to the progression of the drill bit, there is an increase load of chip that flows over the pins. As stated in Section 3.1, a built-in rib parallel to the cutting edge or the drill flute would resolve this issue.

It is also observed that chip length decreases with an increase in the feed rate, regardless of chip breaker (CB) or conventional drill. It is due to the chip thickness increase with the feed rate. As the chip thickness increases, the chip ductility reduces that causes chip to fail comparatively in an earlier stage. However, when comparing with the performance of drills without CB, it is found that the chips are always long and continuous. This reveals that a CB on the drill bit can help breaking the chip that is coming out from the cutting edge.
Figure 7 shows the tools at two different conditions for both the drill conditions at two different drill diameters. Both are the example of the lower feed rate. Though the chips are seem to be on the drill when pins are used, the amount of chips and the way of their wrapping with the drill can reveal that the chips did not stuck at the cutting edge, but a bit way. Since the pins failed at the last moment, a small amount of chips is seen to wrap around. In contrast, in the case of drills without pins, the chips are found to be stuck and tightly wrapped around the drill bit proving that a conventional drill is ineffective to drill aluminum.

Table 2: Al6061 chips obtained with and without pin on the drill flute for drilling one hole. (Images are presented as 70 mm x 53 mm)

| Drill size | Drill condition | Cutting condition (spindle speed in rpm, feed rate in mm/rev) |
|------------|-----------------|-------------------------------------------------------------|
| 5.95 mm    | With CB         | ![Image](image1)                                             |
|            | Without CB      | ![Image](image2)                                             |
| 8.0 mm     | With CB         | ![Image](image3)                                             |
|            | Without CB      | ![Image](image4)                                             |

Table 3 shows the chips collected after drilling with and without CB when drilling Inconel 625, while the drilling condition is different from Al6061. For all four drilling conditions, again it is seen that most chips broken in the case of CB used on the drill flutes. These broken chips are even smaller.

4.2 Inconel 625

Table 3 shows the chips collected after drilling with and without CB when drilling Inconel 625, while the drilling condition is different from Al6061. For all four drilling conditions, again it is seen that most chips broken in the case of CB used on the drill flutes. These broken chips are even smaller.
than in the case of Al6061. However, when using a conventional drill, chips are very long, and found to be accumulated around the drill. Figure 8 shows photographs of the chips for two drilling conditions for the two drill sizes. Though chip breakability is observed to be a little better for Inconel 625 as that compared to Al6061, it is due to the effect of material properties. However, overall chip breakability is improved when using pins on the drill flutes.

Table 3: Inconel 625 chips obtained with and without pin on the drill flute for drilling one hole. (Images are presented as 70 mm x 53 mm)

| Drill size | Drill condition | Cutting condition: spindle speed (rpm), feed rate (mm/rev) |
|------------|-----------------|----------------------------------------------------------|
| 5.95 mm    | With CB         | #1: 375, 0.05                                            |
|            | Without CB      | #2: 375, 0.075                                           |
| 8.0 mm     | With CB         | #3: 500, 0.05                                            |
|            | Without CB      | #4: 500, 0.075                                           |

Figure 8: Drills at the end of cutting of a hole when drilling Inconel 625 plate with and without pin-based chip breaker using 5.95 mm and 8 mm tools.

Thrust force and power data measured during the drilling also have been analyzed. Force and power are directly related to each other. Both the data are found to be reduced from 5 to 9% in the case of CB used when drilling both the materials, as shown in Table 4 for Al6061 and Table 5 for Inconel 625. Lower force and power values are due to the ease of chip evacuation from the hole through the flutes. Usually, when the chips get stuck on the drill flutes within the hole, the chip load on the drill also increases. This in turn increases the force and the motor power values. This means that the inserted pins not only help breaking the chips with a lift up, also they assist improving the machinability. This also indicates that the coolant delivered during the drilling process could penetrate
better between the interface formed by the tool rake and the chip underside. Thus, it can be stated that the proposed obstruction-type chip breakers may be useful for improving drilling process.

### 5. Conclusions and Future Work

In this work, obstruction-type chip breakers are proposed for drilling tool with an aim to improve chip breakability as well as cooling and lubrication for achieving long tool life. The concept is described with chip formation phenomenon. Chip breakability is tested with drilling experiments using pin insertion on the conventional drill flutes. Experiments are performed on two engineering materials including Al 6061 and Inconel 625 at four different cutting conditions (by varying speed and feed) using two different tool sizes. Each combination is tested for a single hole. In all conditions, most chips are found to be broken into small pieces and some split into two fractions due to the inserted pins near the cutting edge. In contrast, drills without chip-breakers produced very long chips that are stuck within the flutes/hole. Force and power values with the pin-based chip-breakers used in this study were found to be decreased from 5-9% over conventional drill bits. This indicates that an obstruction improves machinability, while also could be helping coolant penetration of the cutting interface by lifting the chip up when flowing over it. This result indicates that the proposed obstruction-type chip-breakers like rib(s) along the drill flutes or parallel to the cutting edge can be easily produced and implemented for obtaining controllable chip while also improving coolant flow at the cutting edge through the tiny tool-chip interface.

| Table 4: Force and power values obtained for Al6061 with and without chip breaker (CB) pin on the drill flute for drilling one hole. |
|---|---|---|---|---|---|---|
| **Output** | **Drill size** | **CB** | **Cutting condition: spindle speed (rpm), feed rate (mm/rev)** |
|  |  |  | #1: 2500, 0.05 | #2: 2500, 0.1 | #3: 3500, 0.05 | #4: 3500, 0.1 |
| Force (N) | 5.95 mm | Yes | 225 | 421 | 428 | 654 |
|  | No | 242 | 458 | 456 | 702 |
|  | Yes | 268 | 498 | 526 | 724 |
|  | No | 282 | 556 | 603 | 830 |
| Power (W) | 5.95 mm | Yes | 81 | 142 | 141 | 211 |
|  | No | 95 | 156 | 156 | 226 |
|  | Yes | 102 | 188 | 195 | 329 |
|  | No | 112 | 201 | 208 | 359 |

| Table 5: Force and power values obtained for Inconel 625 with and without chip breaker (CB) pin on the drill flute for drilling one hole. |
|---|---|---|---|---|---|---|
| **Output** | **Drill size** | **CB** | **Cutting condition: spindle speed (rpm), feed rate (mm/rev)** |
|  |  |  | #1: 375, 0.05 | #2: 375, 0.075 | #3: 500, 0.05 | #4: 500, 0.075 |
| Force (N) | 5.95 mm | Yes | 354 | 452 | 498 | 684 |
|  | No | 381 | 489 | 528 | 775 |
|  | Yes | 402 | 523 | 596 | 867 |
|  | No | 445 | 563 | 650 | 911 |
| Power (W) | 5.95 mm | Yes | 104 | 126 | 130 | 179 |
|  | No | 112 | 137 | 157 | 191 |
|  | Yes | 120 | 148 | 152 | 223 |
|  | No | 129 | 156 | 163 | 236 |
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