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Cryogenic manufacturing processes

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ABSTRACT

Cryogenically assisted manufacturing processes are emerging as environmentally-benign, toxic-free, hazardless operations, producing functionally superior products. This paper presents an overview of major cryogenic manufacturing processes, summarizing the state-of-the-art and significant developments during the last few decades. It begins with a summary of historic perspectives, including definitions, scope, and proceeds to analysis of process mechanics and material performance covering tribological and thermo-mechanical interactions, followed by surface integrity, product quality and performance in cryogenic manufacturing. Process analysis and applications includes machining, forming and grinding. Economic, safety and health issues are then discussed. Finally, progress in developing predictive performance models and future outlook are presented.

1. Introduction

1.1. Historical perspective, definitions and application range

For over a century, the science and technology of producing low temperature environments is generally referred to as cryogenics, even though more scientific and precise definitions emerged later. The word “Kryos” has its Greek origin, meaning cold and frost. In 1877, Cailletet and Pictet (Paris) liquefied oxygen [199]. Heike Kamerlingh Onnes at the University of Leiden (Netherlands) was the first to build a cryogenic laboratory for the production of very low temperatures in 1882, and this lab became the leading center for cryogenics for over five decades. In 1898, Dewar (London) showed liquefaction of hydrogen, and in 1908, Heike Kamerlingh Onnes liquefied helium, which led to the discovery of superconductivity in 1911.

There are inconsistencies in identifying at what point on the temperature scale refrigeration ends and cryogenics begins. However, most research and standards organizations assume that it starts at or below −150 °C (123 K; −238 °F). The Cryogenic Society of America defines cryogenic temperatures as being temperatures below 120 K (−244 °F, −153 °C). Gunston [79], along with the National Institute of Standards and Technology (NIST) consider cryogenic temperatures below −180 °C (−292.00 °F or 93.15 K). This appears to be a logical dividing line, as the normal boiling points of numerous permanent gases (e.g., helium, hydrogen, neon, nitrogen, oxygen, and normal air) are all below −180 °C, while the Freon refrigerants, hydrogen sulfide, etc., have boiling points above −180 °C.

1.2. Origin of cryogenic material processing

Liquid nitrogen (LN_2) is most commonly used in cryogenics due to its widespread availability worldwide. The earliest use of liquefied gases as coolant in machining operations is reported by Reitz [184] in 1919, where carbon dioxide (CO_2) was used as a coolant in machining. During World War 2, scientists found that metals frozen to low temperatures showed more wear resistance. This led to the development of cryogenic hardening. In 1966, the term cryogenic processing was first introduced by CryoTech Company (Detroit, MI, USA), when they showed a 200–400% increased life in metal tools by cryo-tempering. Cryogenic engineering application guidelines were established early in 1976 [61], and more recently by ASHRAE [6].

Despite these established definitions and practices, in processing operations, various researchers have used the term cryogenics

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to refer to temperatures below 0 °C, largely including CO_2 applications [1,45,60,136,220,238].

The term "cryogenic machining" was first used by Uehara and Kumagai in 1968 [221]. In machining operations, liquid gases such as nitrogen, carbon dioxide and helium are used as alternative coolants to traditional oil and water-based coolants/lubricants. Cryogenic machining furthermore aids in altering material properties of cutting tool and workpiece material as well as dissipation of the heat generated at the cutting zone [57,91,93]. In this way, cryogenic machining was shown to have the ability to generate engineered surfaces while reducing/eliminating damage induced by the heat from the machining process.

1.3. Sustainability concerns in manufacturing on the use of cutting fluids and progress in sustainable manufacturing operations

In recent years, using the principles of sustainability science and engineering in new product development has been an emerging trend in manufacturing, as well as a major research focus. The indiscriminate and abundant use of cutting fluids in manufacturing processes and the associated costs and energy consumption has been a major sustainability concern.

1.3.1. Moving from flood cooling to dry and near-dry machining

The use of water as a coolant in machining processes dates back to 16th century [26]. However, the modern application of oil and water-based cutting fluids became common in the early 20th century in machining of steel alloys. Cutting fluids lubricate the cutting zone to control abrasion and can improve heat dissipation from the cutting zone and therefore reduce the thermal and chemical wear mechanisms whilst improving part quality [29,44,64,88,204]. On the other hand, recent studies [2,205,208] have indicated that exposure to cutting fluids is related to the later development of various types of cancers, dermatitis and respiratory diseases. The most recent well-documented CIRP keynote paper by Brinksmeier et al. [24] reviews the progress made in developing metalworking fluids.

When coated cutting tools were introduced in the early 1970s, dry machining operations emerged as sustainable processes. However, with over four decades of active research and applications, dry machining has not yet found widespread use, largely due to lack of effective coating materials and technologies and the ever-increasing application range. Near-dry machining (also known as MQL, Minimum Quantity Lubrication) emerged in the 1990s as a progressive and more sustainable solution to significantly reduce the amount of coolants/lubricants in machining applications. While the application range for such machining still continues to expand with improved machining performance in terms of tool-life, surface roughness, power consumption, etc., the actual effectiveness of such applications is somewhat limited. Also, the environmental and health effects of such mist application are still not well-known. Well-documented CIRP keynote papers on these topics can be found in Klocke and Eisenblatter [119], Byrne et al. [27], and Weinert et al. [234].

1.3.2. Significance and impact of cryogenic manufacturing

In cryogenic machining, which has been shown to be a sustainable alternative to conventional metalworking fluids, a liquefied gas, typically LN_2, is used to replace conventional cutting fluids. Nitrogen is an inert, non-hazardous, non-toxic, non-flammable, colorless and odorless gas, which constitutes 79% of air [105,170]. It is lighter than air, and disperses into air after application, thus reducing the requirements for maintenance, post-machining cleaning and disposal [37,46,86,89,97,141,207]. Also, lower temperatures result in increased hardness and toughness in the cutting tool material, which in turn allows higher material removal rates, and therefore lower energy consumption and higher productivity [105,113,191,206]. Recent studies report that cryogenic cooling has significantly improved the functional performance of machined components in terms of wear and corrosion resistance, and fatigue life [105,113,167,168,224,242]. Fig. 1 shows the three major sustainable machining options.

Process performance depends very much on the coolant/lubricant application conditions influencing friction, temperatures, cutting forces, etc., and thus affecting tool-life, workpiece accuracy, and surface integrity of the components. Industrial use of such coolants/lubricants is largely limited to flood cooling with emulsion or oil.

The application of cryogenic media offers the advantage of dry machining in combination with rapid cooling effect. The two gases of CO_2 and LN_2 have to be distinguished regarding the mechanisms for generating low temperatures that imply different requirements for their use. A new aerosol strategy using small quantities of oil particles, in MQL form, combined with cryogenic CO_2 or LN_2, has also been developed during the last decade to provide lubrication of the cutting zone. Table 1 shows various cooling strategies and a comparison of sustainability concerns.

1.4. Scope and objectives of the paper

This paper is aimed at presenting a summary of recent progress in cryogenic manufacturing processes with a state-of-the-art review, focusing on fundamentals of cryogenic processing describing the process mechanics, product quality and performance of components produced from cryogenic manufacturing, major results from cryogenic manufacturing processes covering machining, grinding and forming processes and other hybrid processes. Also, summarized in the paper is the progress toward developing predictive performance models for various cryogenic manufacturing processes. Conclusions are drawn from the analysis of cryogenic manufacturing with a research outlook.

2. Process mechanics and material performance: tribological and thermo-mechanical interactions

2.1. Review and general background

Since the very early work by Uehara and Kumagai [221], for over two decades no significant progress was reported on cryogenic machining until the work by Chattopadhyay et al. [31]. Subsequently, Dillon et al. [57] presented a thermal and metallurgical analysis of the process on a few materials. Paul et al. [163,164] and Paul and Chattopadhyay [160–162] studied cryogenic machining and grinding processes extensively and reported on the benefits of tool-life, surface finish, dimensional accuracy and residual stresses on a range of steels. Significant work

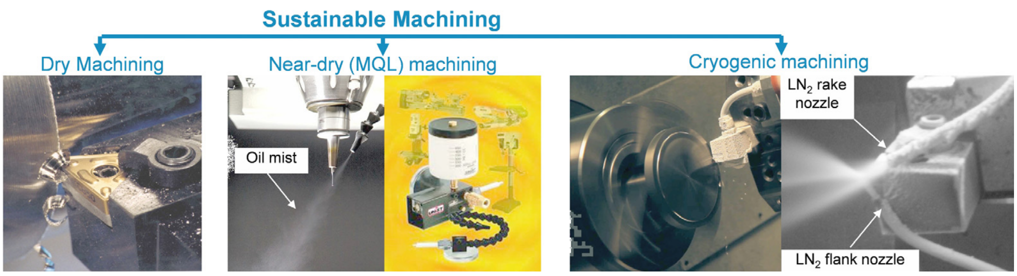

Fig. 1. Sustainable machining options.

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