Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Machine Tools & Manufacture 46 (2006) 1786–1794

INTERNATIONAL JOURNAL OF
MACHINE TOOLS
& MANUFACTURE
DESIGN, RESEARCH AND APPLICATION

www.elsevier.com/locate/ijmactool

Experimental and numerical modelling of the residual stresses induced in orthogonal cutting of AISI 316L steel

J.C. Outeiro[a,]*, D. Umbrello[b], R. M'Saoubi[c]

[a]Portuguese Catholic University, 3080-024 Figueira da Foz, Portugal
[b]Department of Mechanical Engineering, University of Calabria, 87036 Rende (CS), Italy
[c]Corrosion and Metals Research Institute (KIMAB), SE-114 28 Stockholm, Sweden

Received 4 October 2005; received in revised form 21 November 2005; accepted 24 November 2005
Available online 4 January 2006

Abstract

Residual stresses in the machined surface layers are affected by the cutting tool, work material, cutting regime parameters (cutting speed, feed and depth of cut) and contact conditions at the tool/chip and tool/workpiece interfaces. In this paper, the effects of tool geometry, tool coating and cutting regime parameters on residual stress distribution in the machined surface and subsurface of AISI 316L steel are experimentally and numerically investigated. In the former case, the X-ray diffraction technique is applied, while in the latter an elastic–viscoplastic FEM formulation is implemented. The results show that residual stresses increase with most of the cutting parameters, including cutting speed, uncut chip thickness and tool cutting edge radius. However, from the range of cutting parameters investigated, uncut chip thickness seems to be the parameter that has the strongest influence on residual stresses. The results also show that sequential cuts tend to increase superficial residual stresses.

Keywords: Metal cutting; Machining; Residual stresses; Modelling; FEM

1. Introduction

The reliability of a mechanical component depends to a large extent on the physical state of its surface layers. This state includes the distribution of residual stresses induced by machining. Depending on their nature (compressive or tensile stresses) they could either enhance or impair the ability of a component to withstand severe loading conditions in service such as fatigue, creep, stress corrosion cracking, etc. Furthermore, the residual stress distribution on a component may also cause dimensional instability (distortion) after machining [1]. This poses enormous problems in engine/structural assembly and affects the structural integrity of the whole part.

The direct influence of residual stresses on the functional behaviour (the static and dynamic strength, chemical and electrical properties, fatigue, rust, etc.) of the component is relatively well known. However, a number of questions still persist about the causes and the mechanisms of residual stress generation in machining and how these residual stresses could be controlled in order to achieve a desirable distribution. Therefore, the understanding of residual stresses and proper control of these in machining is a prerequisite in order to enhance component performance and minimize risks of failure.

The study of machining residual stresses is particularly important when critical structural components are machined, especially if the objective is to reach high reliability levels. This is the case of austenitic stainless steels, widely used to produce critical structural components in chemical industries and nuclear power stations because they provide a unique combination of high mechanical properties and corrosion resistance. However, austenitic stainless steels are often regarded as difficult-to-machine materials because of their low thermal conductivity, high sensitivity to strain and stress rate and severe work hardening. Moreover, their low thermal conductivity leads to heat concentration in the cutting zone, resulting in high localized temperatures. As a result, machining of such steels induces

---

*Corresponding author. Tel.: +351 233 428445; fax: +351 233 428847.
E-mail address: jcouteiro@crb.ucp.pt (J.C. Outeiro).

0890-6955/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2005.11.013

Nomenclature

E	Young's modulus, MPa
v	Poisson ratio
ρ	mass density, kg/m^3
T	temperature, °C
h	convection coefficient, W/m^2 K
k	thermal conductivity, W/m K
V_c	cutting speed, m/min
t_1	uncut chip thickness, mm
w	width of cut, mm
ε	plastic strain
$\dot{\varepsilon}$	strain rate, s^{-1}
$\dot{\varepsilon}_0$	reference plastic strain rate, s^{-1}
T_m	melting temperature, °C
T_{room}	room temperature, °C
A	yield strength, MPa
B	hardening modulus, MPa
C	strain rate sensitivity coefficient
n	hardening coefficient
m	thermal softening coefficient
γ_n	rake angle, deg
α_n	flank angle, deg
κ_r	tool cutting edge angle, deg
λ_s	tool cutting edge inclination angle, deg
r_n	tool cutting edge radius, mm

relatively high residual stresses in the machined surface layers, and therefore, greatly affects the properties of these steels and their ability to withstand severe loading conditions.

Several studies on residual stresses induced by machining have been performed. Unfortunately, due to limitations in finite element (FE) modelling of the metal cutting process and the complex physical phenomenon involving the formation of machining residual stresses, most of these studies remain experimental in nature [2–4]. Although many studies on FE modelling of the orthogonal cutting process have been published until now, these were mainly applied to predict with reasonable accuracy the strains, stress and temperatures during cutting [5,6]. Only a few studies on FE modelling involving the prediction of the machining residual stresses with decent accuracy can be found in the literature, with special attention to the residual stresses in plain carbon steels and hardened steels [5,6]. Concerning modelling machining residual stresses in stainless steels, the available studies are even more restricted.

Wiesner [7] studied the residual stresses generated after orthogonal cutting of AISI 304 steel using uncoated cemented carbide tools. Using the X-ray diffraction technique, Wiesner determined the influence of the cutting speed and cutting depth on in-depth distribution of the residual stresses in the direction of primary motion (the cutting speed direction). High tensile residual stresses (close to +700 MPa) were found on the machined surface. In order to explain these high tensile residual stresses, a finite element method (FEM) was employed to analyse the influence of the thermal and mechanical effects on the residual stress state separately, although in the paper he presents the results for the thermal effect only. Wiesner concluded that the thermal effect is not the only reason for tensile residual stresses in machined components. The mechanical effect does not always produce compressive residual stresses, but can also contribute to tensile residual stresses.

Liu and Guo [8] proposed an FE model to investigate the effect of sequential cuts and tool-chip friction on residual stresses in a machined layer of AISI 304 steel. They reported a reduction in the superficial residual stresses when the second cut is performed. Moreover, the residual stresses can be compressive, depending on the uncut chip thickness of the second cut. They also found that residual stress on the machined surface is very sensitive to the friction condition of the tool–chip interface. Later, using the same work material, Liu and Guo [9] presented a similar study on the effect of sequential cuts on residual stresses. They showed that decreasing the uncut chip thickness below a critical value in the second cut may result in favourable compressive residual stress distribution. Thus, they conclude that it would be better to set an appropriate finishing cut condition in consideration of the effects of sequential cuts to control the residual stress distribution. Unfortunately, Liu and Guo did not present any experimental evidence for the work material under investigation (AISI 304 steel) to validate their FE model.

Yang and Liu [10] performed a sensitivity study of the friction condition on the tool–chip contact, the cutting forces and the residual stresses in machining-affected layers of AISI 304 steel. In this study they proposed a new stress-based polynomial model for modelling the tool–chip contact, which represents a simple curve fitting the experimentally obtained shear and normal stresses acting at the tool–chip interface. When comparing this new friction model with other friction models based on an average friction coefficient deduced from cutting forces or from stresses, they found significant differences among the predicted residual stresses. They concluded that the conventional force-based friction model is inadequate to predict the residual stresses induced by machining, and they showed the potential for improving the quality in predicting machining residual stress by adopting the stress-based polynomial model. Although it is widely accepted that friction conditions will change along the tool–chip contact length, the authors did not present any experimental evidence to support their conclusions.

The prior investigations show that modelling residual stress in machining stainless steel was studied for a very limited range of cutting conditions and for specific analysis