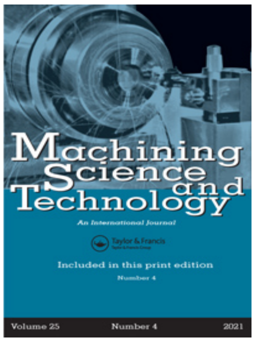

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Nuray Bekoz Ullen

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Characterization of machinability of sintered steel foams having different porosities during drilling operations

Nuray Bekoz Ullen

Metallurgical and Materials Engineering Department, Engineering Faculty, Istanbul University-Cerrahpasa, Istanbul, Turkey

ABSTRACT

Steel foams are a new class of engineering materials with exceptional structure and properties. Foams produced by powder metallurgy generally have a near-net shape, however, sometimes machining operations may be required. The presence of porosity in steel foams significantly affects the cutting process and causes poor machinability. This study deals with the evaluation of the machinability of Cu-Ni-Mo-based steel foams having different porosity produced by powder metallurgy. High speed steel and carbide-tipped drills were used for the drilling. All tests were performed in dry condition with drill diameter of 3 mm. The drilling characteristics were evaluated in terms of the surface roughness, chip formation, drilling force, tool wear, microstructure and hardness change after drilling. The machinability was also evaluated by measuring average width of breakout and skewness values of the hole drilled. The results indicated that the increase of porosity negatively affected the drilling quality of high porous steels. Both drills broke the chips in powder form and produced discontinuous chips. High porous parts exhibited higher hardness change as compared to lower ones. The carbide drill showed acceptable drilling forces and surface quality. HSS drill is not suitable for drilling due to poor hole quality and high drill wear.

HIGHLIGHTS

- Steel foams exhibit poor machinability due to highly porous structure.
- Porosity and tool type significantly affect the surface integrity of steel foams.
- Surface roughness and drill wear increased with increasing porosity; however, feed force decreased.
- Intense presence of pores decreases the tool life remarkably.
- The skewness values of hole are positive in all porosities.
- Carbide-tipped drill produced the finest hole quality.
- The larger damage was observed at the exit of the drilled holes with HSS drill.

KEYWORDS
Drill life; drill type; drilling; hole quality; porosity; steel foam

CONTACT Nuray Bekoz Ullen nbekoz@Istanbul.edu.tr Metallurgical and Materials Engineering Department, Engineering Faculty, Istanbul University-Cerrahpasa, Avcılar, Istanbul 34320, Turkey.

Introduction

Steel foams can be used in various functional and structural applications thanks to their properties such as high impact energy absorption, strength, heat resistance and low cost. Examples of these applications such as parts of sound, energy and heat absorption required parts of transport vehicles, machine parts, sandwich panels can be given (Ashby et al., 2000; Smith et al., 2012). The combinations of these properties cannot be achieved with dense materials. In recent years, significant processing technologies have been developed for steel foam production. Previous efforts for steel foam production have related to the use of powder metallurgy (PM) techniques. In particular, the space holder-water leaching technique in PM is fairly flexible, cost-effective and leads to desired properties (Banhart, 2001), and allows the combined irregular cellular structures with open or closed pores (Bakan, 2006; Bafti and Habibolahzadeh, 2010). The technique is a near-net shape process that tends to eliminate the requirement of a secondary machining processes. It is also worth noting that, near-net shape is regarded as an ecological friendly processes due to shortening production processes, preserving natural energy and resources, reducing production cost and the extracted material emissions. However, in practice, some machining process is often required after sintering in order to create the desired geometry of the porous part (Bram et. al., 2000; Bakan, 2006; Tutunea-Fatan et al., 2011; Bekoz and Oktay, 2013a). The success in the use of steel foams depends not only on the invention of new methods for producing cheap and advances quality, but also on the improvement of a detailed understanding of the machining characteristic.

Relationship between high porous structure and machinability

The machinability of a PM component depends on the tool material properties, cutting conditions and parameters used in machining. Chemical composition and porosity of the workpiece, free machining additives and production process parameters such as compaction and sintering methods also influence the machinability (Höganäs, 2004a). Among the various characteristics of PM steels when compared with the conventional steels, the porosity and heterogeneous microstructure are often highlighted as the main distortion factor for machinability (Salak et al., 2005, 2006). Compared to dense PM steels and highly porous PM steel machining, there are different workpiece characteristics affected, for example, expressed by complex pore morphologies and lower mechanical properties depending on processing conditions. These differences can be seen in tool wear, cutting force, surface quality and chip formation and which allows machinability to be defined. The greatest difficulty in machining ductile porous material is

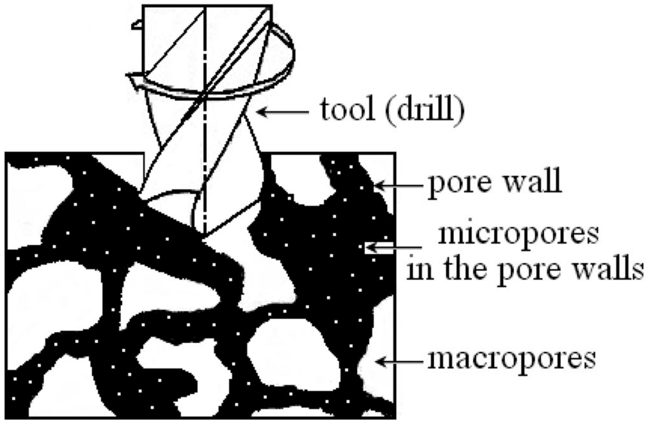

Figure 1. Schematic of the drilling operation of high porous workpiece.

the high level of plastic deformation that leads to the closure of pores during cutting, whereas the main problems in machining brittle porous material are the brittle fracture around the pores, pores filled with chips (Heidari, 2018). Therefore, the methods used to avoid processing difficulties must be different. The steel foams manufactured by the space holder-water leaching technique in PM, two types of pore formation are generally prominent: macropores as a result of the material used as a space holder and micropores in the pore walls resulting from the sintering and compression during the formation of steel foam (Bekoz and Oktay, 2013a, 2013b). The presence of these pores in the foam is the most important criteria to evaluate the machinability of porous materials. A particular problem of highly porous materials requiring machining is their porous structure that makes cutting difficult and complicated. Understanding of the pore factor in the structure is necessary to distinguish how the machinability of steel foams will inherently different from dense PM steels. A schematic illustration of the drilling operation of the high porous workpiece is shown in Figure 1.

Unlike with dense PM materials, the properties of highly porous PM materials can be changed not only by parameters such as sintered density, sintering and pressing conditions but also by macro and micro porosity content (Salak et al., 2005, 2006). The high macroporous content makes solid foams very brittle and hard to machine. The effect of the macropores in the foams on the parameters used in machining is more dominant than the micropores formed in the pore wall, as it can be seen in Figure 1. Machinability is deteriorated by the presence of pores which can be assumed as an air gap for macropores as a sort of soft inclusions for micropores. The cutting action of the tool is continuously interrupted, resulting in accelerated wear of the cutting edge due to the macropores in the foam structure. The micropores in the pore wall will make the cutting process more complicated and difficult, in this way, their cutting mechanism will be markedly distinct from those of dense PM materials. This structure of the foam reduces thermal conductivity and increases the cutting edge temperature locally and thus causes shorter tool life (Engstrom, 1983; Smith, 1998). Several researchers (Engstrom, 1983; Smith, 1998; Salak et al., 2005, 2006) have reported that the porosity reduces the thermal conductivity of PM steels, therefore, temperatures of the cutting edge and region may increase rapidly. The macropores in porous PM parts possess much greater surface area than dense PM steels. This probably increases the potential for chemical and physical reaction between the tool and the porous workpiece, which accelerates tool wear. Furthermore, the open or closed pore structure influences the requirements regarding the cutting process (Danninger et al., 1997; M'Saoubi et al., 2014). Knowledge of the basic characteristics of machining for dense PM steels has been gained for a long time, and therefore, it is basic and applies for studying the machinability of high porous steels. However, there are differences between high- and low-density PM steels in microstructure and mechanical properties, which is the reason for the needed complex investigation of the machinability of high porous steels (Smith, 1998; Salak et al., 2006). When cutting a high porous part, a larger area of material is deformed than sintered dense parts at the expense of porosity. The influence of porosity on the machinability of porous parts has not been sufficiently described, and therefore research is needed to explain the pore effect. The presence of dense pore is assumed to have a negative effect in the decrease of thermal conductivity in the contact zone of tool and workpiece, and to promote wear mechanisms on the cutting tool (Robert-Perron et al., 2007a; Trent and Wright, 2000). The hardness, impact and tensile strength are significantly reduced with increasing porosity. The presence of the pores has a weakening effect on the structure and also negatively affects the contact between the powder particles. Consequently, the porous structure is generally ruptured from a region containing stress concentration zone (Causton and Shaede, 2003). The machinability and cutting response of steel foams can be explained exactly by their porosity. The effect of porous structure on machining was not declared, and so could be an interesting research topic. Due to the low machinability of the steel foams under study, selecting the machining conditions and parameters is crucial. The technical and scientific inadequacy in the processing porous parts results in a reduced machined surface finish which has a significant effect on the restriction of their application. The presence of pores causing the low machinability of steel foams should be investigated to improve the machinability of steel foams from a scientific point of view. Consequently, this article focuses on explaining the machinability of the steel foams in terms of the influence of porosity.

The effect of porous structure on improvement of machinability

Recently, several studies have been conducted to improve the poor machinability of dense PM parts. Closing or sealing of porosity improves the machinability of dense PM steels significantly by changing the cutting process from intermittent to continuous. The clearance between particles due to the presence of pores causes an intermittent cutting action, which can be repaired with infiltration using a metallic component such as copper or with vacuum impregnation using nonmetallic materials such as resins and waxes (Engstrom, 1983; Salak et al., 2005). Copper infiltration and polymer impregnation are efficient ways to cover porosity. Both of them may require an additional process step (Causton and Shaede, 2003). However, for highly porous metal parts, the above-mentioned improvement in machinability might not be possible due to the highly macro porous structure. The porous nature of foam metals is one of its important characteristics. Therefore, it is important that the machined surfaces maintain their porous structure. Cleaning of the filled pores for the high porous structure is difficult or impossible after machining operation. The lubricant is often preferred to reduce the temperature at the tool and chip interface, but it is difficult to avoid contamination with the lubricant trapped in the pores. Interconnected porosity provides a way of cutting fluids to escape from the cutting zone. This reduces the cutting edge cooling and lubrication capabilities. It can also reduce their ability to wash chips from the cutting zone. The use of cutting fluids is not recommended because it remains in the pore of the machined material, which then causes subsequent corrosion. Machining of PM steels is carried out as dry machining due to the presence of porosity, especially in the steel foams. However, this situation causes an increase in tool wear due to the temperature increase in the cutting zone (Trent and Wright, 2000; Causton and Shaede, 2003; Robert-Perron et al., 2007b; Czampa et al., 2013). But at the same time, machining in a dry condition without any coolant is a very interesting opportunity both from economical and environmental viewpoints (Wyatt and Trmal, 2006). Green machining could also be an alternative, however, the mechanical properties of the green porous parts are very weak to be machined due to its dense porous structure (Desbiens et al., 2012; Robert-Perron et al., 2007b). The elimination of the poor machinability of high porous PM steel is not sufficiently defined and therefore it is important to study the issue in this area.

Drilling in PM

Because most of the manufactured parts include holes or threads, the drilling process is widely used in advanced manufacturing, and it is one of the most common secondary processes in the PM industry (Höganäs, 2004a;

Heidari, 2018). In drilling, the most important objectives are low cost and high hole quality (Meral et al., 2019). The predominant machining operations common in PM are mainly drilling (about 30%), turning, tapping and boring (about 25%), threat, cutting, grinding and others (milling and-broaching) in minor extent. For a large part of the parts, concerns about machinability only result in unwanted delays and costs after the part is manufactured (Höganäs, 2004a; Salak et al., 2005). Therefore, it becomes necessary to incorporate machinability problems earlier in the design process. However, in the case of difficult materials machining, such as high porous steels, the drilling is still a less explored manufacturing process despite the above-mentioned features (Robert-Perron et al., 2007a). Drilling was selected to conduct the present research to fill this lack of literature. For the determination of drillability properties of the porous part, the parameters such as the drill type and the porosity content of the workpiece play an important role in machining as discussed in detail in this study.

The drilling process contributes to a significant amount of chip removal in the conventional machining. During hole drilling, it is of critical significance that the chip is effectively evacuated from the workpiece. Otherwise, inadequacies in chip evacuation can lead to high heat production and friction leading to an increase in radial forces and surface roughness, and even if these problems cannot be controlled, the drill can break. Chip disposal in the drilling process is one of the most serious problems as it causes the chip adhesion to cut tool surface, resulting in poor surface quality, and the cutting tool breakage (Robert-Perron et al., 2007d; Jin and Liu, 2012; Meral et al., 2015). In cutting the PM material to an edge as occurs during drilling, the drill deforms some of the workpiece material which then separates as a chip. It is known that the chip type obtained by the machining has a significant impact on surface quality (Salak et al., 2005; Robert-Perron et al., 2007c). The formation of chips is strongly dependent on the physical and structural characteristics of a material (Robert-Perron et al., 2007c). The basic factors affecting the chip flow are friction between the tool, chip-workpiece and drill type (Jin and Liu, 2012). The chip formation and chip continuity of dense PM part has been expressed in many studies (Robert-Perron et al., 2007c, 2007d; Hwang and Chandrasekar, 2011; Jin and Liu, 2012). However, there are no publications regarding the chip properties formed during machinability of steel foams. In the content of this study, chip formation is discussed in the drilling of porous PM steels.

Tool type in machining

In the machining operation of highly porous materials, choosing cutting tools is an important task according to workpiece properties to obtain high-quality product (Heidari, 2018). If the machining of PM parts plays an important role in the production stage, selection of the most suitable tool material for use should start at the design stage in part development (Blais et al., 2001). The tool choice guidelines are needed to improve the machining performance of steel foams in their various applications. There are several handbooks used to identify cutting tools for the machining of dense PM materials but not for machining of highly porous materials. Several grades of high speed steel (HSS) and cemented carbide materials have been vital in the development of machining tools for PM components (Blais et al., 2001; Ramulu et al., 2002). Standard HSS drills are useful with a wide range of dense PM materials. Carbide grade is mainly used in the development of machining tools for PM parts. Micrograin K10 grades which are a kind of carbide are the most common thanks to the good combination of their hardness and toughness. Carbide drills are essential to attain acceptable productivity and tool life in the most difficult and abrasive PM materials (Ramulu et al., 2002; Höganäs, 2004a; Czampa et al., 2013). This article addresses the machinability of the steel foams using HSS and carbide drills. In particular, HSS cutting tool needs to be investigated due to its low usage in the industrial mass production.

The importance and purpose of the study

It is very advantageous to use of pre-alloyed powder in terms of the mechanical properties of sintered materials. Distaloy AB used in this study, one of the low alloy steel powders available on the market, it is a partially pre-alloyed iron powder containing nickel, copper, and molybdenum which alloyed by diffusion. The alloying level of Distaloy AB gives high compressibility, good machinability and sizing properties in the sintered state (Höganäs, 2004b). Bekoz and Oktay (2013a, 2013b) manufactured Distaloy group steel foams having different porosities by the space holder-water leaching technique in PM. In the past years, high porous steel parts by the PM technique were produced by many researchers (Ashby et al., 2000; Gülsoy and German, 2008; Zhang and Zhao, 2008; Banhart, 2001; Mutlu and Oktay, 2012). In all mentioned studies, the processing and properties of the produced porous steels were investigated. However, there are no publications regarding the machinability of steel foams.

In order to achieve high efficiency and low cost in the production of PM components, guidance is required for the wear mechanism and machining processes. Cutting operations are well understood in dense PM part machining, but some problems arise when applied to the machining of porous PM products (Alizadeh, 2008; Tutunea-Fatan et al., 2011). To date, no research articles have been encountered discussing the drilling conditions of PM steels with an approach similar to this study. The details of the machinability characteristics should be examined from a broad perspective in order to increase the usability of steel foams. Some researchers have reported difficulties in machining high porous metal and limited information about their machinability (Engstrom, 1983; Smith, 1998; Salak et al., 2005; Tutunea-Fatan et al., 2011; Heidari, 2018). The main purpose of this study was to resolve these lacking mentioned in the literature.

The most frequent machinability tests found in the PM literature: tool wear, cutting force, chip formation and surface integrity tests in machining (Blais et al., 2001; Salak et al., 2005). In all the machinability tests mentioned have been investigated, the machinability of low alloy sintered steel foams having different porosity levels using a different kind of twist drills in this study. The drilling characteristics were also evaluated by measuring the average width of the breakout and the skewness values of the hole drilled, and in terms of the microstructure and hardness change after drilling as a function of porosity. Also, various scientific studies on the machinability of sintered steels have been reviewed in this study. One of the main objectives of this study is to provide a research platform for future studies in this field.

Experimental procedure

Workpiece materials

Low alloy steel foams having different porosities were chosen as the workpiece material for this research. These steel foams were manufactured by the space holder-water leaching technique in PM. The chemical composition of the water atomized Distaloy AB steel powders available from Höganäs Company, Sweden was 1.5 wt.% Cu, 1.75 wt.% Ni, 0.5 wt.% Mo, and balance-Fe. The foam specimens were sintered at 1200 °C for 60 min in a Lenton UK model tube furnace under high purity hydrogen. Cylindrical specimens with a diameter of 20 mm and a height of approximately 10 mm were produced. Details on the steel foams and the fabrication processes are described in detail a previous article (Bekoz and Oktay, 2013a). Figure 2 shows the photograph of the sintered steel foams having different porosities. The sample to the left of the figure has 51.9%, the three samples in the middle have 62.9% and the sample to the right has 70.7% porosity. It is possible to define the machinability of the material by a good description of the material properties. Usually, metal foams are structurally characterized by the porosity content, pore size and shape (Bekoz and Oktay, 2014). The porosity content and density of the sintered foams were determined by Archimedes principle using a Sartorius balance with a density measuring kit. The fractions of open and closed porosity content of sintered porous

Figure 2. Photograph of the sintered steel foams.

Table 1. Density, total, open and closed porosities of the steel foams.

Density (g cm^{-3})	Total porosity (%)	Open porosity (%)	Closed porosity (%)
4.28 ± 0.13	45.1 ± 1.6	28.6	16.5
3.75 ± 0.11	51.9 ± 1.4	38.3	13.6
2.89 ± 0.09	62.9 ± 1.7	52.1	10.8
2.28 ± 0.12	70.7 ± 2.1	63.6	7.1

specimens were calculated by weight measurements prior to and after dipping the steel foams at 150 °C in boiling paraffin. Table 1 shows the sintered density, amount of total, open and closed porosity of the sintered specimens.

The SEM images of the surfaces of the steel foams having 45.1% and 70.7% porosities are given in Figure 3. Mean pore size was between 913.6 and 1014.1 µm for macro pores. The pores clearly separated from each other with the pore walls are clearly visible. There are no cracks in the porous structures, but there are a high proportion of micropores in the pore walls. Two types of pores were typically observed in the steel foams: macropore and micropore, as stated in Introduction. The presence of these pores in the foam has a considerable effect on the machinability properties. Details on this issue are being discussed later in this study. The pore walls tend to crack and break brittle as a result of the high macropores and micropores content of the pore walls (Bekoz and Oktay, 2014). In practice, the machinability of the PM steels may be represented better by their microstructure and mechanical properties (Hamiuddin and Murtaza, 2001; Andersson and Berg, 2005; Ozcatalbas, 2014). The detailed on the microstructure and mechanical properties of sintered steel foams in this study was described in Bekoz and Oktay (2013a). The microstructure and hardness values of the surfaces changes after drilling operation compared to the machined surfaces are being discussed later in this study.

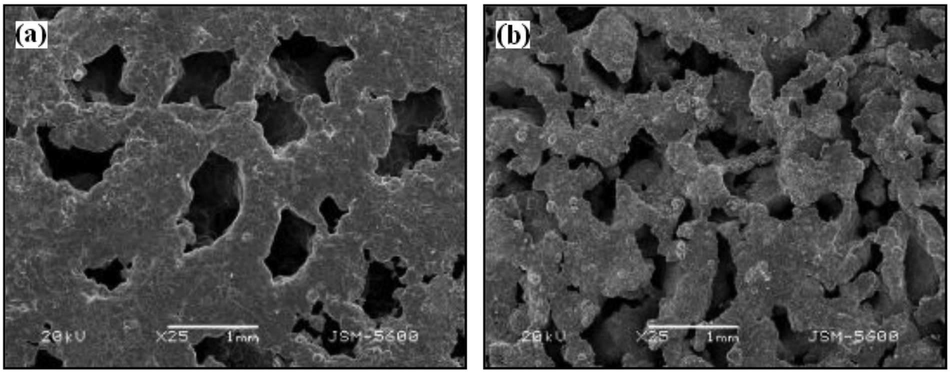

Figure 3. SEM images of the steel foams having (a) 45.1% and (b) 70.7% porosities.

Machinability tests of porous workpieces

As stated in the Introduction, drilling is the most appropriate operations to be applied to the porous metal part. The machinability is discussed in drilling operation of steel foams from the viewpoints of the chip formation, surface roughness, hole quality, cutting force, tool life and microstructure and hardness change after drilling as a function of porosity. The machinability was also evaluated by measuring the average width of the breakout and the skewness values of the drilled hole. Drilling experiments were performed on a commercially available VCM 4824 model CNC milling machine repeating the same conditions for each material. The drill cut completely through the test piece on each hole. Metal removing operations can cause severe surface distortion or damage to metal foams, thus cutting should be carried out at very low speed and feed (Agapiou et al., 1988). The drilling was performed using two different cutting tools while a cutting speed 30 m/min, a feed rate of 0.20 mm/rev and a cutting depth of 10 mm is kept constant. In these tests, 3 mm diameter holes were drilled using two types of drill bits manufactured by Kennametal:TiN coated HSS drill and TiN-coated solid carbide-tipped drill. (HSS drill ISO No: B00007800300 and carbide drill ISO No: B041A03000CPG KC7325). Technical specifications of drills are presented in Table 2. In general, results were obtained for at least three drills for each porosity level, using a new drill for each cutting. The drilling process was performed in a dry condition without using coolant.

Characterization of the surface finish of drilled high porous specimens was carried out using an SJ-201P model Mitutoyo surface roughness measurement device. The arithmetic average of the surface roughness (Ra) was achieved by significantly bigger than the pores with a chisel point pen to eliminate the effects of pore size change on the measurements. The spherical type of stylus has a cone angle of either 60° with a typical tip radius of 2 μm. The chisel is 0.8 mm wide to allow for easy alignment to the fine

Table 2. Technical specifications of the drills used in experiments.

Drill material	Coating	Helix angle (°)	Point angle (°)	Point geometry
HSS	TiN coated	35	118	Split
Carbide	TiN coated	30	118	Split

edge or small diameter being measured. The hysteresis of the hole surfaces was measured using the same stylus for hole surface finish measurement. The surface quality was assessed by measuring the average width of break-out near the outlet edge. Micrographs were captured using analyzed using an image analysis software (Clemex Vision) and a profilometer and an SJ-201P model Mitutoyo profilometer. The skewness values of the drilled holes were calculated for each drilled holes. The drilled surface and tool wear were characterized using a scanning electron microscope (SEM). During the drilling process, chips were collected after each cut and examined visually for general characteristics. Mean size range of the chip process in drilling was determined by Malvern mastersizer particle size analyzer. The cutting force during drilling was measured using a Kistler piezoelectric dynamometer. The pores of the steel foams were filled with cold-hardening epoxy resin then etched in 2% Nital solution for optical examination before and after machining. Hardness measurements to evaluate surface hardness changes were performed under the load of 1 N with 10 s using a micro Vickers hardness tester (HMV-G21S; Shimadzu). The number of drilled holes before total drill failure in the drilling test was chosen as a criterion to define the drillability. To ensure the accuracy of test results, all machining tests were repeated twice for each drill bit under the same conditions.

Results and discussion

Hole quality in drilling

Photograph of the workpiece materials having 70.7% porosity before and after drilling operations are given in Figure 4. The upper photograph shows the drilled porous part with HSS drill and the drilled porous part with carbide drill in the photo below. Drilling operation has to be reached without any deterioration of the highly porous structure of the steel foams. As shown in Figure 4, brittle fracture was the quite prominent mechanism on the surface of the part where drilling starts. The surface roughness of the machined surfaces is the most commonly used to determine the surface quality characteristic. The surface quality is the result of interactions between the workpiece properties and the type of cutting tools used in machining. Especially, porosity in PM parts has a strong influence on the hole quality of the drilled workpiece (James, 1994; Blais and L'Espérance, 2002; Robert-Perron et al., 2007a; Czampa et al., 2013). Figure 5 shows the

Figure 4. Photograph of the steel foams before and after drilling operations (non-machined (left), chips on the machined workpiece (middle), machined workpiece (right).

average surface roughness, Ra, of high porous steel depending on the workpiece porosity content and drill type. Average surface roughness values of drilled steel foams having 45.1%, 51.9%, 62.9% and 70.7% porosities with HSS drill were measured 3.31, 4.16, 4.57 and 5.92 µm, respectively. For carbide drill at similar porosity, these values were 3.05, 3.75, 4.12 and 4.57 µm, respectively.

The results showed that the porosity of the material and the drill type have a relatively considerable effect on the measured hole quality features. The presence of pores in the structure of steel foams causes intermittent cutting during machining. This leads to a decrease in surface quality for PM parts (Engstrom, 1983; Salak et al., 2006). The increase in porosity levels of steel foams significantly deforms its machined surface, and the surface roughness of steel foams is rather big. One reason for this decrease in surface quality is the direct reason of porosity, which reduces thermal conductivity, regional raise the temperature of the cutting edge, which may result in edge and crater deformation (Engstrom, 1983; Smith, 1998). Also, the presence of macropores in the structure of steel foams leads to vibrations during drilling. According to Smith (1998), pores at the machined surface provide impact loading and microscopic shock to the cutting edge. This probably increases the potential for physical and chemical reactions between the tool and workpiece that may reduce the surface quality. According to Salak et al. (2005), the edge wear resulting in a significantly reduced surface quality predominated in drilling the high porosity material. Heidari (2018) reported that porous steel is a high brittle material with high toughness, and this structure lowers the surface quality by introducing an unstable regime to the cutting edge. Generally, the vibrations in machining may be minimized with accuracy selection of drill type (Engstrom,

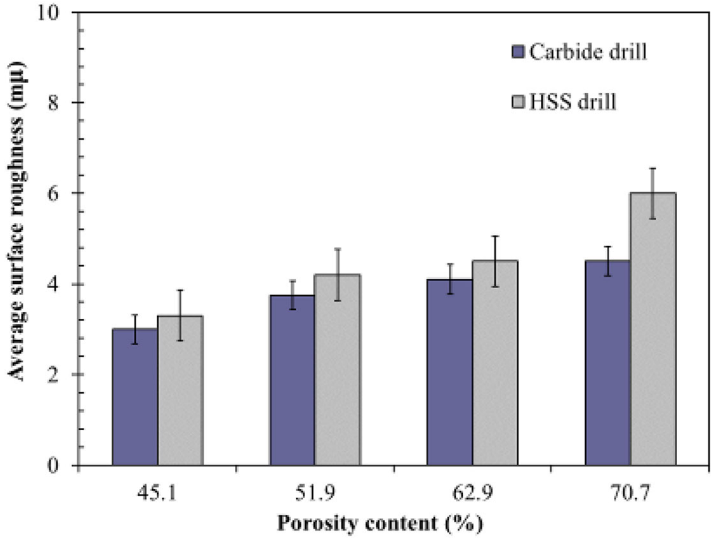

Figure 5. The effect of porosity content and drill type on the surface roughness.

1983). The highest surface roughness was exhibited when drilled with HSS type, and the smallest one when drilled with a carbide drill bit at similar porosities. The carbide drill showed the best surface performance in machining operations of the steel foams for all porosity contents. Some research has shown that the carbide drill has important positive ideas that production rates can be increased without sacrificing hole quality (Robert-Perron et al., 2007a; Czampa et al., 2013; Tambani et al., 2018).

Achieving the desired hole diameter within tolerances is the main aim of drilling operations (Meral et al., 2015). In case of drilling high porous parts, both dimensional accuracy and hole geometry are widely reduced. The surface finish of the drilled holes and the average width of breakouts as machinability criteria were used to optimize the machining performances of drilling through holes in porous steel parts. Many researchers working on PM machinability have declared the breakout measurements by scanning technique (Gagne and Chagnon, 1999; Benner and Beiss, 2004; Kulkarni and Dabhade, 2019). This technique can help provide a three-dimensional image of the output, like to the laser scanning technique (Kulkarni and Dabhade 2019). The characteristic micrograph breakout zones of drilled holes using HSS and carbide drills shown in Figure 6. At both drills used, the significant breakout occurred around the hole as the drill exited because high porosity steel foams are inadequate for machining. Geng et al. (2019) reported that he drilling-induced delamination usually occurs at the hole entry and hole exit of the drilled hole periphery. For HSS drill, larger damage was observed at the exit of the drilled holes. The

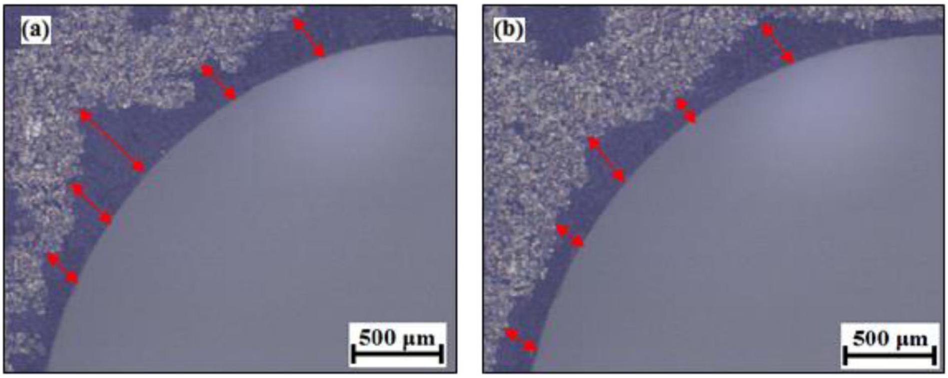

Figure 6. Micrographs of drilled holes with (a) HSS and (b) carbide drills.

drilled surface may be ruined by unstable heat and vibration distributions from macropores as discussed earlier. Heidari (2018) expressed that a very large tensile stress zone is formed from the bottom of the cutting tool tip extending into the pore when the tool reached the pore edge. This type of stress often results in rapid crack advancement and causes brittle fractures. The influence of the density on the exit-edge-breakout and surface finish has been reported by many researchers (Robert-Perron et al., 2005, 2007a; Kulkarni and Dabhade, 2019). The properties of the cutting tool have been accepted by the researchers to maintain the second-largest effect on the breakout after the density.

Table 3 present the average width of breakouts results obtained in each drilled hole with HSS and carbide drills. The average width of breakouts is the average width of the pieces removed as chip measured on the face of the component surrounding the outlet edge (Robert-Perron et al., 2007a). The size of breakout zones frequently grown with increased porosity, and the mechanical bonds of the pore walls became incapable of holding the particles together. The breakout zones were usually bigger for steel foams drilled with the HSS drill bit. This is due to the fact that the HSS drill wears and breaks more quickly. The effect of the drill type on breakouts size was very prominent at high porosity, where increasing the porosity from 45.1% to 70.7% significantly increased the size of the breakouts. This is because the presence of macropores in the structure of foams causes vibrations during drilling. These observations are consistent with the literature, where an increase in the temperature of parts is related with its high porosity content, it leads to loss of strength and removal of the accelerated particle (Engstrom, 1983; Smith, 1998; Salak et al., 2005). According to most literature, the low-density PM part was associated with bigger breakouts than high-density PM part. This situation is explained that the forceful mechanical bonding between powder particles results in greater breakouts (Cimino and Luk, 1995; Robert-Perron et al., 2005). In the current study, it

Table 3. Average width of breakouts of drilled holes by HSS and carbide drills.

	Average width of breakouts (μm)	
Porosity (%)	HSS drill	Carbide drill
45.1	275 ± 36	215 ± 41
51.9	352 ± 31	307 ± 26
62.9	456 ± 47	419 ± 38
70.7	487 ± 28	451 ± 36

is possible that high porosity causes an increase in temperature, resulting in a more brittle structure. The average width of the breakout observed at the exit of the drilled hole becomes larger with the expansion of the damaged area at high porosity.

In order to explain the material removal mechanism in drilling, the drilled surfaces were observed by SEM. Figure 7a and b shows the surface finish of machined surfaces having similar porosity with carbide and HSS drill bits, respectively. Through the observation at SEM images, mechanisms of material removal were detected in the drilling of porous steel, namely, brittle fracture in different directions has also resulted in high surface roughness values on at portion of the machined surface. The drilled surfaces with both drills are not of similar quality. This is clearly observed in SEM images, which explains the marked differences in the surface roughness of the cut surface among the drilled workpieces with different drills. The surface has become smooth with the carbide drill. But the surface is rough with the HSS drill. Brittle fracture due to macro pores resulting from high porosity is simple to form along the grain boundaries as a result of vibration in the HSS. Some researchers (Robert-Perron et al., 2007a; Czampa et al., 2013; Obikawa et al., 2018; Tambani et al., 2018) have stated that there is serious flank wear on the HSS drill in PM machining; but, carbide drills provided the best surface finish. The size of the micropores within the steel foam is significantly larger than the machining marks left at the surface. A closer view of pore walls can be seen in Figure 8a and b, which shows microcracks obvious in the pore walls of drilled steel foams with carbide and HSS drill bits due to the effects of drilling, respectively. The distribution and densification of micropore of the pore wall consisted of incomplete sintering of the steel powders as well as the drilling process. Some microcracks were observed on the machined surfaces with both drill bits, however, the cracks are more evident and intense when using HSS drills. Traces of smearing can be seen on the surface drilled with HSS drill compared to the drilled surface with carbide drill which is smoother. It can also be said that the density of these microcracks increases with increasing porosity.

The hole quality in drilling can also be characterized by typical skewness values. The variation of skewness values of drilled by HSS and carbide drill

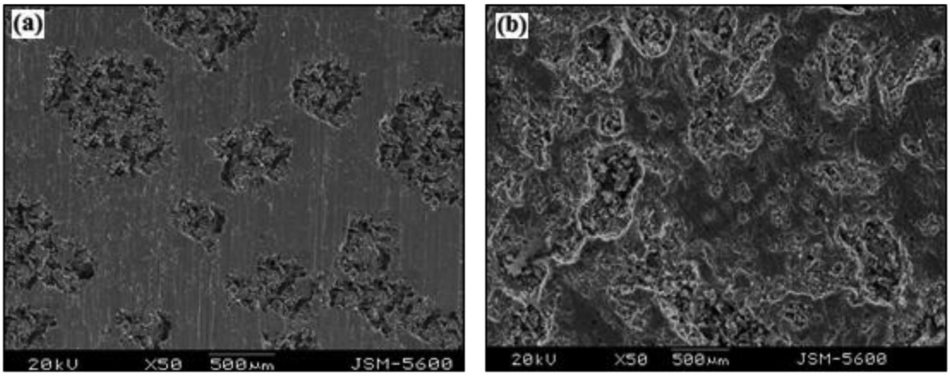

Figure 7. SEM images of drilled surfaces with (a) carbide and (b) HSS drills.

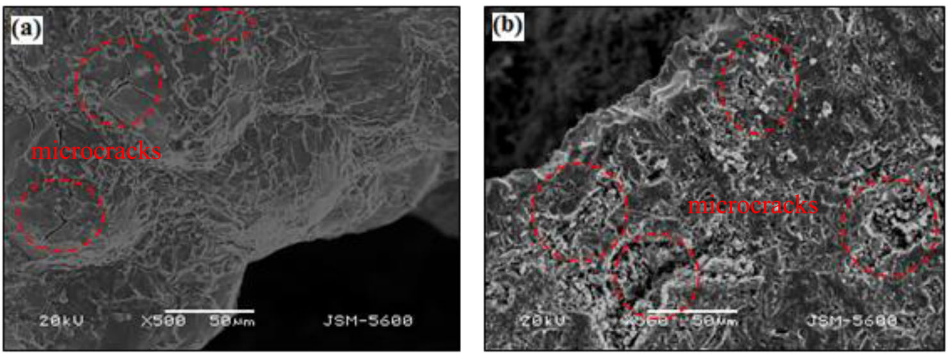

Figure 8. SEM images of microcracks formed in pore walls of drilled surfaces with (a) carbide and (b) HSS drills.

as a function of porosity was listed in Table 4. It is known that for a hole quality, a negative skew is useful (Gadelmawla et al., 2002). However, in the current study, all holes drilled by HSS and carbide drills showed positive skewness values for all porosities. This causes deep valleys to sharpen and become sharper, while sharp peaks tend to break on other surfaces. A skewed negative surface indicates a smoother and even surface, whereas a skewed positive surface indicates a rougher surface. The skewness values of the hole drilled by carbide drill are lower positive values. This result showed that the use of carbide tips not only produces lower surface roughness values, but also provides better bearing rates. For that reason, the hole surfaces machined by carbide drills were smooth. The results indicate that drilling of steel foams affects the hole quality due to the local deformation of the drilled surface with extremely dense porosity.

Chip formation

Chip formation is indispensable in understanding the machining performance and providing basic information about the cutting process (Heidari,

Table 4. Skewness values of holes drilled with HSS and carbide drills.

	Skewness values	
Porosity (%)	HSS drill	Carbide drill
45.1	2.81 ± 0.85	2.82 ± 0.75
51.9	3.05 ± 0.72	2.97 ± 0.67
62.9	3.72 ± 0.69	3.11 ± 0.82
70.7	4.86 ± 0.81	3.26 ± 0.79

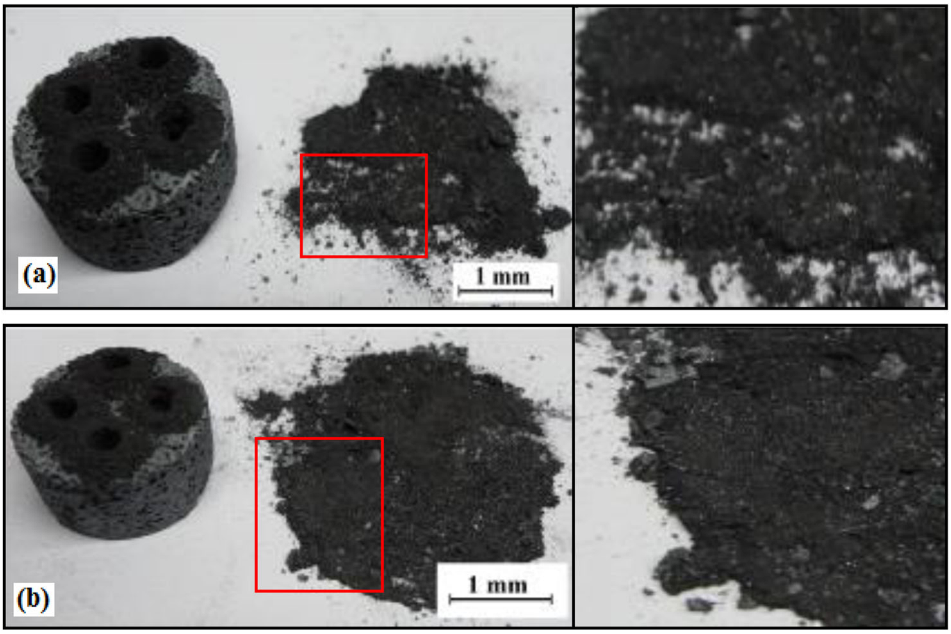

Figure 9. Chips formed in drilling processes of the foams: (a) carbide and (b) HSS drills.

2018). Figure 9 presented the appearances of chips generated from drilling operation. During the drilling of steel foams having different porosities, the chips were collected and examined to determine their general characteristics. Both the HSS and carbide-tipped drills broke the chips in powder form and produced discontinuous chips. Only plastic deformation of the metal occurs due to the very brittle structure of steel foam structures produced in this study when the cutting forces reach the yield strength of the material. Since there is no elastic deformation, the chip structure is in powder form (Heidari, 2018). The chips formed in the machining of porous materials are in powder form since the surfaces of the compacted pores are not cold-welded, although the cut occurs in a deformed layer (Salak et al., 2005). The standard chip forms were determined according to ISO 3685. The most desirable, the easiest to remove are the short and discontinuous chips. Particularly in drilling, this is a basic criterion, to ensure chip evacuation from the drill flutes. The formation of the short chip is important in terms of safety of the operator, the safety of the cutting tool and the

Table 5. The mean size range analysis results of the chip particles.

Drill type	Workpiece porosity (%)	Chip particle size (%) >150 μm (+100 mesh)	150–45 μm (−100 + 325 mesh)	<45 μm (−325 mesh)
HSS drill	45.1	48	36	16
	51.9	62	25	13
	62.9	74	16	10
	70.7	86	9	5
Carbide drill	45.1	49	33	18
	51.9	55	27	18
	62.9	69	17	14
	70.7	82	12	6

machine, the quality of the machined surface, and the ease of chip removal (Ozcatalbas, 2003). According to Ramulu et al., 2002, breaking the chips and discontinuous chips is necessary for an optimum machining process. The results in the current study indicate that with the use of different drill types has not seen a clear change on the chip shape. The colors of the chips extracted from the workpiece were very close to the color of the workpiece materials.

The size distributions of the chips varied with the porosity of workpieces and drill types used in cutting. After drilling, the mean size range of the chips was determined by particle size analysis. Table 5 presents the mean particle size range analysis of the chips formed in the drilling processes as a function of the porosity content and drill type. The chips formed in the drilling of steel foams exhibited large chip size differences by the change of porosity content. This is a consequence of different and big porosity contents of tested materials. The brittle structure formed by high porosity contributes to the formation of powder form chips as mentioned above. As the porosity increases, the average chip size range increases and more heterogeneous distribution occurs. High porosity may result in thicker chip sizes due to the size of breakouts. Chip particle size in drilling operations is not significantly changed by different drill types at similar porosity content. The initial portion of the hole formed in the HHS drilling are more significantly torn, and the presence of pores increase the likelihood of larger break chips. Hwang and Chandrasekar (2011) reported that the direct observation of the chip-tool interface indicates that the character of the contact state varies with the workpiece, but not with the drill type. This shows that the character of the contact condition depends on the workpiece feature rather than the degree of friction on the tool-chip interface.

Cutting forces in drilling

Another important machinability characteristic of materials is the cutting force that is produced during the metal removal process. The resulting

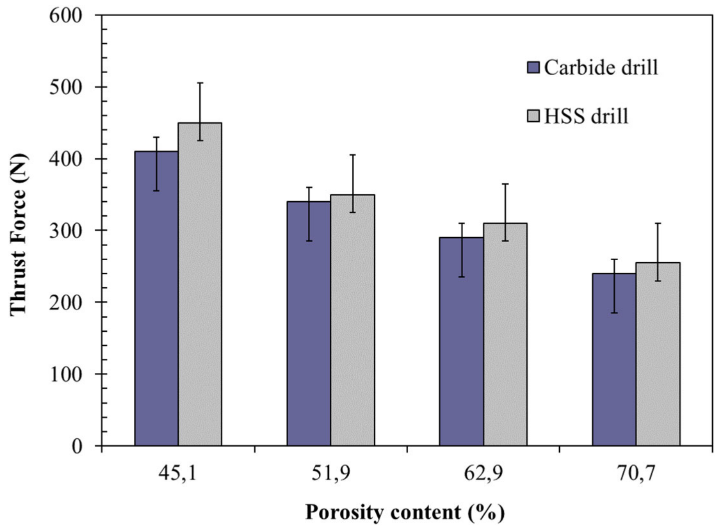

Figure 10. The effect of porosity content and drill type on the thrust force.

cutting force is normally divided into three units, namely feed force (Fx), thrust force (Fy) and cutting force (Fz). These values can be used to identify the tool and workpiece deviations (Tambani et al., 2018). Many researchers reported that the cutting forces acting on the cutting tool are a significant property of cutting, and the density of the material strongly influences the cutting forces (Cimino and Luk, 1995; Robert-Perron et al., 2005; Vitiello and Prisco, 2009). Additionally, the cutting forces are the ones most affected by tool type used in the machining (Vitiello and Prisco, 2009). Figure 10 illustrates the comparison of the thrust forces when drilling holes in workpieces having different porosities using a different kind of twist drills. The obtained values directly indicate the impacts of material porosity and drill type due to the constant cutting parameters.

Figure 10 indicates that the thrust force in the drilling of low porous steel foams is higher than that of high porous steel foams. The brittle material is removed with less machining pressure and lower cutting force (Jin et al., 2011). The result of this, the low cutting pressure that occurs in the machining of porous steel is caused by brittle fractures around the pores. Heidari (2018) reported that the cutting force in the porous titanium machining is lower than in pure titanium due to the presence of pores. The release of edge-induced stress reasons the existence of pores, and the removal of the brittle material results in lower cutting forces. Some researchers reported that the high volume fraction of porosity in the structure reduces the rupture strength value. However, these pores in the cutting area increase the stress that causes chip braking and consequently reduce the cutting force (Kvist, 1969; Blais et al., 2001; Salak et al., 2005; Heidari, 2018). Some results obtained in PM steel drilling tests showed that the high

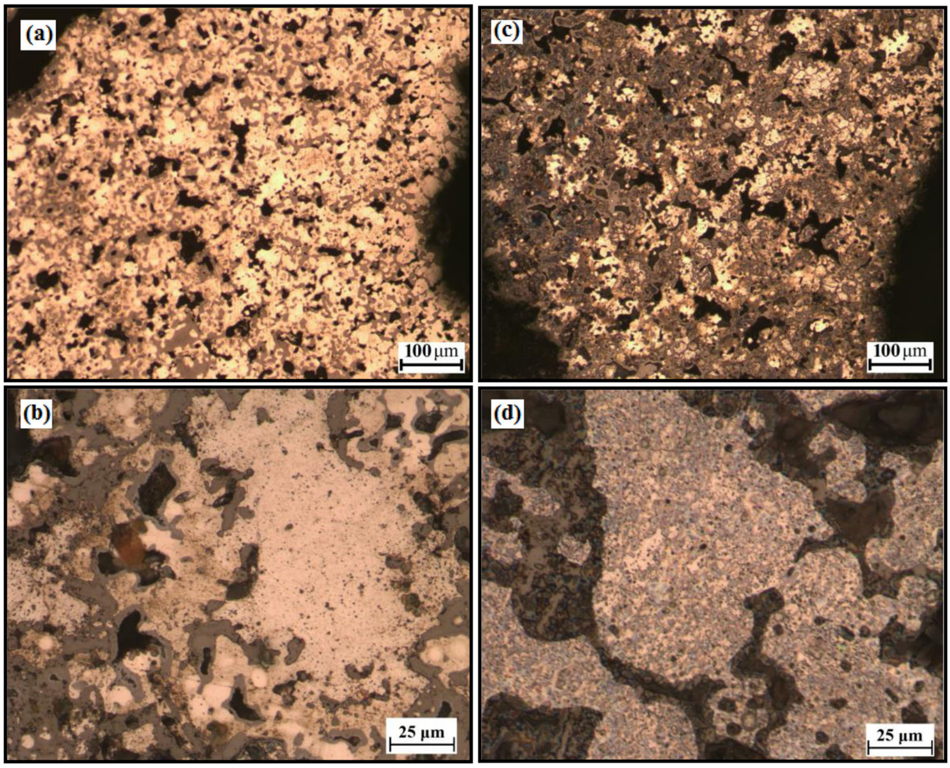

Figure 11. Microstructures from the pore wall of the steel foams: (a) and (b) unmachined, (c) and (d) machined.

porosity material was more easily machined with lower cutting forces (Blais et al., 2001; Robert-Perron et al., 2007a; Czampa et al., 2013). This implies that lower forces are required during the metal removal process in the machining of high porous material. The results obtained are in accordance with the literature. The forces generated by both drill tips showed a decreasing tendency with increased porosity. The carbide-tipped drills produced the lowest forces in comparison with the drilling forces generated by HSS drills as seen in Figure 10. The application of the carbide drill greatly increases the drill life and reduces the power requirement for machining. Drilling with HSS wants more energy to cut the workpiece material and consequently increases heat and cutting forces in relation to increased vibration (Czampa et al., 2013).

Microstructure and microhardness change of the drilled surface

There are structural factors that negatively or positively affect the machinability of PM steels. As we have discussed in detail so far, the porous structure in PM has negative effects on machinability. This is due to the

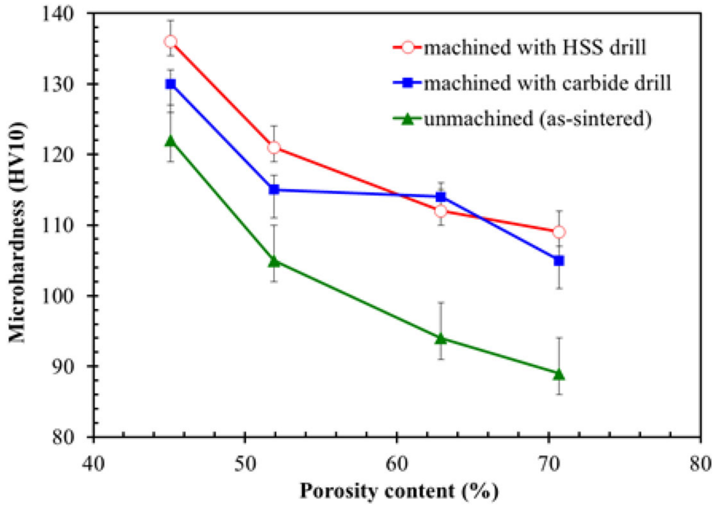

Figure 12. The microhardness changes on the machined surface with varied porosities after drilling operation by different drills.

continuous interruption of the tool edge when separating from the metallic phase into the pores (Höganäs, 2004a). Furthermore, the microstructure of the material, whether heterogeneous or homogeneous, affects the requirements of the machining process (M'Saoubi et al., 2014). The machinability of PM steels and wrought steel is quite different from each other due to porosity and generally heterogeneous microstructure (Salak et al., 2005). Figure 11 shows optic microstructure images taken from the pore wall of the unmachined (as-sintered) and machined steel foams having 62.9% porosity at different magnifications. Micropores in the pore walls of sintered foams clearly can be seen. The as-sintered specimen's microstructure is composed of ferrite, austenite, pearlite, and a few amount of bainite phases, but not the martensite phase. Figure 11b shows the changing microstructure area in the ferritic–pearlitic phases as a result of the temperatures reached in the machining, and the microstructure of machined steel foams are composed of pearlite, bainite and a few amount of martensite phases.

The microstructural analysis allows to at least partially define the effect of the drilling on the porosity. The machining characteristics of material should be defined accurately in relation to the microhardness of the microstructural constituents. Figure 12 presents the microhardness values of steel foams before and after machining with HSS and carbide drills. Although the effect of porosity on the hardening of the machined surfaces is very pronounced, the effect of the drill bit type is not excessive. The machined surface of the steel foams exhibits higher hardness on both drill bits. The microhardness test results have the same trend for both drill bits. The Vickers hardness of the surface of the workpiece exhibited an increase of approximately 7–18% and 11–19% after machining compared to that before machining with carbide and HSS drill, respectively. The hardness differences between the machined and the unmachined surfaces arise from the new microstructure formed during cutting. Many studies on machinability show that the microstructural components in the machined fields are significantly hardened by the cutting process (Salak et al., 2005, 2006; Heidari, 2018). Alizadeh (2008) reported that the work hardening results from plastic deformation or microstructure alteration on the machined surface. Robert-Perron et al. (2007a) reported that the increase in porosity results in reduced thermal conductivity of the PM material, which eliminated the ability of the workpiece to reduce the heat generated in the cutting zone. This causes work hardening at high temperatures locally generated in the cutting tool and workpiece contact zones. In another study, it was explained that the high hardness produced is mainly caused by the plastic deformation and the friction between the tool and machined surface (Jin et al., 2011). According to Engstrom (1983); increasing hardness can lead to hardening in material cutting during chip formation. Alizadeh (2008) investigated the microhardness to see the effect of different cutting edge shapes, and found that the cutting edges at the presence of porosity caused greater recession zones in front of the tool. He also found that due to these accumulated edges, material hardening that can be detected by increasing the microhardness in the chip formation zone occurs. Jin et al. (2011) reported that the deformation situation of the material in the cutting region increases with increasing porosity, and found that the increased hardness of the machined surfaces is the results of hardening arising from the effect of machining and material deformation. According to the hardness results in this study, high porous parts exhibited higher hardness change as compared to lower ones. This may be the effect of a wider specific surface area with a lower mass.

Tool life in drilling

Tool wear is a complex system that occurs in different forms. Typically, worn cutting tools negatively affect the surface quality of the workpiece. The principal problem in the machining of highly porous parts is the abrasive nature of the porous structure. Continuous interruption of the cutting action of the tool causes accelerated wear of the cutting edge due to the high pore presence in the material. The highly porous structure brings an unbalanced regime to the cutting edge, resulting in a shorter tool life (Kendall, 2005). Increased cutting edge temperature with reduced thermal conductivity is the direct result of porosity. These effects may result in the crater and edge deformation (Blais et al., 2001; Kendall, 2005; Robert-Perron et al., 2007c). In metal cutting, it is necessary to understand the

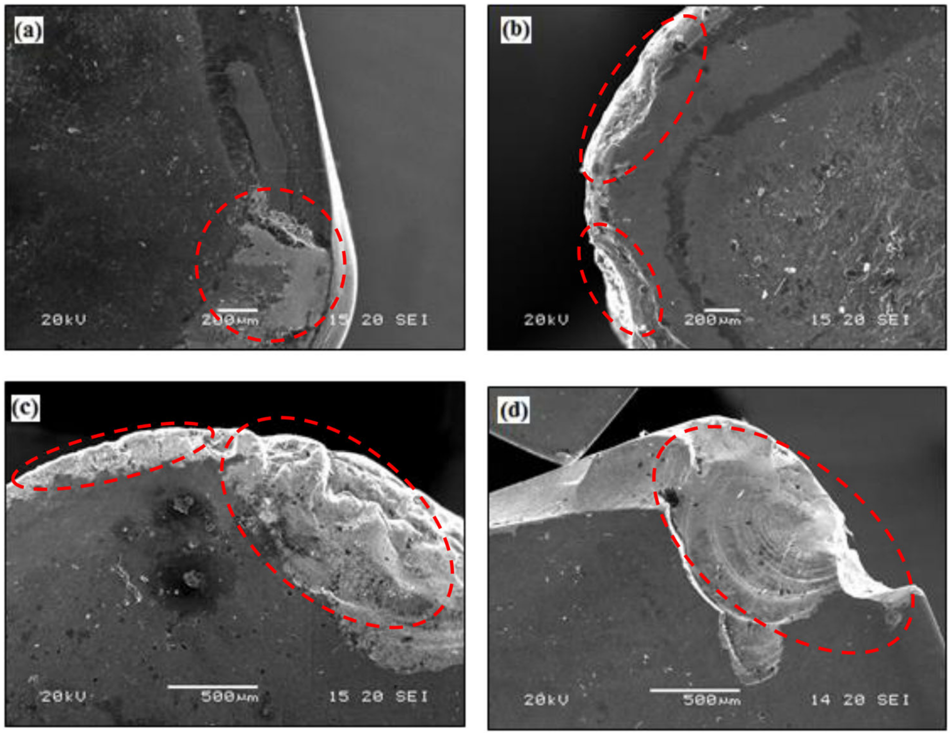

Figure 13. SEM images of drill wear in drilling with (a) carbide drill of workpiece having 45.1% porosity, (b) carbide drill of workpiece having 70.7% porosity, (c) HSS drill of workpiece having 45.1% porosity and (d) HSS drill of workpiece having 70.7% porosity.

factors affecting tool life for the most economical production and optimum tool life. All the consequences of porosity in workpiece structure shorten markedly the tool life in the studies on the machinability of PM steels (Engstrom, 1983; Smith, 1998; Salak et al., 2005; Heidari, 2018). However, systematic tool wear measurements involving high porous PM materials are rarely found in the literature. It is clear that the relationships between wear knowledge and tool life in dense PM materials cannot be expected to be valid for high porous structure. It should be noted that the effect of porosity on the workability of a porous material can be evaluated in combination with the cutting method and conditions, in particular the type of drill which is decisive for tool wear. For this reason, it is necessary to understand the drilling process in porous parts in order to select suitable tool material and produce high-quality holes. Figure 13 shows the drill wear status developed on the cutting edges of the carbide-tipped and HSS-tipped drills after drilling workpieces having 45.1% and 70.7% porosities. The criteria used in the study to determine the tool life could be listed as: visible abrasions on the tool and difficulty in drilling the parts resulting from this, and the change of sound and vibration increase in the machine. SEM images of the drill cutting edge were obtained after a maximum hole

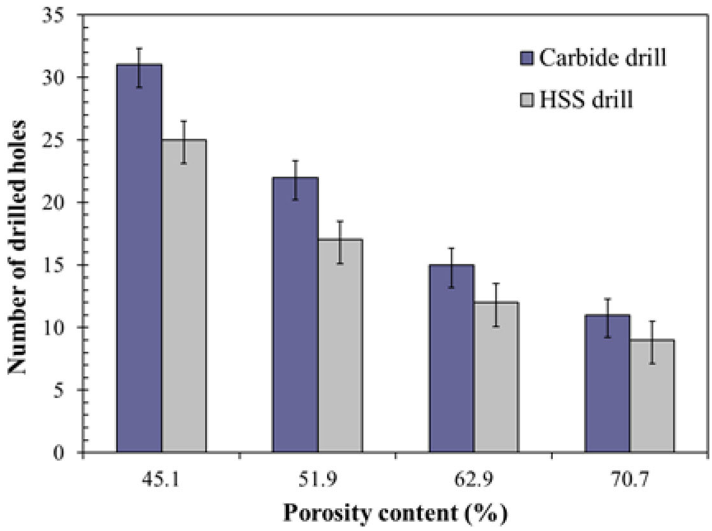

Figure 14. Effect of porosity and drill type on number of holes drilled for high porous steel workpieces.

number. The effects of porosity and tool type on the tool wear mechanism are seen clearly from these SEM images. Both drill bits suffered serious abrasion on their cutting edges because of the highly porous nature of steel foams.

The effect of porosity and drill type on tool wear is clearly revealed as seen in Figure 13. Unstable heat distribution due to high porosity plays a negative role in significantly worn tool coating. The friction movement between the drill bit edges and the hole surface contributes to edge wear and ensures poor surface quality as mentioned in the Hole quality in drilling section. The coating was peeled in the worn area due to wear and breakage of the cutting edge. In addition to the edge wear, flank wear when intense macro pore structure of steel foams impacted the tool edges was also clearly be seen in these figures. Salak et al. (2005) reported that there was a relationship between a wide range of flank wear and density for both the turning and drilling of sintered iron, and found that low-density materials failed due to flank wear, while edge wear was effective in the drilling of highly porous materials. Heidari (2018) showed that the high stress in the machining of high porous parts is one of the leading causes of rapid wear on tools. The cutting action of the tool on the machined surface is continuously interrupted which results in faster wear of the cutting edge. Material adhesion on tool face in high porosity PM steel cutting is lower than those in dense PM steel cutting when the studies in the literature are examined (Agapiou et al., 1988). This may be due to the lower contact pressure between the tool-workpiece and the low density of the structure. Reduction in the thermal conductivity due to the high porosity of steel foam structure may raise the cutting temperature. The poor performance of both drill bits at the higher porosity can be explained by the influence of the heat on the drill. This situation in the literature was explained that metal cutting involves a high amount of heat generation and does not rapidly dissipate due to the low thermal conductivity of this material when drilling high porous steel (Kvist, 1969; Hamiuddin and Murtaza, 2001; Czampa et al., 2013). The HSS drill with a significant degree of tool wears at relatively high levels, which performed poorly than carbide drill during the drilling test. This also explains why the hole quality is poor as mentioned in the Hole quality in drilling section. In the drilling process with HSS drill, peeling of coating, breakage and but built-up edge BUE were observed on the cutting edge as shown in Figure 13d. The edge wear was found to be more severe with increasing porosity. This could be due to the unstable relationship between the drill edge and the machined surface at the expense of high porosity in steel foams. Less wear was found because of the superior hardness of carbide drills compared with the HSS drill bit, but BUE was detected at the cutting edges. Obikawa et al. (2018) reported that the thermal damage of cutting tool would be increased by distribution and adhesion at the tool-chip and tool-work interfaces, and found that the drill has a longer tool life when cermet and coated carbide drills are used in drilling sinter steels. A marked effect of flank wear caused by porosity on the number of holes drilled (drill life) for porous workpiece was determined. The average number of holes drilled before the final tool breakage occurred was determined the relative machinability. Figure 14 presents the relative machinability of the drilled steel foams having different porosity using a different kind of twist drills in the drilling operation.

Drill life is highly sensitive to the porosity content of the workpiece material and tool wear. The carbide drill bits used in drilling steel foams having 45.1%, 51.9%, 62.9% and 70.7% porosities damaged after 31, 22, 15 and 11 through holes, respectively. HSS drill at similar porosity damaged after 25, 17, 12 and 9 through holes, respectively. The increase in porosity caused a marked decreased in drill life (low number of drilled holes) with the use of both drills. Negative impact of machinability with increasing pore rate is also related to increasing open pore rate. Alizadeh (2008); reported that the wear effect of the workpiece material on the cutting tool is due to the pores in the material structure. Benner and Beiss (2004) reported that the tool life is strongly affected by the porosity of the workpiece, and found that the increase in porosity reduces the contact between the tool and the porous workpiece and increases contact pressure on the tool flank. Furthermore, another study explained that as the porosity of the material increases, the thermal conductivity decreases and the cutting temperature rises, thereby increasing thermal wear (Robert-Perron et al., 2007c). Hamiuddin and Murtaza (2001), Kulkarni and Dabhade (2019), Salak et al., (2005) and Heidari (2018) reported that the deformed layer thickness and plastic deformation increase as the tool wears out due to porosity, microstructural and microhardness alterations. The present results demonstrated that the worst results were obtained in the use of the HSS drill. The carbide-tip drill gives acceptable results at similar porosity. The results obtained in this study indicated that the tool wear caused the impacts specific to the high porous steel foams should be considered different from those studied so far. Based on our results, it was concluded by that decrease the porosity of workpiece improves the drilling status, extends tool life and maintains the dimensional geometry accuracy of the machined hole.

Conclusions

The research work summarized in this article deal with the characterization of the effect of porosity and drill type on the machinability of Cu-Ni-Mo based steel foams in the drilling operations. The main conclusions of this work can be summarized as follows:

- The hole quality of the steel foams decreased with the increasing porosity when drilling with both drill bits. The large BUE formed at high porosity increased the surface roughness.
- The carbide drill showed acceptable drilling forces and hole quality compared with the HSS drill.
- The effect of the drill type on the size of breakouts was clearly determined at high porosity. The larger damage was observed at the exit of the drilled holes with HSS drill, which cause a significant increase in microcracks of around pore walls.
- The skewness values were determined as positive by both drills in all porosities. The skewness values of the hole drilled by carbide drill showed a lower positive value.
- Both drills broke the chips in powder form and produced discontinuous chips. It was not seen a clear change on the chip shape with drill types.
- The thrust forces generated by the HSS drill bit were slightly higher compared to the carbide drill at all porosity rates. The increased porosity content resulted in a decrease in thrust forces for both drill bits due to the brittle fractures around pores.
- There is a significant difference in hardness between unmachined and machined workpiece surfaces, but not between the drilled surfaces with both drills.

- Intense presence of pores decreases the tool life remarkably in the use of both drills. Drilling process of low porous materials failed primarily because of flank wear while the edge wear predominated in high porosity material drilling.
- In the light of the literature reviewed, the machinability of PM materials consists chiefly of research from PM industries, further theoretical and experimental investigations on the characteristic effects such as shape and distribution of pores is required, especially for highly porous PM steels. I hope that this study will help researchers working on the subject.

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Notes on contributor

Assistant professor Dr. Nuray BEKOZ ULLEN is currently working in the Department of Metallurgical and Materials Engineering, Istanbul University-Cerrahpaşa (IUC), Turkey. She obtained her BSc, MSc and PhD degree at Department of Metallurgical and Materials Engineering from Istanbul University, Turkey in 2003, 2006 and 2011, respectively. Her main research interest includes powder metallurgy, metal foams, coating technology, surface treatments, material characterizations, machinability and welding. In recent years, she has focused on improving the surface properties of dense porous materials. She has collaborated actively with researchers in several other disciplines of mechanical, chemistry and physics. She has taught on engineering materials and deformation mechanisms, highly porous material production techniques and characterization, failure of materials. She had role as a consultant in master theses in the fields of material characterization. She has published several research articles on material production, characterization and processing.

ORCID

Nuray Bekoz Ullen http://orcid.org/0000-0003-2705-2559

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