CIRP Journal of Manufacturing Science and Technology 10 (2015) 92–101

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

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

Experimental investigations of thermally enhanced abrasive water jet machining of hard-to-machine metals

Divyansh Patel, Puneet Tandon *

PDPM Indian Institute of Information Technology, Design and Manufacturing Jabalpur, Dumna Airport Road, Jabalpur, 482005, India

ARTICLE INFO

Article history:
Available online 12 May 2015

Keywords:
Thermally enhanced machining
Thermal softening
Abrasive water jet machining
Surface morphology
Material removal rate

ABSTRACT

This work explores thermally enhanced abrasive water jet machining (TEAWJM) process to improve the machining capabilities of conventional abrasive water jet machine by heating the work by an external heat source. The present work describes an experimental study of thermally enhanced machining (TEM) by adding an oxy acetylene gas welding setup as an external heat source to the machine setup which heats the work locally and temperature is measured by non-contact laser thermometer. The experimental data of cutting parameters at critical temperatures of hard-to-machine metals Inconel 718, Titanium (Ti6Al4V) and mild Steel (MS-A36) (ductile in nature) with full factorial DOE is presented here. Further, the effect of thermal treatment (during cutting) on surface morphology of the material machined has been studied for analyzing the effectiveness of the proposed methodology. Due to TEM, an increase in material removal rate, reduction in power consumption machining time is observed.

Introduction

Abrasive water jet (AWJ) technology and its applications had been commercialized since long. Since then, significant advances have been made in AWJM in the form of hardware and software integration, abrasive suspension jet machining (ASJM), cryogenic abrasive water jets, super-water jetting, percussive (rapidly pulsing jets) machining, and oscillation pulsed jet along with newer applications in drilling, milling, taper cutting, turning, threading, etc. A wide range of materials (Inconel, Titanium, Incoloy, glass, ceramics, composites, heat-sensitive alloys, etc.) is shaped for different applications with this process. The demand of higher strength and heat resistant material is increasing particularly in aerospace industries. However, these materials are often difficult to machine due to their physical and mechanical properties such as high strength and low thermal conductivity, which requires very high cutting energy and makes the cutting forces and cutting temperature very high, and even leads to a short tool life.

The mechanism behind the material removal in conventional AWJM is erosion caused by abrasive particles entrained in high velocity water jet. If the machining is carried out at high temperatures, plastic deformation of the material occurs at cutting zone, which leads to increase in material removal rate and depth of cut. As flow stress and strain hardening rate of materials normally decrease with increase in temperature due to thermal softening (shown in Fig. 1 as the dependence of strength on temperature), this opens an avenue of thermally enhanced machining (TEM) for hard-to-machine materials. TEM may use an external heat source to heat and soften the workpiece. As a result, the yield strength, hardness and strain hardening of the workpiece reduces and deformation behavior of the hard-to-machine materials changes to allow the plastic deformation. This enables the difficult-to-machine materials to be machined easily along with low energy requirement, which leads to increase in material removal rate and productivity.

Sun et al. (2010) studied the benefits of thermally enhanced machining by focusing on laser and plasma assistance to machine ceramics, metals and metal matrix composites. They also made an attempt to integrate the external heat source with cutting tools. Madhavulu and Basheer (1994), represented an experimental study of improving material removal rate of difficult-to-cut alloys with high temperature plasma arc, which is used to provide intense localized heat, softening only the chip material, leaving the work piece relatively cool and metallurgically undamaged. Amina et al. (2008) investigated polycrystalline cubic boron nitride (PCBN) inserts in end milling of hardened steel AISI D2 (60–62 HRC), under room temperature and workpiece preheated conditions and found that tool flank wear is slightly higher while

* Corresponding author. Tel.: +91 761 2632924; fax: +91 761 2632524.
E-mail addresses: divyanshpatel_008@yahoo.co.in (D. Patel), ptandon@iiitdmj.ac.in, tandon_p@rediffmail.com (P. Tandon).

http://dx.doi.org/10.1016/j.cirpj.2015.04.002
1755-5817/

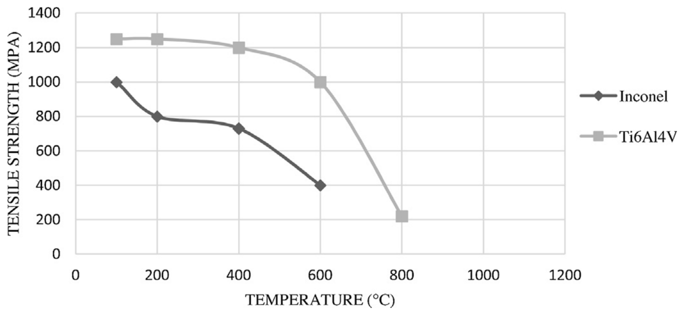

Fig. 1. Effect of temperature on the ultimate tensile strength for various hard-to-machine materials (Sun et al., 2010).

machining at elevated temperature. Leshock et al. (2001) presented analytical investigation of surface temperatures due to plasma heating and established three-dimensional finite difference model to determine the temperature distribution in a cylindrical workpiece subjected to intense localized heating. Ozler et al. (2001) investigated the influence of surface temperature, cutting speed, feed rate, and depth of cut on the tool life. Anderson and Shin (2006) evaluated the machinability of Inconel 718 under varying conditions by replacing plasma enhanced machining by laser-assisted machining and by examining parameters like tool wear, cutting forces, surface roughness, and specific cutting energy. Chang and Kuo (2007) presented a study on the application of laser-assisted machining for Al_2O_3 ceramics and observed the changes in cutting forces and workpiece surface temperature as well as surface integrity and tool wear. Ding and Shin (2010) investigated subsurface integrity for laser-assisted turning and grinding of hardened steel (hollow) shaft in terms of surface finish, size control, micro-hardness, microstructures and residual stresses. Boyer (1996), discussed in detail the properties and advantages of titanium alloys like a high strength-to-weight ratio, excellent corrosion resistance, and compatibility with composite structure. Leshock et al. (2001) presented a numerical and experimental analysis of plasma enhanced machining (PEM) of Inconel 718. Surface temperatures due to plasma heating are systematically characterized through numerical modeling and experimental investigations using infrared radiation thermometer. Dandekar et al. (2010) proposed a hybrid machining process involving lasers to improve the tool life and the material removal rate. The effectiveness of the process was studied by varying the tool material and material removal temperature while measuring the cutting forces, specific cutting energy, surface roughness, microstructure and tool wear. Jeon and Pfefferkorn (2008) examined the effect of laser preheating on micro end milling of 6061-T6 aluminum and 1018 steel. Through these experiments it was shown that locally preheating a metal, even a relatively soft metal, can reduce the specific cutting energy required for machining and thus it became possible for a micro end mill to achieve significantly higher feed rates and levels of productivity. Rahman Rashid et al. (2012) aimed to investigate the behavior of the Ti-6Cr-5Mo-5V-4Al beta titanium alloy under laser assisted machining (LAM). Anderson et al. (2006) summarized the progress and benefits of thermally enhanced machining of ceramics, metals and metal matrix composites. In cryogenic abrasive jet micromachining, Getu et al. (2011) found that the thermal front moved nearly twelve times faster than the material removal front, implying that the target material was sufficiently cooled prior to micromachining.

The objective of the present work is to experimentally analyze cutting parameters in AWJM for different temperatures of workpiece. The work focuses on especially understanding the effect of standoff distance and jet pressure in machining three different materials at room temperature (RT) and elevated temperatures. An external heat source i.e., oxy acetylene gas-welding torch is added to the machine setup for thermal treatment of the materials. Neutral flame is used for elevating the temperature and softening the workpiece so as to reduce the amount of required cutting energy. The temperature rises at the local front (cutting zone) of AWJ nozzle and reduces the yield strength and work hardening of hard-to-cut materials. To understand the effect of high temperatures, the surface morphology of three materials i.e., Inconel 718, Ti6Al4V and mild steel is studied after being machined by thermally assisted AWJ. The proposed experimental procedure leads to improvements in the response parameters like material removal rate, depth of cut, power consumption, etc. The work presents improvements in some of the response parameters on application of the proposed methodology.

Experimental setup

Experiments are performed on abrasive water jet machine tool designed by OMAX Corporation (Fig. 2). The three cylinder direct drive pump can produce a pressure of up to 420 MPa. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, pneumatically controlled valves and a work table with dimension of 3000 mm × 1500 mm. A sapphire orifice was used to transform the high-pressure water into a collimated jet, with a carbide nozzle to form an abrasive waterjet.

An Oxyacetylene gas welding setup is attached together with the existing AWJM setup as an external heat source. Acetylene is the primary fuel for oxy-fuel welding and chosen for repair work and general cutting and welding. The welding setup is used to heat the workpiece up to a critical temperature where the material loses its strength. The temperature of the cutting zone is controlled with the help of a laser thermometer. Non-touch laser thermometer works on the principle of infrared thermal camera, which detects the temperature with respect to emissivity of the material and temperature range. Each material has an emissivity for a specific range of temperature according to their thermal and mechanical properties. It is not possible to heat the specimen while machining if oxy-acetylene gas is used as an external heat source. The process can be improvised by heating the workpiece with laser instead of gas as the specimen might be heated during machining.

Thermally assisted abrasive water jet machining process contradicts the fact that heated material may experience rapid cooling by the high velocity abrasive water jet. Indeed, this happens when the cutting takes place under water in catcher tank. Thus, in present work the machining is not executed under water

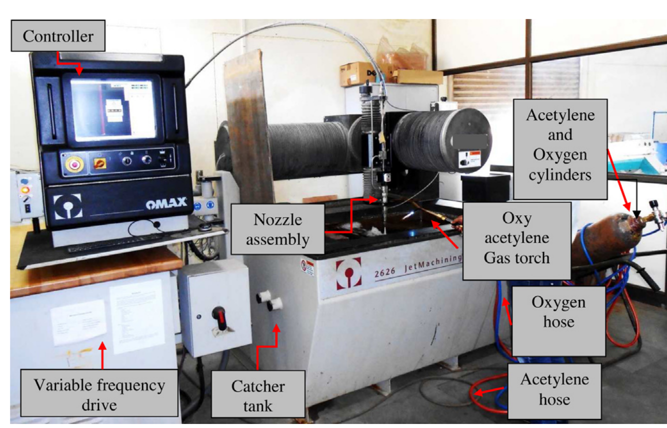

Fig. 2. Experimental abrasive water jet machine setup assisted with oxy acetylene gas cutting.