Optimization of the hydro abrasive jet cutting process of thick steel sheets

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Abstract. In this paper is studied the issue of thick steel sheets cutting on abrasive waterjet machine, due to the abrupt curvature of the jet, caused by energy loss at high thicknesses. Depending on the hardness of the processed material, incomplete cutting occurs and it is evident at a thickness of sheets larger than 30-50 mm. Achieving a cutting with different configuration regimes implies on most of the equipment, turning off the machine, a new configuration and restarting the process of abrasive waterjet cutting which leads to the appearance of traces and marks on cut surface. Choosing the parameters in such a way that cutting is achieved (automatic configuration), leads to obtaining an uncut zone at the exit of the material. This uncut area can be eliminated by an oversized configuration of input parameters, or just reduced by a randomly selected configuration. Both cases lead to large economic losses. The correct choice of machining regime for abrasive cutting of thick sheets, depending on the thickness and the hardness of the material is the aim of these studies and proposed calculation method can be implemented.

1. Introduction
Hydro abrasive jet processing, due to the advantages it possesses, has been a major development in recent years. The possibilities of the technological process have led to intense research in the field and to a diversification manifested in particular by an exponential growth of equipment manufacturers and an increase in the type of processed materials. The technological hydro abrasive process allowed the production of work pieces with thermally unaffected surfaces, with high precision and association with CAD programs has made it possible to obtain variants, simple and easy, at a reasonable price. The parameters of the technological process are configured according to the capabilities of the equipment used, the possibilities offered by the producer as well as the processed material. In hydro abrasive jet cutting of thick steel sheets, the specific elements of the machine (the water pressure p, made with a pump, the diameter d of the orifice to create a jet, type of mixing chamber, the length and diameter of the mixing tube) as well as the selected parameters (distance to the part and abrasive type) are chosen depending on the possibilities.

Configuration is limited by the capabilities available. The only continuous variable element is the traverse speed Vt, who, in condition of maintaining certain input parameters, depends on the thickness of the material h and its machinability M. Traverse speed is set so that the minimum condition to cutting the material. In the case of additional quality and precision requirements, this may be modified in the sense of lowering it, until the desired roughness is achieved. From the exit of the mixing tube, to the
part, due to the very small distance between the tube and the part, as well as due to the high velocity of the jet $V_j$, we can consider the trace of a particle, perfectly perpendicular to the part, no matter how big they are traverse speed $V_t$. With the contact between the jet component and the surface of the piece, the velocity begins to decrease due to the loss of kinetic energy occurring at the collision of the jet particles with the material of the part [1]. If the cutting is bigger and the machinability is lower, the speed $V_t$ decreases after a curve with accelerated slope, the angle of this slope can be seen on striations appearing on the surface of the part (figure 1).

![Figure 1. Hydro abrasive cutting of thick steel part.](image)

As shown in figure 1, when cutting the thick sheets, an unprocessed area with length $L$ appears, due to the energy losses of the jet caused by speed decrease, and due to the tendency of the particles to migrate to the area where they do not encounter resistance (area already processed). At the exit of the jet from the material, in the upper part, trajectory of the particles, without any resistance returns to rectilinear shape, thus favors the occurrence of uncut areas. The present paper studies the influence of the traverse speed and the machinability of the material on the unprocessed area, for steel sheets, with a thickness of 50 mm, 60 mm and 70 mm. The processed materials was SAE 3310, SAE 8620 and 316L.

2. Theoretical consideration
The jet curvature occurs due to deflection of particles caused by kinetic energy loss [2, 3]. The impact of a waterjet on steel causes minor material removal, this is determined by the kinetic energy of the abrasive particles. In the zone I (figure 1), particles have a sufficient level of kinetic energy, so the resulted surface is free of striation and the unprocessed area does not occur. In the zone II, due to the kinetic energy loss, the cutting power of particles, decrease and to the end of cut, occurs an unprocessed area. This phenomenon is illustrated in figure 1 and figure 2 and must be looked at a process of cutting in waves. The first wave consists in particles with the lowest energy, the next waves having more energy. This, leaves trace marks on the surface, generally called striations disposed at a variable angle which depends on the jet’s traverse speed $V_t$, on the jet’s velocity $V_j$ and on the material’s machinability $M$. This angle leads to a gap between the jet entry point and the exit point, noted with $L$. As the cutting depth increases, the gap becomes bigger and the unprocessed area occurs [4, 5].

$$V_t = \frac{R_m}{d_n h},$$

where: $V_t$ is traverse speed of abrasive jet [mm/s]; $R_m$ is the rate of removal unit volume of material [mm³/s]; $d_n$ is the nozzle bore diameter [mm]; $h$ is jet cutting depth in the chosen material [mm].
\[ R_m = \frac{1}{2} I_m V_j^2 M \]  

(2)

where: \( I_m \) is impulse given to the abrasive mixture in unit time [g m/s]; \( V_j \) is abrasive jet velocity at the exit of the nozzle [m/s]; \( M \) is specific machinability of material [6, 7].

\[ V_j = \mu \xi \sqrt{\frac{2p}{\rho_a}} \]  

(3)

where: \( \mu \) is acceleration coefficient of the orifice ring for high speed; \( \xi \) is a coefficient that takes into account the characteristics of abrasive, grinding, friability, inhomogenities; \( p \) is the pressure of the liquid in the mixing tube [MPa]; \( \rho_a \) is the density of the abrasive fluid [g/mm³].

According Eq. (1) and Eq. (2), material influence on traverse speed is given by the thickness and specific machinability \( M_s \).

\[ V_t = \frac{1}{2} I_m V_j^2 M \frac{d_n h}{d_n h} \]  

(4)

The condition for eliminating the unprocessed area is:

\[ V_{jin} = V_{jmin} = \sqrt{\frac{2V_t d_n h}{I_m M}} \]  

(5)

where: \( V_{jin} \) is speed of abrasive jet [mm/s] at final of zone I; \( V_{jmin} \) is jet speed at output of processed part.

3. Experimental work

For experiments were chosen SAE 3310, SAE 8620 and 316L alloy steel with thickness \( h = 30 \text{ mm}, 50 \text{ mm} \) and 70 mm. The materials have the following properties: SAE 3310 - Hardness Brinell, HBW = 240; machinability, \( M = 78 \); modulus of elasticity, \( E = 200 \text{ GPa}, \) SAE 8620 - HBW = 150; \( M = 90 \); \( E =190 \text{ GPa} \) and 316L - HBW = 210; \( M = 82.5 \); \( E =210 \text{ GPa} \)

Setting the AWJ machine, Maxiem 1530 from Omax Corporation, has been executed with water pressure provided by the pump to the maximum value \( p = 350 \text{ MPa} \) (figure 3). Total length of cut is \( l=100 \text{ mm} \). Higher virtual thicknesses were chosen to change the traverse speed and this has been established after the timing of the run of total length (figure 4).
The method of changing the traverse speed is shown in figure 4.

![Figure 4](image.png)

**Figure 4.** Changing the traverse speed by choosing virtual thickness.

The measurements of length \( L \) of unprocessed area were performed using a digital caliper and an optical comparator measurement machine 321 GL. The media of results of measurement are shown in table 1, table 2 and table 3.

**Table 1.** Value of length \( L \) of unprocessed area at steel sheets (30 mm).

| Type of steel | Machinability | Traverse speed \( v_t \) [mm/min] | Length of uncut area \( L \) [mm] |
|---------------|---------------|-----------------------------------|----------------------------------|
|               |               | 1 2 3 4                          | 1 2 3 4                          |
| SAE 3310      | 78            | 40 30 20 10                      | 0.5 0.2 0 0                      |
| SAE 8620      | 90            | 60 50 40 30                      | 0.3 0 0 0                       |
| 316 L         | 82.5          | 50 40 30 20                      | 0.4 0.1 0 0                     |
Table 2. Value of length L of unprocessed area at steel sheets (50 mm).

| Type of steel | Machinability | Traverse speed V_t [mm/min] | Length of uncut area L [mm] |
|---------------|---------------|-----------------------------|----------------------------|
|               |               | 1  | 2  | 3  | 4  | 1  | 2  | 3  | 4  |
| SAE 3310      | 78            | 30 | 20 | 10 | 5  | 1.6| 1.0| 0.7| 0.1|
| SAE 8620      | 90            | 40 | 30 | 20 | 10 | 1.4| 0.9| 0.5| 0  |
| 316 L         | 82.5          | 35 | 25 | 20 | 8  | 1.4| 1.0| 0.6| 0.1|

Table 3. Value of length L of unprocessed area at steel sheets (70 mm).

| Type of steel | Machinability | Traverse speed V_t [mm/min] | Length of uncut area L [mm] |
|---------------|---------------|-----------------------------|----------------------------|
|               |               | 1  | 2  | 3  | 4  | 1  | 2  | 3  | 4  |
| SAE 3310      | 78            | 15 | 10 | 6  | 3  | 2.5| 1.9| 1.2| 0.5|
| SAE 8620      | 90            | 20 | 15 | 10 | 5  | 2.3| 2.0| 1.0| 0.3|
| 316 L         | 82.5          | 20 | 12 | 8  | 4  | 2.4| 1.8| 1.2| 0.4|

4. Conclusions
The wide use of cutting jet do occur in the cutting process, a growing number of materials such as multilayer materials or welded materials. This research opens the door to extensive research in this area, in order to optimize cutting abrasive water jet. As shown in table 1, 2 and 3, the growth of thickness of materials leads to the appearance of uncut area with length L. With decrease of traverse speed, L tend to decrease.

Chart for the SAE 3310, for traverse speed V_t=10 mm/min and V_t=20 mm/min is shown in figure 5.

Figure 5. Diagram of length of uncut zone function of thickness of material for SAE 3310.
It can be seen up to the thicknesses of sheets $h = 30$ mm, uncut area does not occur. When the thickness to $h = 50$ mm, an uncut area with $L$ comprised between 0.5 mm and 1 mm, appears causing an issue when cutting plates of steel. When the thickness increases over 50 mm, the uncut area grows strongly.

Chart for the SAE 8620, for traverse speed $V_t=20$ mm/min and $V_t=30$ mm/min is shown in figure 6.

![Figure 6. Diagram of length of uncut zone function of material thickness for SAE 8620.](image)

For SAE 8620, with hardness much less than the hardness of SAE 3310 steel, when the thickness of materials grows to 50 mm the uncut area is lower than to the SAE 3310.

Chart for the SAE 3310, for traverse speed $V_t=8$ mm/min and $V_t=20$ mm/min is shown in figure 7.

![Figure 7. Diagram of length of uncut zone function of material thickness for SAE 316L.](image)

The main difference between the three materials is machinability. It can be concluded that the length of the uncut area depends on three important factors: material thickness, traverse speed and material
machinability (the machinability, at the same values of traverse speed, at bigger values leads to shrinking the uncut area). Both, the thickness of the material and its machinability are properties of the work piece that can not be changed. One possibility to fix this problem is to work with 2 traverse speeds, on the last part, lowering the traverse speed to low values.

![Diagram of length of uncut zone function of material thickness for SAE 3310, SAE 8620 and 316L steel at traverse speed \( V_t = 20 \text{ mm/s} \).](image)

**Figure 8.** Diagram of length of uncut zone function of material thickness for SAE 3310, SAE 8620 and 316L steel at traverse speed \( V_t = 20 \text{ mm/s} \).

In figure 8 it is shown the increase of uncut area for different materials at the same speed. All graphics revealed the rise of uncut zone with the increase of thickness of materials and with the increase of traverse speed. The length of uncut zone may be controlled with the optimization of values of traverse speed. Optimization results in increased dimensional precision and increased surface quality.

**References**

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