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Impact of Chilled Air Nozzle Types on Surface Integrity in Drilling of Aluminum Alloy 1050

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ABSTRACT

Using cutting fluid in the machining process for Aluminum Alloy 1050 is advantageous as it helps mitigate the effects of temperature generated during cutting. It can shorten tool life and impair the quality of machine parts. Despite its benefits, cutting fluids has several disadvantages, such as high expenses, potential environmental harm, and user health risks. This research evaluates the effects of green cutting conditions, particularly nozzle types, on the metallurgical properties of the material. Their impacts on tool wear, X-Ray Diffractometer (XRD) pattern, Full Width at Half Maximum (FWHM), crystallite size, and hardness during the drilling process were investigated. The findings indicate that using chilled air with dual nozzles for cooling and lubrication is highly effective, resulting in less tool wear and a relatively purer crystalline structure of the material compared to other conditions. These results emphasize the importance of controlling cutting conditions, especially nozzle types, to produce high-quality parts with improved metallurgical properties.

1. Introduction

Aluminum, which is naturally soft and has a low melting temperature, may not be ideal for industrial use due to the formation of a slimy coating during cutting or machining that can damage tools [1]. To address this issue, aluminum is often mixed with alloying elements like copper, magnesium, and manganese to create aluminum alloys [2]. These alloying elements are denoted by a series number, ranging from 1 to 8, indicating aluminum's purity in the alloyed metal [3]. The addition of alloying elements modifies the mechanical and chemical properties of the alloy, making some alloys easier to cut, shape, or mill compared to others. Aluminum alloys, with their manipulable properties and high ductility, are widely used in various industries such as aerospace, automotive, and general engineering [4]. One of the most used aluminum alloys is Aluminum Alloy 1050 (AA1050). It is a soft aluminum alloy that is easy to form and shape, making it ideal for applications that require

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a high degree of formability [5]. Although this material is known for its good machinability, it can still develop a Built-Up Edge (BUE) during machining, which has the potential to adversely affect both the surface finish and the durability of the cutting tool [6]. To mitigate this issue, using sharp cutting tools with appropriate cutting parameters is recommended for machining AA1050. However, during machining operations, the cutting edges experience heating and cooling cycles, resulting in expansion and contraction due to temperature fluctuations, which can lead to fatigue [7]. The high temperatures can also cause damage to the aluminum workpiece and the cutting tool, as the material can become sticky and adhere to the cutter [8]. Elevated temperatures concentrated within a limited section of the tool-workpiece interface can significantly impact various quality parameters, such as tool wear, tool longevity, surface quality, precision, and the formation of chips [9]. The use of coolants or lubricants during machining can help reduce heat buildup and improve surface finish. Nevertheless, cutting fluids has some drawbacks, including high costs, negative environmental impacts, and health risks to operators [10]. Direct skin contact with cutting fluids has been linked to 80% of operators' occupational injuries, leading to medical complications [11]. Purchasing, maintaining, and disposing of cutting fluids can significantly increase manufacturing costs by up to 20% compared to tool replacement [12]. The fluid must be properly disposed of once it has chemically and biologically degraded to the point where it can no longer function effectively, as it can otherwise corrode or oxidize the tool and workpiece. In the final stage of its life cycle, the fluid is considered hazardous to users and highly toxic to aquatic life [13]. Although chlorine additives have been used in cutting fluid disposal treatment, they are still classified as hazardous waste and threaten the environment.

Dry cutting [14], Minimal Quantity Lubrication (MQL) [15], cryogenic cooling [16], chilled air [17], and solid lubricants [18] have been proven to be effective alternatives to conventional lubrication processes for improving machining performance and reducing hazards. Chilled air drilling, in particular, is a unique cutting fluid produced using a vortex cold air cannon and aided by technology. Consequently, the chilled air is cooled through a system that directs high-pressure air from a compressor into a vortex nozzle. Since no additional lubricant is used, the chilled air is clean and odorless [19]. Producing chilled air is easy and cost-effective, as it only requires air from a compressor, and it is also safe for operators and environmentally friendly, posing no risks. Moreover, a literature review reveals that most research on aluminum alloys has focused on their effects on tool wear, surface roughness, and burr and chip formation, with limited or no scientific investigation into their impacts on metallurgical properties. The metallurgical properties of a material, including its microstructural qualities and hardening effect [20] caused by a worn tool, can significantly influence its performance in a given application, such as its strength, toughness, ductility, and hardness. White layers, among the features within surface integrity, represent one of the most crucial aspects due to their potential to significantly influence the performance and anticipated lifespan of a component during service [21]. In addition, it was discovered that the presence of a white layer on the machining surface led to extremes in near-surface residual stress [22]. Therefore, the higher hardness observed in cross-sectional samples for the white layer compared to the bulk material must result from a combination of work hardening and grain refinement. Again, extremely high strain rates experienced during machining when compared to other production processes [23]. It was reported that by utilizing XRD inspection, the influence of machining-induced surface integrity across all aeroengine alloys suggests that measuring the XRD peak breadth may serve as a useful method for detecting anomalous surfaces [20]. Still, there is a lack of research on the influence of drilling aluminum alloys using three different chilled air nozzles from a cold air gun: the single nozzle, dual nozzle, and anti-frost nozzle on machining-induced surface integrity.

2. Methodology

2.1 Experimental Setup and Machining Conditions

The workpiece material was an AA1050 plate, with the size being 150 mm length, 150 mm width, and 4 mm height in dimensions. Here, the composition of AA1050 was confirmed by arc spark analysis. The results of the arc spark experiment confirmed that the specimen being tested was AA1050. Subsequently, the arc spark experiment results have been recorded and tabulated in Table 1, presenting the specific composition of AA1050 in weight percentage. In addition, Figure 1 illustrates the X-Ray Diffractometer (XRD) pattern for the original, undeformed aluminum alloy specimen. The peaks represent the different crystalline phases present in the specimen, and the heights represent the relative abundance of each phase.

The cutting tool selected was a 2-flute High-Speed Steel (HSS) drill bit with 6.0 mm in diameter. All tools were inspected using an optical microscope prior to the machining process to examine their geometry and cutting-edge radius quality. Note that this drilling experiment was conducted using the Haasbuilt-VF-2-CNC Vertical Mill machine. A constant cutting velocity of 110 m/min, feed rate of 0.2 mm/rev, and depth of cut of 20 mm were used as established from pilot tests.

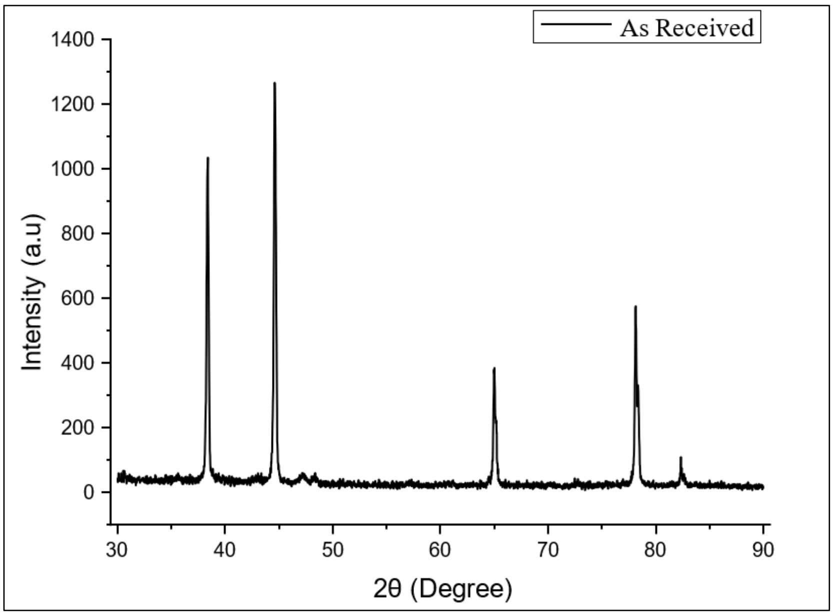

Fig. 1. XRD Pattern for As Received AA1050

Table 1
Specimen Component Percentage

Element	Composition (%)
Aluminium, Al	99.43
Silicon, Si	0.084
Iron, Fe	0.367
Copper, Cu	0.063
Manganese, Mn	0.019

Two cutting conditions were utilized in this particular experiment: dry cutting and chilled air. Chilled air was generated using a VORTEC adjustable cold air gun, as illustrated in Figure 2. It is powered by compressed air, with no specific gas employed but drawing from the surrounding air. It was used to convert filtered compressed air into a cold air stream down to as low as -35℃, with an airflow speed of 8.3 m/s. In addition, this experiment focused on manipulating three different types of nozzles used, as displayed in Figure 3 in the vortex tube: a single nozzle cold air gun, a dual nozzle cold air gun, and an anti-frost nozzle cold air gun, all of which were tested. VorTech UK supplied the system used: Model 610BSP, Adjustable Cold Air Gun System, which has a magnetic base and filter. Figure 4 shows the experimental setup for drilling AA1050.

Fig. 2. A VORTEC adjustable cold air gun

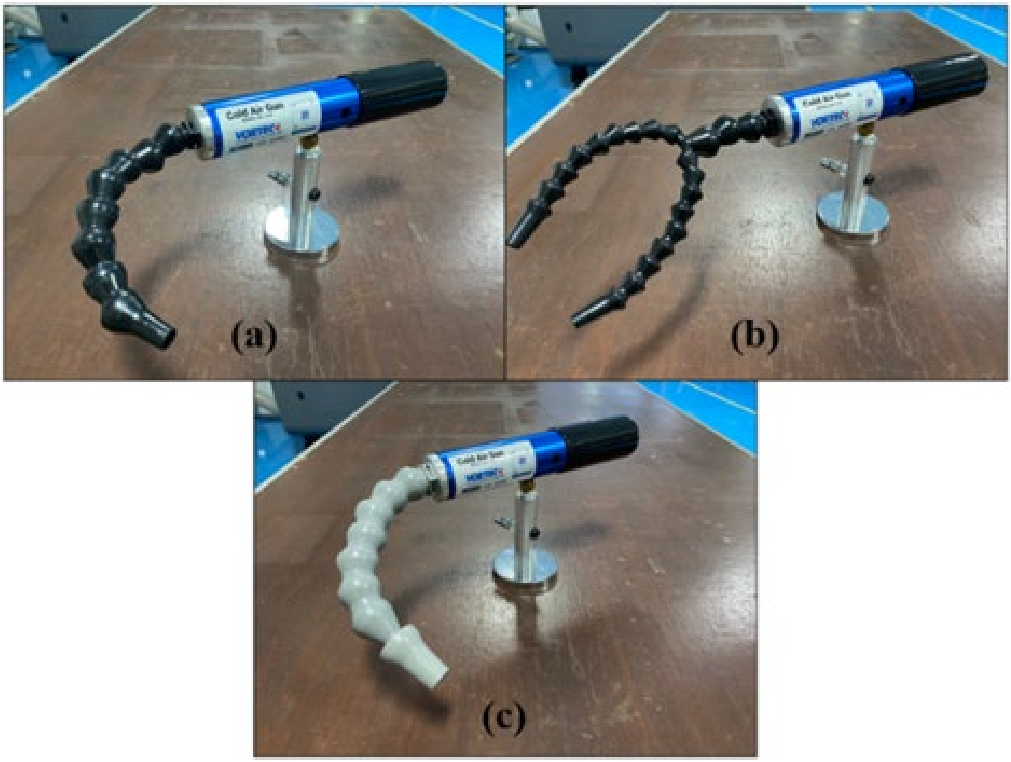

Fig. 3. Three different types of nozzles (a) single nozzle (b) dual nozzle and (c) anti-frost nozzle

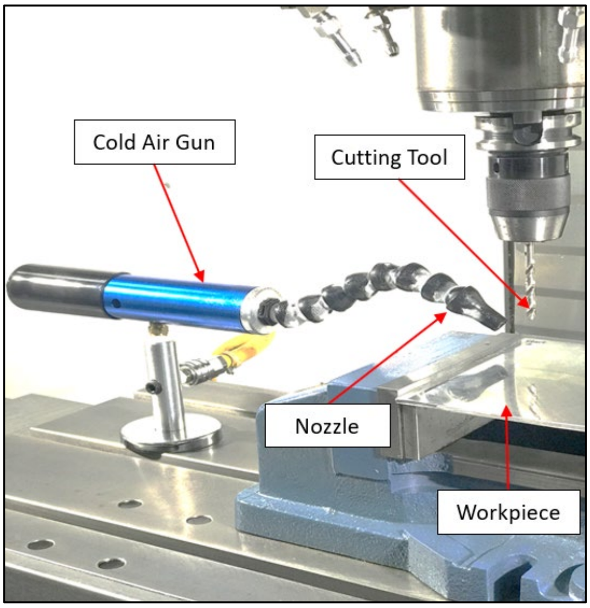

Fig. 4. Experimental setup for drilling AA1050

2.2 Tool Wear, XRD Pattern, Full Width at Half Maximum (FWHM), Crystallite Size, and Hardness

Each tool was then examined using the Xoptron XST60 Stereo Microscopy System to measure average flank wear (V_B). Consequently, their impact on the workpiece machined surface was investigated in terms of crystal structure and orientation using the Shimadzu 6000 XRD. The instrument is highly precise and capable of detecting small variations in the crystal structure of a material. Note that the hardness of each specimen was measured using an MHV-50Z Digital Vickers Hardness. This was done near the drilled hole zone to determine the work-hardening effect. Before indentation, the specimen was polished with 6, 3, and 1-micron diamond slurry monocrystalline paste to obtain a mirror-like surface free from scratches. Systematic uncertainties were minimalized by first calibrating the equipment to be used. In addition, random vagueness was addressed by performing each measurement at least five times.

3. Results
3.1 Tool Flank Wear

In this experiment, several types of wear can be observed: chipping, chisel, and flank. For all different types of chilled air nozzles, the most dominant wear was at the flank face, resulting in flank wear. To analyze V_B, the lines were drawn parallel with the cutting edge to the end of the wear area according to ISO 8688-2 [24]. Table 2 presents average flank wear under all cutting conditions after 30 holes were drilled. Here, chilled air with a dual nozzle displayed the most significant result in minimizing wear. Since heat is a major factor that causes thermal degradation of the cutting tool material, a dual nozzle helps to dissipate heat generated during machining processes more effectively. This system provides a larger coverage area than a single nozzle system. With two nozzles, the coolant or cutting fluid can be directed from multiple angles, resulting in a wider coverage of the cutting zone, including the tool and the workpiece.

Table 2
Average Flank Wear

Condition	Average Flank Wear (mm)
Dry cutting	0.15
Chilled air with single nozzle	0.11
Chilled air with dual nozzle	0.02
Chilled air with anti-frost nozzle	0.03

In addition, the observation of tool wear outcomes revealed the presence of a heat affected zone (HAZ). It is evident that dry drilling exhibits the highest degree of tool surface burn, followed by the anti-frost nozzle. Conversely, both the single and dual nozzles display relatively lower levels of tool wear in terms of burn marks. The occurrence of tool wear can be attributed to gradual alterations in the tool's geometry and a rise in cutting temperature at the interface between the tool and the workpiece.

Under dry machining, the cutting tool's edge appeared blackish (Figure 5) on the surface where it contacts the workpiece. This discoloration indicates the occurrence of a HAZ, which is caused by excessive heat generated during continuous contact between the tool and the workpiece. The HAZ can dominate over the flank wear, which is the wear that occurs on the side of the tool due to the severity of the heat generated during machining. This can lead to decreased tool life and reduced machining efficiency. It is, therefore, important to carefully manage the temperature during machining processes to avoid excessive heat buildup and minimize the impact of the HAZ on the tool's performance.

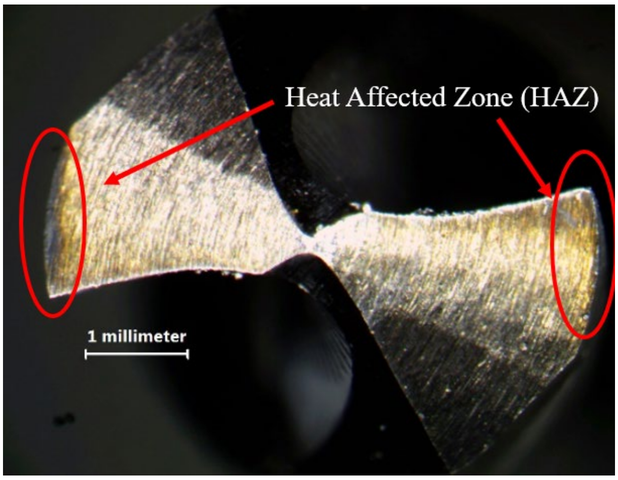

Fig. 5. Heat Affected Zone under dry cutting

The upcoming sections will examine how tool wear impacts crystalline phases, crystallite size, and hardening effects on drilled surfaces. This investigation aims to understand the relationship between tool wear and the quality of drilled materials, providing insights into potential implications for practical applications. Hence, analyzing changes in these parameters can offer valuable information for optimizing drilling processes and improving drilled component performance.

3.2 XRD Pattern

Figure 6 depicts the XRD patterns for various cutting conditions, compared to the as-received specimen shown in Figure 1. Notably, all cutting conditions, particularly dry cutting and chilled air with a single nozzle, exhibit reduced intensity in the XRD peaks.

The decrease in peak heights during dry cutting could be attributed to mechanical deformation, which distorts the material's crystal structure. The absence of cooling and lubrication during dry cutting can generate high friction and heat at the cutting edge, leading to disordered atoms and the formation of defects such as dislocations, twins, and grain boundaries. Another possible reason for the reduced peak heights could be the effect of high temperatures on the sample, causing increased atomic vibrations and resulting in broader and lower peaks in the XRD pattern. Similar findings were also established by [17].

In contrast, chilled air with dual and anti-frost nozzles shows higher intensity peaks closer to the as-received specimen. This suggests that the material's crystalline structure is relatively purer and less susceptible to deformation under stress or strain. This could be due to the samples recovering from deformation, where the material is restored to its original, undeformed state. Note that chilled air with dual and anti-frost nozzles may have provided effective cooling and lubrication, preventing excessive friction and heat generation during drilling.

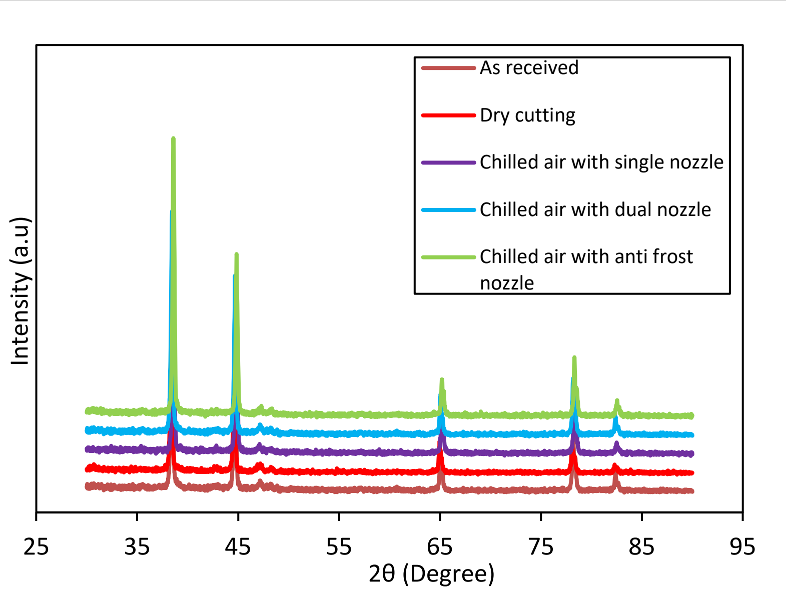

Fig. 6. XRD Pattern Under Various Cutting Conditions

3.3 Full Width at Half Maximum (FWHM)

The Full Width at Half Maximum (FWHM) of a diffraction pattern in an XRD spectrum reflects how sharp the peaks are, which is related to the sample's crystallinity and quality. It is used to determine the size of crystallites, with smaller values indicating smaller crystallite sizes. Note that smaller FWHM values mean sharper and more defined peaks, while larger FWHM values mean broader and less defined peaks.

Table 3 presents peak width and FWHM values for various conditions. The original specimen's FWHM value is lower than most drilling cases, except for chilled air with a dual nozzle. Therefore, a higher FWHM value after deformation suggests that the crystal structure of the material has become less ordered and more disordered, possibly due to the introduction of defects or disruptions. The only exception is chilled air with a dual nozzle, which displays a lower FWHM value than the original. This indicates that the crystal structure has become less disordered, potentially due to material recovery from plastic deformation. Larger crystallites have a lower ratio of grain boundary to dislocations, which can lead to lower strength [25].

Table 3
Peaks Width and FWHM Values of Each Specimen Conditions

As Received	Dry Cutting	Anti-Frost	Dual Nozzle	Single Nozzle
0.1771	0.1378	0.9446	0.1968	0.1968
0.2165	0.6298	0.2165	0.1574	0.1181
0.4723	0.551	0.4723	0.0960	0.1968
0.1378	0.4723	0.4723	0.1181	0.1920
0.1378	0.1574	0.0984	0.1574	0.1440
0.2283	0.3897	0.4408	0.1451	0.1695

The FWHM values can also be used to determine the crystallinity of the sample, with higher crystallinity corresponding to smaller FWHM values. The crystallite sizes are determined using Scherrer's equation [26], and it was determined that the average crystallite sizes are in the range of 21-33 nm, as presented in Table 4. The size and shape of the crystals in a deformed specimen can be affected by the amount of strain the material has undergone. As the material is deformed, the strain can cause the crystals to become elongated or distorted, changing their size and shape.

Table 4
Average crystallite sizes and strain

Specimen Conditions	Crystalize Size (nm)	Strain
As Received	26.28	0.73
Dry cutting	21.80	1.20
Chilled air with single nozzle	24.76	0.88
Chilled air with dual nozzle	32.90	0.64
Chilled air with anti-frost nozzle	27.55	1.10

3.4 Hardness

Figure 7 illustrates the average hardness values of machined and as-received specimens near the drilled hole zone to evaluate the work-hardening effect. The results demonstrate that the dry-cutting method generates the highest hardness [17] due to the significant heat from drilling, resulting in increased tool wear. This increased tool wear can cause more plastic deformation and compressive residual stress on the workpiece, contributing to a harder surface. This result agrees with other works on the same alloy [27]. As the cutting edge wears down, the material requires higher force to deform, leading to larger strains and deformations in the workpiece and, ultimately, higher residual stresses. On the other hand, using chilled air with dual nozzles results in the lowest hardness level closer to the received specimen since it is more effective in maintaining the sharp edges of the cutting tools. A sharper cutting tool can more readily penetrate and deform the workpiece.

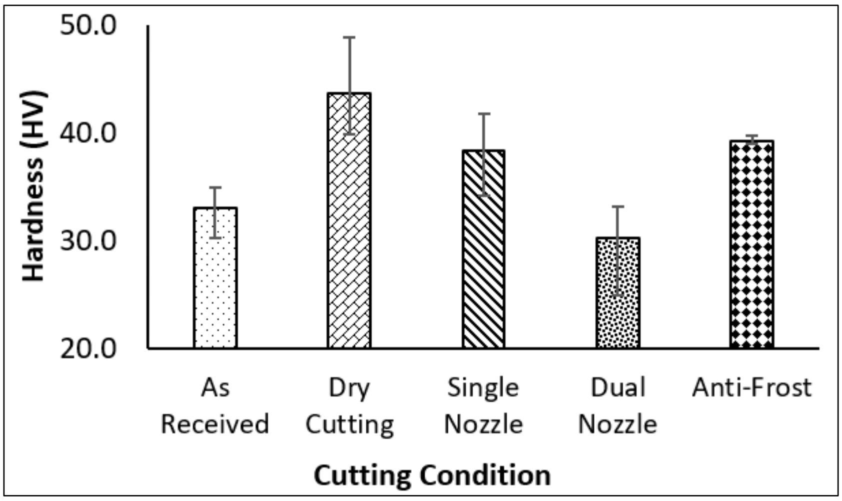

Fig. 7. Average Hardness Values Under Various Cutting Conditions

4. Conclusions

In summary, the experiment investigated different types of nozzles in the drilling process of Aluminum Alloy 1050. It analyzed the effects on flank wear, XRD pattern, FWHM, crystallite size, and hardness. The results presented that chilled air with a dual nozzle provided effective cooling and lubrication, resulting in a relatively purer crystalline structure of the material and less tool wear. Dry cutting, on the other hand, caused high friction and heat at the cutting edge, leading to disordered atoms and the formation of defects. After deformation, the FWHM value indicated that the material's crystal structure became less ordered and more disordered, except for chilled air with a dual nozzle, which displayed a lower FWHM value than the original, indicating material recovery from plastic deformation. In terms of the impact of work hardening, dry cutting generated the highest hardness due to the significant heat produced from drilling, resulting in increased tool wear. Overall, the findings suggest that selecting the appropriate cooling technique for nozzle types is crucial to optimize the drilling process and improve the quality of drilled materials.

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