Precision Engineering 51 (2018) 78–87

Contents lists available at ScienceDirect

Precision Engineering

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

Laser cutting using off-axial supersonic rectangular nozzles

A. Riveiro[a,*], F. Quintero[a], J.del Val[a], M. Boutinguiza[a], R. Comesaña[b], F. Lusquiños[a], J. Pou[a]

[a] *Applied Physics Department, University of Vigo, EEI, Lagoas-Marcosende, Vigo, 36310, Spain*
[b] *Materials Engineering, Applied Mechanics and Construction Dpt., University of Vigo, EEI, Lagoas-Marcosende, Vigo, 36310, Spain*

ARTICLE INFO

Article history:
Received 16 March 2017
Received in revised form 20 July 2017
Accepted 25 July 2017
Available online 27 July 2017

Keywords:
Laser cutting
Supersonic nozzle
Rectangular nozzle
Aluminium alloy
Molten material

ABSTRACT

Laser cutting is a well-established process in the industry, mainly for cutting metallic materials such as steels. However, the utilization of this laser technique to process advanced materials, such as ceramics or some aluminium alloys, is restricted due to the formation of a large heat affected zone (HAZ), rough cut edges, presence of dross, or thermal cracks. These defects are closely related to the performance of the assist gas during the removal of molten material. Previous works have demonstrated the impressive improvement in cut quality with the utilization of off-axial supersonic axisymmetric nozzles to inject the assist gas. This is due to the higher removal of molten material. However, these results can be even improved if the geometry of the gas jet is tailored to the cut kerf. In the present work, a cutting head with an off-axial supersonic rectangular nozzle was developed to improve the efficiency of the current assist gas injection systems. The performance of this system was compared with that of a converging (coaxial) nozzle, and an off-axial supersonic axisymmetric nozzle during the processing of Al2024-T3 sheets. Results demonstrated the superior performance of the new assist gas injection system in terms of cut quality and productivity (cut edge roughness was 6.5 times lower, and the cutting speed is 1.98 times higher as compared to the results found for a converging coaxial nozzle).

1. Introduction

Laser cutting was one of the first applications of lasers in the industry, and now is a consolidated processing technique to cut sheet metal parts. The main laser cutting technique, called laser fusion cutting, is based on the melting, and removal of molten material by an auxiliary high-pressure gas jet [1]. This technique involves the localized melting, and partial evaporation of the workpiece throughout in depth, and the simultaneous injection of an assist gas jet in order to remove the molten material [2,3]. The coupling of the laser beam energy with the workpiece, and the removal of the molten material determine the success of this technique. However, several works pointed out that the limiting factor in this process is fundamentally the removal of molten material by the assist gas [4,5]. Indeed, a correct removal of molten material is required to maximize the cut speed but also the quality.

Theoretical analyses performed by Vicanek et al. [6] showed that the removal of molten material by the assist gas jet is a consequence of two main actions: the shear stress, and the pressure gradient exerted by the assist gas on the molten material along the cut front. It was found that both factors are of the same order of magnitude, and they increase with the gas velocity. Consequently, the improvement of the cut quality requires their maximization. This is especially important when cutting certain materials. Ceramic materials or glasses are prone to cracking due to thermal stresses consequence of the poor removal of molten material [7,8]. In this case, the high viscosity of the melt makes the removal of the molten material very hard, and cut edges with dross, resolidified material, and a large heat affected zone (HAZ) are obtained [9]. For other materials, the final application of the workpiece demands the maximization of the removal of molten material to obtain high cut quality, and/or a reduced HAZ. In this sense, cutting composites is a complex task due to the large HAZ typically formed in laser cutting [10]. Cutting aluminium alloys for aerospace applications demands cuts with high quality and an extremely reduced HAZ to meet the exigent mechanical performance of the workpiece [11,12]. Therefore, an improvement of the current assist gas injection systems, or new developments are required to enhance the current cut quality.

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[*] Corresponding author at: Applied Physics Department, University of Vigo, EEI, Lagoas-Marcosende, Vigo, 36310, Spain. Tel.: +34 986-812-216, fax: +34 986-812-201.

E-mail address: ariveiro@uvigo.es (A. Riveiro).

http://dx.doi.org/10.1016/j.precisioneng.2017.07.013
0141-6359/

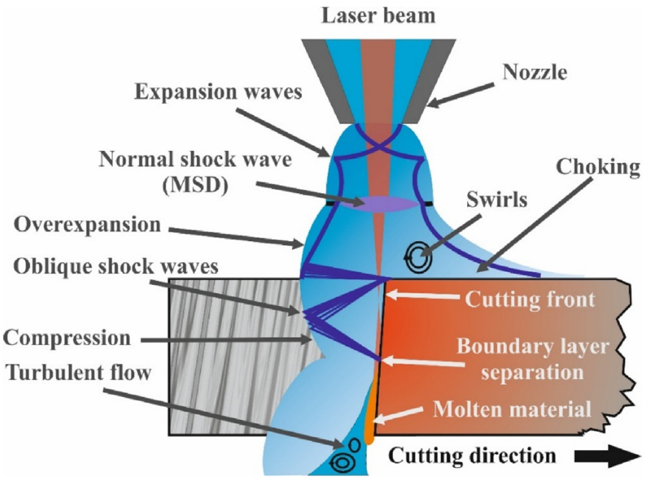

Fig. 1. Aerodynamic interactions during laser cutting using a converging (sonic) coaxial nozzle at underexpansion ratios $P/P_0 > 1.89$.

In this work, the main phenomena related with the interactions of the assist gas jet with the workpiece are briefly reviewed. Then, a new assist gas injection system to overcome the current limitations is proposed. Finally, this system is experimentally assessed by means of cutting trials, and the results are compared with those obtained with two of the most commonly used assist gas injection systems, i.e. converging (coaxial) nozzles, and supersonic axisymmetric nozzles.

2. Aerodynamic interactions during laser fusion cutting

2.1. Cutting with converging nozzles

High-pressure inert gas laser cutting partially alleviates the previously cited limitations in cutting difficult materials, namely, presence of dross or resolidified material, and a large HAZ; however, several phenomena related to the compressibility of the assist gas degrade the jet quality, and then, the removal capacity. These prevent the application of this approach to cut materials for mechanically demanding applications where an outstanding cut quality is required [13]. The root of these limitations arises due to the structure of the jets expelled by the converging nozzles (commonly used in laser cutting), and they are aggravated due to the interaction with the workpiece.

The aerodynamic interactions of the assist gas jet during conventional high-pressure gas laser cutting have been studied in the past by different authors [14–16]. In this injection system, a converging (or also called sonic) nozzle, coaxial with the laser beam, and positioned close to the workpiece is used to inject the assist gas into the cutting zone (see Fig. 1). The assist gas is normally supplied at pressure ratios (or underexpansion ratios, i.e. the ratio between the static pressure P in the flow just at the nozzle exit, and the ambient static pressure P_0) $P/P_0 > 1.89$, which produce underexpanded jets [17]. This induces a severe shock wave pattern in the jet; decelerates the flow, and reduces both the shear stress, and the gradient pressure along the cut front. Then, the removal of molten material is severely compromised. On the other hand, the normal impingement of the jet onto the surface of the workpiece reinforces this shock wave pattern, and a normal shock wave, called Mach Shock Disk (MSD), stands over the inlet kerf [18]. The strength of this shock depends on the assist pressure, and the nozzle-workpiece distance (also called stand-off distance) [19].

The MSD reduces even more the kinetic energy of the jet available to remove molten material from the cut kerf. Furthermore, the static pressure of the gas increases after the MSD, produces an underexpansion of the jet, and the generation of expansion waves just into the inlet kerf. These waves, after being reflected in the jet boundaries, form compression waves which can build up a single stronger branch. The impact of this compression oblique shock wave on the cut front seriously disturbs the flow of the assist gas over the cut front. The laminar boundary layer formed by the assist gas on the molten material can be separated due to the adverse gradient pressure imposed by the interaction with this compression wave. The assist gas flow downstream the separation is unsteady, chaotic, and transformed into a turbulent regimen; therefore, decreasing the capacity of the gas to remove molten material from the kerf [20]. The boundary layer separation (BLS) is easily detected in the cut edge because a rough surface finish, recast material, and strong dross attachment in the lower cut surface is observed [21]. Furthermore, some swirls can be formed after the boundary layer separation [22–24]. These can trap ambient air which can penetrate into the cut kerf, and react with the molten material. The oxygen from the atmosphere can produce an undesirable oxidation of the cut front during laser cutting using inert gases. On the contrary, nitrogen or other impurities from the atmosphere can also reduce the cutting performance during laser cutting using oxygen because of the reduction in the gas purity [25,26].

These phenomena are also aggravated due to the strong choking suffered by the jet in the entrance of the cut kerf. La Rocca et al. estimated the area blockage of the jet to be around 90% [27]. This promotes a strong turbulence, and the formation of a stable vortex ring just at the inlet kerf [14,28]. These swirls can produce the contamination, and reduction in purity of the assist gas due to the suction of ambient gases. This contamination, and the higher residence times of the gas can also promote the formation of plasma [29].

2.2. Supersonic and off-axial nozzles

Several strategies were followed to solve the aforementioned problems. The utilization of supersonic (also called converging-diverging or De Laval) nozzles were proposed to obtain jets free of shock waves, and to avoid the energy dissipation [30–33]. These are axisymmetric (i.e. with circular cross-section), and have a converging-diverging internal geometry. They supply a high velocity assists gas jet, but avoiding the reduction in kinetic energy because the jet is absent of shock waves. Cutting experiments with supersonic axisymmetric nozzles performed on several materials, ranging from mild steel to wood, detected a remarkable improvement in the cut quality, and processing speed [31,32,34].

On the other hand, off-axial nozzles, supplying the assist gas jet tilted certain angle with regard to the laser beam, were proposed to avoid the problem of the choking. In this way, the area blockage of the jet is greatly reduced, because more gas can enter into the cut kerf. Ketting et al. [35] found the enlargement in the parameter range leading to dross-free cuts during high-pressure laser cutting of an Al-Mg aluminium alloy when the laser beam is placed in front of centre of nozzle as compared to on-axis cutting.

Quintero et al. merged the precedent approaches using an off-axial supersonic nozzle. Using this injection system, dross free cuts were obtained during Nd:YAG, and CO_2 laser cutting of thick sectioned mullite-alumina workpieces [36,37]. Using the same experimental setup, Riveiro et al. confirmed the superior performance of this assist gas injection system during the CO_2 laser cutting of 2024-T3 and 7075-T6 aluminium alloys [11,38]. Dross-free cuts, and smooth cut edges were obtained (with an average roughness close to $R_a = 1\ \mu m$) [39]. Also a high processing rate, and a noticeable reduction of the HAZ, as compared to samples processed by means of a cutting head assisted with a converging nozzle, were observed.