International Journal of Mechanical Sciences 142–143 (2018) 595–602

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

A study on the machining characteristics using plasma assisted machining of AISI 1045 steel and Inconel 718

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A R T I C L E I N F O

Keywords:
Plasma
Plasma assisted machining
Laser assisted machining
Machining
Difficult-to-cut material

A B S T R A C T

Difficult-to-cut materials such as titanium, Inconel and nickel alloys are being increasingly used in aerospace, automobile and medical equipment. However, these materials are difficult to machine using conventional machining (CM) methods, because of their superior material properties. New machining methods are being studied and developed for these materials. One of these machining methods, Thermal assisted machining (TAM,) applies a heat source to enhance the machinability of the materials. Laser assisted milling (LAMill) is a widely used type of TAM. In the LAMill process, a laser heat source softens the materials in front of the cutting tool. However, LAMill is expensive. A plasma heat source has been widely used for welding, melting, preheating, etc., and at a cost of about one tenth that of a laser heat source. But few studies on Plasma assisted machining (PAM) have been conducted. In this study, a PAM process was developed and investigated, and its performance compared with LAMill and CM. The proper preheating temperature and depth of cut (DOC) were determined by thermal analysis. Experiments were carried out with the PAM system on AISI 1045 steel and Inconel 718 using the determined preheating temperature and DOC. It was found that PAM reduced cutting force and improved the surface quality.

1. Introduction

Difficult-to-cut materials are being increasingly used in various industries, such as automotive and aerospace, because of their excellent mechanical characteristics. However, these materials are difficult to machine using conventional methods because of high toughness and high strength at high temperature. To solve this problem, thermally assisted machining (TAM) has been studied and developed by researchers [1–5].

TAM is an efficient method of machining difficult-to-cut materials by adding an external heat source to conventional machining (CM). If the entire material has a high temperature than the annealing temperature, the material can be deformed or heat treated, and thus the machining accuracy can be reduced. However, The local application of an external heat source increases the temperature of the materials to a high temperature, which reduces the mechanical strength of the difficult-to-cut materials, making them more easily machined with lower mechanical energy [6–10]. Kim and Lee [11] predicted the cutting force and preheating-temperature equations using a materials of Inconel 718 and AISI 1045 with laser assisted machining (LAM). S. Sun *et al.* [12] reviewed hard-to-machine materials of thermally enhanced machining. This review summarizes the up-to-date progress and benefits of thermally enhanced machining of ceramics, metals and metal matrix composites. Lee *et al.* [13] reviewed the laser and arc manufacturing process over the past five years and suggested future direction for individual and hybrid processes using laser and arc heat sources. T. Kizaki *et al.* [14] studied quantitative relationship between the machining conditions and the machinability of the Y-TZP by experiment using TAM, analyzed the cutting resistance and tool wear by material temperature. Kim and Lee [15] proposed a new back and forth preheating method for LAM of ceramic and compared the cutting force and the surface roughness based on the three machining methods such as CM, LAM (One-way preheating) and LAM (Back-and-forth preheating).

LAM is a type of TAM. In the LAM approach, workpieces are locally preheated by a laser heat source applied ahead of the cutting region. Laser assisted turning (LAT), one of the types of LAM, is already used in many industries. LAT has been steadily researched because it results in excellent machining under different machining conditions [16–18]. B. Yang *et al.* [19] studied the mechanisms of edge chipping at high temperature during the laser assisted milling (LAMill) of silicon nitride ceramics. Research on LAMill has also increased, but is still in the basic stage of development, because laser control is difficult, and the preheating path is complicated. Bermingham *et al.* [20] investigated the tool path for machining complex shaped products with LAM. Kim et al. [21] studied the LAT and heat treatment through classifying these technologies into three categories such as the equipment and mechanism, machining process and analysis research. C. Brecher *et al.* [22] studied

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https://doi.org/10.1016/j.ijmecsci.2018.05.020
Received 7 January 2018; Received in revised form 24 April 2018; Accepted 9 May 2018

the cutting force and flank wear during the LAM of advanced material such as Inconel 718. Alberto Bucciarelli *et al.* [23] analyzed the micro-machinability of nickel content steels, such as surface morphology, burr and tool wear, according to experimental results.

Plasma assisted machining (PAM) involves the use of a plasma heat source with CM. A narrowed-down plasma jet is sprayed on the workpiece to be cut, making the surface locally soft. T. Kitagawa *et al.* [24] studied the tool wear and machinability of a ceramic material by applying a plasma heat source to the turning processes. S. Elhami *et al.* [25] suggested a new hybrid machining process that combines thermally enhanced machining with ultrasonic assisted milling, and analyzed the process through experiments. L.N. Lopez de Lacalle *et al.* [26] proposed Plasma assisted milling and studied the machinability of superalloys using a milling cutter.

In LAMill, high laser power is required to preheat the workpiece to high temperature, because the laser is the only heat source used for preheating. Moreover, to maintain the high power, a high cost laser device is required. PAM can overcome this limitation of LAMill because the preheating to high temperature can be performed with an inexpensive plasma device.

Studies on plasma welding have been widely reported, and plasma welding has already been commercialized in many countries. However, few studies of PAM have been made to date [27–30]. R. Zhang *et al.* [31] studied to compare of energy acted on twin-body workpiece of the plasma arc welding. Cho and Na [32] studied numerical analysis of CO2 laser and arc hybrid welding. Z Liu *et al.* [33] studied the keyhole exit deviation distance and weld pool thermo-state in plasma arc welding process.

In this study, AISI 1045 steel and Inconel 718 were used for confirming machining characteristics using CM, LAM and PAM. AISI 1045 is most frequently used as structural steel in the industry, and Inconel 718 is one of the most widely used difficult-to-cut material. Inconel 718 is excellent in heat resistance and wear resistance, and demand for high-tech industries such as aerospace industry and nuclear industry is increasing. However, for Inconel 718, it is difficult to machine by conventional machining method. Therefore, two materials are selected to machine effectively and to enhance the machining efficiency by TAM.

The purpose of this study is to apply PAM to flat machining, and to investigate the machining characteristics of PAM in comparison with CM and LAM. In terms of literature, there are no studies on the machining efficiency of PAM and LAM under the same machining conditions. Therefore, the novelty of this study is to compare the machining efficiency of PAM and LAM under the same machining conditions. The optimum preheating temperature was selected in consideration of the mechanical strength of the material according to the temperature, and the effective depth of cut (DOC) was selected by confirming the temperature distribution through the thermal analysis results. The plasma preheating experiments were performed to only determine the torch angle with the best preheating effect. Also, the cutting force and surface roughness of AISI 1045 steel and Inconel 718 were measured based on the machining conditions, and the machinability of CM, LAM and PAM were compared.

2. Concept of PAM and LAMill

Fig. 1 shows a schematic diagram of PAM and LAMill. The size of the plasma heat source is about 6 mm, and the size of the laser heat source is about 3 mm. The heat source heats the machining path in front of the tool. The closer the distance between the plasma torch and the workpiece, the higher the preheating temperature that can be obtained, so the plasma torch was placed at a height of 1.5 mm.

Fig. 2 shows the plasma torch used in this study. Plasma torches are classified as a transferred type or a non-transferred plasma type, depending on the plasma generation method. The transferred plasma type generates the plasma between the workpiece and the torch, while the non-transferred plasma type generates the plasma inside the torch. The transferred type plasma torch has a disadvantage in that the distance between the plasma torch and the workpiece must be kept constant in order to generate plasma, and the plasma can be generated only from conductive materials. So, in this study, the non-transferred type plasma torch was used to avoid the disadvantages of the transferred type plasma.

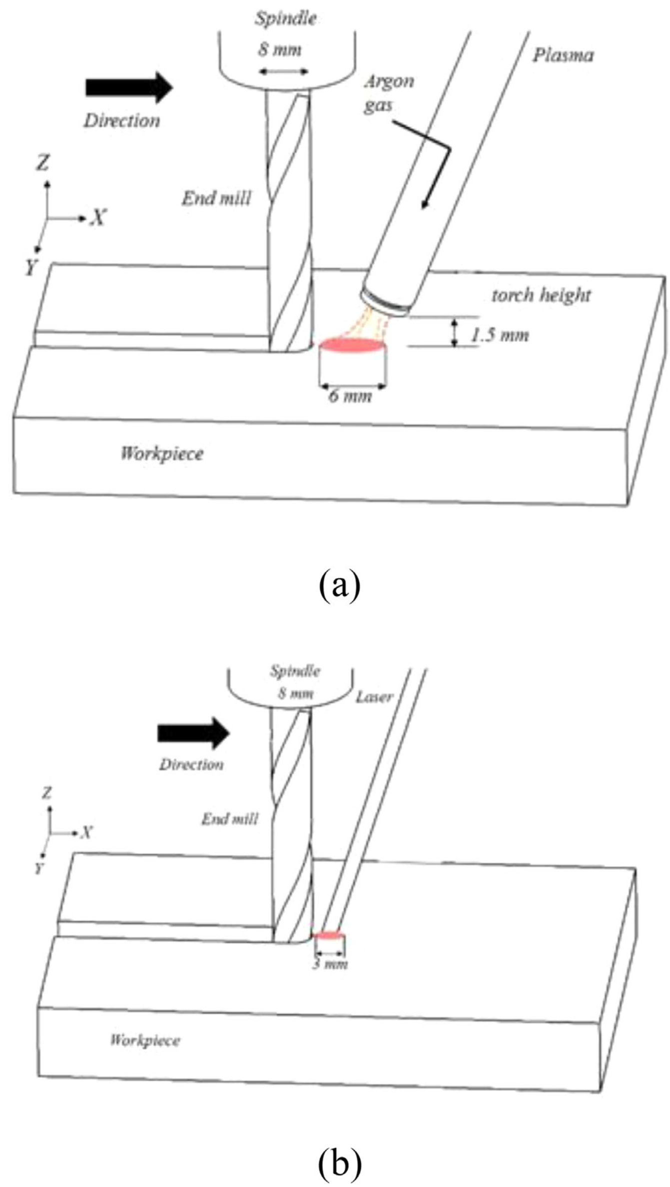

Fig. 1. Main component of the (a) PAM and (b) LAMill system.

3. Preheating temperature prediction

3.1. Thermal analysis

To determine the machining conditions in this study, it was essential to first establish the relationship between the temperature and the depth of the heated zone. The strength of the material decreases when the temperature of the material increases, and this influences the effective DOC of the cutting tool. Before the machining experiment, a thermal analysis was performed to predict the DOC depending on the temperature.

Laser and plasma heat sources are continuously heated and moved over time, but in the thermal analysis, heat source is repeatedly input and moved in pulses at 0.01 s intervals. In this study, it is assumed that this is similar to actual continuous movement.