Review on Heat Affected Zone (HAZ) in Laser Machining

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Abstract. Laser machining being a non-contact process possesses several advantages such as no tool wear or damage and no contact force induced problems. Laser cutting involves thermal process and it does not depend on the strength and hardness of the work piece, thus making it ideal for cutting non-homogeneous material. In this research work several papers related to the heat affected zone (HAZ) of laser machining of CFRP and GFRP are reviewed. It was found that laser parameters such as specific laser energy, laser power, repetition rate, work piece temperature determine the extent of HAZ. In CFRP HAZ in perpendicular laser grooving is much higher than that in parallel grooving. Presence of nitrogen jet decreases the work piece temperature leading to lower HAZ. Observations of the HAZ area of CFRP material revealed fiber swelling of 50 or 60% and fibers near the top are seen to curl up. In case of GFRP charred black material called shell and melted glass fibers are observed in the HAZ. It is also observed that the extent of HAZ affect the static tensile and bending strengths of CFRP. Tensile strength reduces linearly as HAZ increases. A comparison of laser cutting on CFRP using three types of laser is also presented here. Nd:YAG laser cutting on CFRP at optimized parameters has produced least HAZ and highest bending strength.

1. Introduction

Laser machining being a non-contact process possesses several advantages such as no tool wear or damage and no contact-force- induced problems. Contact processes are accompanied by crack or mechanical degradation of the material being machined. Laser cutting involves thermal process and it does not depend on the strength and hardness of the work piece, thus making it ideal for cutting non-homogeneous material. Laser delivers high power-density beam which upon impact on the work piece is converted into heat. As the impact zone is very small very high temperature capable of melting or volatilizing the material can be attained. This leads to material removal. Laser cutting can be optimized by adjusting several parameters. Laser drilling which is a non-contact process produce small holes in various materials having high degree of precision and reproducibility. Due to the anisotropic nature of composites distorted holes and HAZ may result. In this work, papers involving HAZ formed due to laser machining were reviewed.

2. Literature Review

A lot of researches were undertaken regarding the heat affected zone (HAZ) in laser cutting. Hocheng and Pan represented HAZ by sectional area [1]. They used unidirectional carbon/PEEK composite with 60% fiber volume fraction for laser cutting. Carbon dioxide laser was employed. For cooling, a jet of liquid nitrogen (N_2) with 100kPa and 200kPa was utilized. It also created an inert atmosphere to carry out the laser cutting. They showed by dimensional and experimental analysis that,

$$A = \text{function (const. } SQ/F)$$

where A represented section area of thermal damage, peak power (S), pulse duty (Q) and traverse speed (F).

The term 'SQ/F' is called laser energy per unit length or specific laser energy. They found out that the section area of HAZ (A) increased with decrease in traverse speed (F) and increase in specific laser energy. It was also seen that HAZ is less when nitrogen pressure, P is high. Thermal conductivity is higher along the fiber direction compared to that normal to the fiber direction causing HAZ to be larger for cutting perpendicular to the fiber. They carried out a series of research on HAZ of CFRP. In all those research works they developed a numerical model considering the composite to be anisotropic and they also carried out experimental studies [2, 3]. In their second research paper they used section area to represent the HAZ. Here also they found that HAZ is proportional to the specific laser energy, PQ/V which is consistent with all three of their papers. In their third research work they developed a more advanced model which incorporated temperature dependence of thermal conductivity [3]. Here instead of using section area to represent HAZ they used, w_d which was maximum width of HAZ at $T = T_c$ (char temperature of matrix). They carried out the grooving at 0°, 30°, 60° and 90° to the fiber axis. In contrast to previous research work the simulated result with temperature dependent k, in perpendicular grooving is much closer to the experimental one. They also developed a mathematical model for grooving in off principal material axes. It was seen that maximum HAZ was found for grooving perpendicular to the fiber axis and least for parallel grooving. Laser drilling was carried out on APC-2 (PEEK and 61%carbon fiber) composite [4]. The laser used was Nd:YAG pulsed laser. They observed that the matrix melted and volatilized from around the hole. Appreciable swelling of carbon fiber of the order of 50% could be seen in the region around the hole as shown in Figure 1.

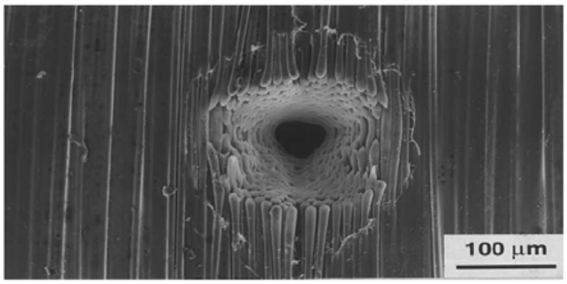

Fig. 1. SEM of laser drilled hole in composite showing matrix volatilization and fiber swelling [4]

Voisey et al. suggested a mechanism of fiber swelling [5]. Authors have concluded that the extent of fiber swelling depended on the impurities in carbon fibers used. They used three types of carbon fibers, T300 (low modulus), high modulus (HM) and P100 with polymeric matrix. They used these fiber composites with and without heat treatment. Heat treatment was carried out for 12h at 2000°C in an argon atmosphere. Nd:YAG was used for drilling. They found that maximum swelling occurred with T300 fibers and fiber swelling in HM fibers was very little and in P100 fibers there was almost no swelling. Thus a swelling of the order of 60% was observed. When the same materials had undergone heat treatment prior to laser drilling, only slight swelling is observed in them. Heat treatment increases carbon content by reducing impurities. When the carbon fiber composites are heated rapidly as in laser drilling the impurities evaporate creating high gas pressure. This high pressure leads to swelling of the fibers within the HAZ which are retained even when the material cools down and returns to normal pressure. Further investigation on HAZ of composite was carried out using GFRP [6]. The laser used was Nd:YAG. Charred materials are seen at the hole wall. A mechanism for HAZ formation was proposed. During laser drilling epoxy resin volatilized into gas and decomposed into carbon, whereas the glass fiber is melted and does not become gas. Some melted material sticks to the fiber close to the hole along with carbon which forms the 'shell' during ejection. An equivalent width, w_o to represent the HAZ was also proposed as shown below,

$w_o = A/L$, A is total section area and L is the length of the profile.

They found that w_o increased with increase in average power. It was also seen that w_o increased with repetition rate until 7kHz. After that it began to decrease. It is also observed that the extent of HAZ affect the static tensile and bending strengths of CFRP [7]. Laser cutting on the specimen was carried out using three high power laser sources which were Nd:YAG laser, disk laser and CO_2 laser at optimum laser parameters. The pulsed Nd:YAG generated smallest HAZ where as CO_2 the largest HAZ. Static tensile testing on the specimens revealed that the specimen for abrasive water jet possessed maximum ultimate tensile strength and that for milling was closer to that for Nd:YAG laser cutting. Among the specimens from the three laser cutting processes, CO_2 laser cut specimen exhibited least ultimate tensile strength.

3. Conclusions

Several articles regarding the heat affected zone (HAZ) in laser machining were reviewed. The parameters affecting the extent of HAZ are observed. HAZ is affected by parameters such as specific laser energy, repetition rate, nitrogen jet. Several mathematical models were reviewed. Matrix volatilization and fiber swelling are apparent in the region near the laser drilled hole which form HAZ. Mechanism for fiber swelling in carbon fibers was also reviewed. Several magnitudes for extent of HAZ has been discussed. The extent of HAZ in laser cutting influences mechanical properties [7].

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