Management and Production Engineering Review
Volume 16 • Number 2 • June 2025 • pp. 1–13
DOI: 10.24425/mper.2025.154927

Acceptable Cutting Distance and Feed Rate Values for Sheet Metal Plasma Cutting

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Received: 01 July 2024
Accepted: 12 May 2025

Abstract

Based on operational parameters such as feed rate and cutting distance, efficient plasma cutting operations are verified when the items' dimensions match the projected values. However, acceptable feed rate and cutting distance values are often difficult to verify in scientific articles, catalogs, and manuals. Thus, the main objective of this research is to define acceptable cutting distance and feed rate values for sheet metal plasma cutting. The simulation was developed with the definition of operational parameters values based on the Hypertherm machine, followed by instances characterization, speed dimensional quality variation, distance dimensional quality variation, and cutting layout generation using a bottom-left-fill heuristic combined with tabu search. A cutting distance of 2.8 mm and a feed rate of 2477 mm/min are recommended for SAE 1020 steel, considering a 5 mm thickness, 1.1 mm kerf width, and oxygen gas.

Keywords

Plasma cutting; Sheet metal; Metal-mechanical; Cutting distance; Strip packing problem.

Introduction

The metal-mechanical production chain is fundamental for the automotive, transport, civil, and aerospace transformation industries (Severo et al. 2015; Severo et al. 2017; Armindo et al. 2019). In specific, plasma cutting is a common operation found in metal-mechanical industries to divide sheet metal (e.g., steel or aluminum) into different items (Sáenz et al. 2015; Schleuss et al. 2015; Francescatto et al. 2023a).

Considering cutting and packing problems, the sheet metal plasma cutting can be characterized as a rectangular two-dimensional strip packing problem (2D-SPP) (Wäscher et al. 2007; Neuenfeldt Júnior et al. 2021b), where the objective is to cut the object (sheet metal) into a determined number of items (rectangles), minimizing the sheet metal height (Oliveira et al. 2016; Neuenfeldt Júnior et al. 2023).

The sheet metal plasma cutting process enables high cutting speeds, combining productivity and efficiency (Ramakrishnan et al. 2018). During the cutting process, the plasma generates a narrow heat-affected zone, where the sheet metal structural integrity must be preserved to produce rectangles with minimal dross and slag, reducing non-added value activities as reworks (Nemchinsky and Severance 2009; Cardoso and Rodrigues 2022; Boulos et al. 2023).

Efficient sheet metal plasma cutting operations must be conducted with acceptable dimensional quality when the four edges of the rectangles are equal to the projected dimensions, considering a margin of error, and the required surface finishing level is satisfied without damage and fracture (Ramakrishnan et al. 1997; Petunin and Stylios 2016).

This physicochemical condition varies according to the material, affecting the positioning of rectangles into the sheet metal, named cutting layout (Júnior et al. 2022). For example, the cutting process for stainless steel differs from the SAE 1020 steel, where stainless steel cutting layouts are infeasible to cut SAE 1020 steel, because of the minimum cutting distance required to avoid heat-affected zones.

Depending on the cutting distance between rectangles and cutting speed, raw material waste can be found even considering the plasma cutting precision (Francescatto et al. 2023a). Thus, acceptable values for operational parameters, including the cutting distance between rectangles and cutting speed, are often difficult to define.

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Acceptable values are defined empirically by the machine operator, given the lack of information from scientific articles and plasma cutting machine catalogs and manuals (e.g., Super Tork, Lincoln Electric, ESAB, Eutectic Castolin, and Rojimac).

To obtain rectangles with acceptable dimensional quality, higher cutting distances and low feed rate values can be used, increasing the sheet metal waste and operation time until reaching unacceptable operating costs. Conversely, a null distance between rectangles and a higher feed rate violates the projected dimensions and reduces the edges' surface finishing level, resulting in unsatisfactory dimensional quality (Demailly and Quirion 2008; Thomas 2011).

In both situations, inappropriate cutting distance and feed rate values generate human and non-human resource wastes and efficiency loss in the production process. Thus, the scientific aim of this article is an exploratory analysis to define acceptable cutting distance and feed rate values for rectangular sheet metal plasma cutting. This research extends previous research verified in Francescatto et al. (2023a) and Júnior et al. (2023), contributing to reducing operational costs in metal-mechanical industries and wastes with non-added value activities, especially reworks or scrap rectangles.

This paper is structured as follows. The problem definition and dimensional quality are detailed in Section 2. Section 3 presents the methodology based on the plasma cutting simulation procedure. Section 4 presents the results and the exploratory analysis discussion. Section 5 shows the conclusion.

Problem definition: Dimensional quality

In the plasma cutting process, a nozzle with a hole is used to guide a high-temperature ionized gas, forming an active arc to cut electrically conductive sheet metals into rectangles (Maity and Bagal 2015; Lazarevic and Lazarevic 2022; Hussain et al. 2024). A table controlled by computer numerical control (CNC) is the automation device, and the cutting layout of the rectangles must be previously defined using solution methods (e.g., heuristics) (Gupta et al. 1998; Neuenfeldt Júnior et al. 2018; Neuenfeldt Junior et al. 2021a; Júnior et al. 2022; Czerniachowska et al., 2023; Neuenfeldt Júnior et al., 2024).

For dimensional accuracy and surface quality, the plasma cutting process, when compared to the laser cutting process, for example, is inferior. However, the penetration capacity, especially for sheet metal with a thickness greater than 25 mm, as well as the reduced operating costs, are the main advantages (İrsel and Güzey, 2021).

For metal-mechanical industries, wastes are verified in non-added value activities (Singh et al. 2017; Francescatto et al. 2023b; Zaky et al. 2023), being classified, considering lean manufacturing production systems, in seven losses: (i) Overproduction; (ii) waiting; (iii) stock; (iv) transportation; (v) over-processing; (vi) movement; and (vii) defects (Ohno 1988; Bakri et al. 2012; Gupta and Jain 2013).

Defect losses in sheet metal plasma cutting prevent the commercialization and use of defective rectangles throughout the production chain, affecting operational cost, given by: (i) Raw material disposal and scrapping; (ii) production system asynchronism because of the low cutting speed, where operations following plasma cutting do not receive all rectangles with acceptable dimensional quality in the expected period, generating delays; (iii) inputs (mainly electrical energy) waste; and (iv) increased operational time and human resources required to rework defective rectangles (Čiarnienė and Vienažindienė 2012; Dixit et al. 2015).

In a production system, operational costs given by defect losses are used to verify dimensional quality (DQ) variations concerning cutting layouts, being composed of two indicators, speed dimensional quality (SDQ) and distance dimensional quality (DDQ).

The SDQ is verified according to the cutting machine speed options, given by the operational parameter feed rate (mm/min) lower and upper limit values. For a feed rate close to the lower limit (e.g., 1513 mm/min), the cutting speed is reduced, increasing the probability of obtaining edges with good dimensional quality but with a higher operational time required to cut all rectangles. Conversely, a feed rate close to the upper limit (e.g., 3442 mm/min) allows a faster cutting speed, reducing the probability of obtaining edges with the required surface finish level and leading to rework or scrap rectangles (Majeske and Hammett, 2003).

The DDQ is assigned according to minimum distance variations between rectangles in the cutting layout, given by factors as the defective surface layer size (heat-affected zones) caused by the active arc thermal energy, cutting plasma process inaccuracy because of poor cutting machine maintenance, failure to change machine torch inputs at the required time, unevenness in the cutting table, and/or imperfections in the sheet metal surface (Zajac and Pfeifer 2006; Salonitis and Vatousianos 2012; Kadirgama et al. 2013; Lazarevic and Lazarevic 2017; Masoudi et al. 2019; Gostimirović et al. 2020; Magid 2021).

Using the operational parameters values defined in the Section 3, lower (2.0 mm) and upper (3.6 mm) cutting distance limits were assigned. Based on tests developed before the present research, wide cutting distances (upper to 3.6 mm) allowed better dimensional qualities, given the lower risk of a rectangle cut interfering with the neighboring rectangles' dimensions, increasing unused sheet metal areas and raw material waste. For short cutting distances (lower than 2.0 mm), the unused sheet metal area is reduced, but the risk of a rectangle cut interfering with the neighboring rectangles' dimensions increases, demanding reworks or generating scraps.

Both SDQ and DDQ are measured quantitatively using a five-value scale (from one to five), based on feed rate and cutting distance, respectively, as shown in Table 1. One represents the feed rate upper limit (3442 mm/min) and cutting distance lower limit (2.0 mm), relating to cuts with low DQ levels. Five is used for the feed rate lower limit (1513 mm/min) and cutting distance upper limit (3.6 mm), relating to cuts with high DQ levels.

The DQ is calculated by the SDQ and DDQ arithmetic mean, where non-integer values (e.g., 1.5) are allowed. Finally, the rework or scrap rectangles demand was defined for SDQ or DDQ values equal to or lower than 3.0, when the feed rate is higher than the recommended for the plasma cutting characteristics proposed in the research and the risk of a rectangle cut interfering with the neighboring rectangles' dimension is improved by small cutting distances.

Methodology: Plasma cutting simulation

The research was divided into four steps (Fig. 1) to develop the exploratory analysis: (i) Operational parameters values definition; (ii) instances' characterization; (iii) SDQ and DDQ values variation; and (iv) cutting layouts generation.

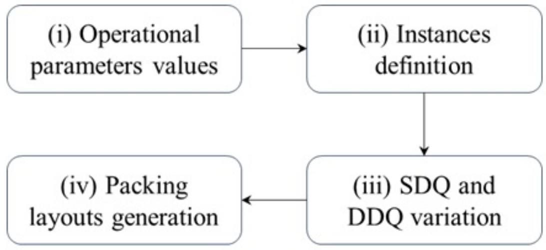

Fig. 1. Research steps

In the first step, values for seven operational parameters, based on physicochemical factors, were defined to simulate the cutting process: (i) Kerf width (1.1 mm); (ii) preheat time (.5s); (iii) pierce delay time (.4s); (iv) pierce height (5.0 mm); (v) plunge rate (5.0 mm/min); and (vi) cut height (1.5 mm). The feed rate and the cutting distance were reserved to vary SDQ and DDQ values. The Hypertherm Powermax45 XP machine operator manual (Hypertherm, 2018) was used as a reference, considering the SAE 1020 steel, with 5 mm thickness, 45 A electric current, and oxygen as ionized gas.

For the simulation, the "cutting rule" defines the machine torch movement path and the cutting sequence, given by three options ("all inside first", "shortest path", "keep parts together"). "All inside first" prioritizes holes located inside the rectangles. For the "shortest path", the machine torch movement is minimized, unfavoring any rectangles' special characteristics (e.g., size, shape, or manufacturing order). Finally, in "keep parts together", the edges and holes of each rectangle must be completed to continue the process. The "shortest path" was selected as the "cutting rule", where the cutting process starts at the origin coordinate (0,0) at the lowest and leftmost sheet metal position. Also, the rectangles approached did not have holes or any special characteristics.

In the second step, based on demands related to the practical metal-mechanical manufacturing applicability, as well as rectangles and sheet metal geometric characteristics, ten instances were characterized, eight from Neuenfeldt et al. (2019), *pt12_30_3*, *pt2_23_42*, *pt10_23_40*, *pt9_27_3*, *pt16_26_84*, *pt1_22_3*, *pt1_24_60*, and *pt1_24_89*, one from

Table 1
SDQ and DDQ quantitative scale

Feed rate (mm/min)	SDQ	Cutting distance (mm)	DDQ	DQ [(SDQ+DDQ)/2]	Risk of rework or scrap?
3442	1.0	2.0	1.0	1.0	High
2960	2.0	2.4	2.0	2.0	High
2477	3.0	2.8	3.0	3.0	Medium
1995	4.0	3.2	4.0	4.0	Low
1513	5.0	3.6	5.0	5.0	Low

Berkey and Wang (1987), *bwmv159*, and one from Jakobs (1996), *J1*.

Table 2 shows the instances' characteristics including the number of rectangles, the sheet metal width (W), and the lower-bound (LB) calculated based on Martello et al. (2003), as well as the maximum, minimum, and mean dimensions between all rectangles in each instance.

The third step is the SDQ and DDQ values variation, where five values for both feed rate (3442, 2960, 2477, 1995, and 1513 mm/min) and cutting distance (2.0, 2.4, 2.8, 3.2, and 3.6 mm) were attributed, respectively, using the scale one to five proposed in Table 1.

The values are used to define the SDQ and DDQ variations and to test the DQ behavior, calculated by the SDQ and DDQ arithmetic mean, keeping a linear incremental pattern by using homogeneous intervals, and avoiding biases in the operational cost analysis. Thus, 25 combinations of SDQ and DDQ values were adopted to simulate plasma cutting conditions for each instance, as described in Table 3.

In the last step, the cutting layouts for each instance were generated using the Bottom-Left-Fill (BLF) constructive heuristic (Chazelle 1983), together with an improvement process using the tabu search (Glover 1990; Júnior et al. 2019), implemented in C/C++, as described in Júnior et al. (2023). For the BLF, the rectangles must be orthogonally allocated one at a time, according to the input sequence order, considering as a reference the sheet metal's lowest and leftmost coordinate.

Tabu search was adopted to improve the cutting layouts. Penalties classified in short-term and long-term lists are applied to the input sequence order, excluding rectangles with input positions already penalized in previous iterations. When selected for the short-term list, the rectangle input position cannot be moved for the next eight consecutive iterations. If selected for the long-term list, the rectangle input position cannot be moved for the next 15 consecutive iterations. The penalties reduce in unit increments with each iteration until zero. Finally, the maximum number of iterations to select a cutting layout for each instance is 200, regardless of the instance size, and the cutting layout with the lowest sheet metal area used (lowest H) is selected.

Next, the selected cutting layouts were digitally drawn using SketchUp 2020 (version 2020-0-1), encoding the coordinates of the rectangles into the sheet metal with the Sheetcam (version 6.0.0) to feed the Mach3 simulation software. The simulation is finished, returning reports used to compare the operational cost values for each test, according to SDQ and DDQ variations.

Exploratory analysis results

In this section, an acceptable value for DQ, considering the operational cost and the 25 test conditions from SDQ and DDQ, is described in the first exploratory analysis section. In the second exploratory analysis section, the impact of non-added value activities on the sheet metal plasma cutting process profit was used to recommend acceptable values for cutting distance and feed rate.

Table 2
SDQ and DDQ quantitative scale

Instance	Sheet metal		Rectangles			
	W	LB	Number	Maximum dimension	Mean dimension	Minimum dimension
pt12_30_3	428	58	25	87	37.1	2
pt2_23_42	329	139	20	91	51.2	15
pt10_23_40	158	529	19	96	64.9	21
J1	1000	375	50	175	86.5	50
pt9_27_3	828	45	42	87	36.1	9
pt16_26_84	134	534	23	97	47.4	1
bwmv159	100	68	20	34	18.6	2
pt1_22_3	158	37	14	59	22.9	9
pt1_24_60	230	69	22	61	27.9	6
pt1_24_89	229	41	7	56	37.1	7

Table 3
25 test conditions from SDQ and DDQ

Test	Feed rate (mm/min)	SDQ	Cutting distance (mm)	DDQ	DQ [(SDQ+DDQ)/2]
1	3442	1.0	2.0	1.0	1.0
2	3442	1.0	2.4	2.0	1.5
3	3442	1.0	2.8	3.0	2.0
4	3442	1.0	3.2	4.0	2.5
5	3442	1.0	3.6	5.0	3.0
6	2960	2.0	2.0	1.0	1.5
7	2960	2.0	2.4	2.0	2.0
8	2960	2.0	2.8	3.0	2.5
9	2960	2.0	3.2	4.0	3.0
10	2960	2.0	3.6	5.0	3.5
11	2477	3.0	2.0	1.0	2.0
12	2477	3.0	2.4	2.0	2.5
13	2477	3.0	2.8	3.0	3.0
14	2477	3.0	3.2	4.0	3.5
15	2477	3.0	3.6	5.0	4.0
16	1995	4.0	2.0	1.0	2.5
17	1995	4.0	2.4	2.0	3.0
18	1995	4.0	2.8	3.0	3.5
19	1995	4.0	3.2	4.0	4.0
20	1995	4.0	3.6	5.0	4.5
21	1513	5.0	2.0	1.0	3.0
22	1513	5.0	2.4	2.0	3.5
23	1513	5.0	2.8	3.0	4.0
24	1513	5.0	3.2	4.0	4.5
25	1513	5.0	3.6	5.0	5.0

Operational cost behavior

The operational cost is calculated by the sum of the raw material waste cost, related to DDQ, and by the processing time cost, related to SDQ.

The raw material waste cost is calculated from the sheet metal purchase value ($248.38), considering 1500×3000 mm dimensions, with the scrap (in mm^2) given by the difference between the used area to cut all rectangles and the total sheet metal area (4.5×106 mm^2).

The processing time cost is associated with the operational time required to cut all rectangles, adding the costs related to the active arc electrical energy consumption (0.070 \$/kWh) during the edges cut (5.85 kW), the electrical energy to keep the machine torch motor activated (1.45 kW), regardless of the arc being active, the gas volume demanded (0.018 \$/L) to keep the active arc (151 L/min), the consumable inputs depreciation (0.2 unity/h) including shield ($13.33), retaining cap ($42.76), swirl ring ($2.76), electrode ($5.81), and gas distributor ($11.66), based on the machine torch use, and the human resources salaries required (7.79 \$/h) (Celesc, 2024; Hypertherm, 2024).

Table 4 shows an example of the operational cost calculation for 25 tests related to *pt2_23_42*. Each test considers the raw material waste and processing time costs while varying the cutting distance, to change the DDQ, and varying the feed rate, to change the SDQ.

The cutting layout ($H = 169$ mm) from test 1 was obtained using a 2.0 mm cutting distance and a 3442 mm/min feed rate, with an operational cost of $2.85 per sheet metal cut for *DQ1.0*, disregarding non-added value activities demands as edges rework.

The cutting layout from test 1 was 38% lower than the test 25 cutting layout ($H = 181$ mm), with a 3.6 mm cutting distance and a 1513 mm/min feed rate, resulting, for *DQ5.0*, in an operational cost of

Table 4
Example of the operational cost for *pt2_23_42*

Test	SDQ	Proc. time (min)	Proc. time cost	DDQ	H (mm)	Raw mat. waste (mm^2)	Raw mat. waste cost	DQ	Operat. cost
1	1.0	02:18	$1.44	1	169	9638	$1.41	1.0	$2.85
2	1.0	02:17	$1.44	2	171	10177	$1.49	1.5	$2.92
3	1.0	02:18	$1.44	3	172	10700	$1.56	1.5	$3.00
4	1.0	02:19	$1.44	4	180	13227	$1.93	2.0	$3.00
5	1.0	02:19	$1.44	5	181	13711	$2.00	2.0	$3.08
6	2.0	02:30	$1.59	1	169	9638	$1.41	2.0	$3.19
7	2.0	02:30	$1.59	2	171	10177	$1.49	2.5	$3.37
8	2.0	02:29	$1.58	3	172	10700	$1.56	2.5	$3.14
9	2.0	02:31	$1.58	4	180	13227	$1.93	2.5	$3.32
10	2.0	02:32	$1.61	5	181	13711	$2.00	2.5	$3.50
11	3.0	02:46	$1.78	1	169	9638	$1.41	3.0	$3.46
12	3.0	02:50	$1.83	2	171	10177	$1.49	3.0	$3.51
13	3.0	02:47	$1.80	3	172	10700	$1.56	3.0	$3.36
14	3.0	02:48	$1.79	4	180	13227	$1.93	3.0	$3.58
15	3.0	02:49	$1.82	5	181	13711	$2.00	3.0	$4.01
16	4.0	03:11	$2.09	1	169	9638	$1.41	3.5	$3.61
17	4.0	03:11	$2.09	2	171	10177	$1.49	3.5	$3.72
18	4.0	03:11	$2.09	3	172	10700	$1.56	3.5	$3.65
19	4.0	03:11	$2.07	4	180	13227	$1.93	3.5	$4.09
20	4.0	03:11	$2.11	5	181	13711	$2.00	4.0	$3.82
21	5.0	03:53	$2.60	1	169	9638	$1.41	4.0	$4.00
22	5.0	03:53	$2.60	2	171	10177	$1.49	4.0	$4.16
23	5.0	03:53	$2.60	3	172	10700	$1.56	4.5	$4.11
24	5.0	03:55	$2.60	4	180	13227	$1.93	4.5	$4.53
25	5.0	03:56	$2.64	5	181	13711	$2.00	5.0	$4.64

$4.64 per sheet metal. Considering all 10 instances, the mean operational cost difference between test 1 and test 25 is 37%, reducing the potential profit contribution of the sheet metal plasma cutting process for the metal-mechanical industrial context.

Based on raw material waste cost and processing time cost, Table 5 shows the operational cost variation for the DQ increase from *DQ1.0* to *DQ5.0*. For DQ with more than one test (e.g., *DQ1.5* with tests 2 and 3), the average cost values were considered.

The raw material cost given by the SAE 1020 steel selling price is predominant in the operational cost, being on average 3.5% higher compared to processing time costs. For example, the operational cost variation in *pt2_23_42*, from *DQ1.0* ($2.85) to *DQ3.0* ($3.45) is 18%, while from *DQ3.0* ($3.58) to *DQ5.0* ($4.64) is 38%.

High cutting distance, represented by *DDQ4.0* (3.2 mm) and *DDQ5.0* (3.6 mm), guarantees cutting quality, keeping the original dimensions projected, but occupying more sheet metal area for the cutting layout. When adopting high cutting distance for plasma cutting (*DQ4.0* and *DQ5.0*), the profit is substantially reduced, as described in Section 4.2.

Lower cutting distance *DDQ1.0* (2.0 mm) and *DDQ2.0* (2.4 mm) allow reduced operational costs, as verified for *pt2_23_42* ($2.85 and $3.09, respectively), given the closer cutting layout, requiring a smaller sheet metal area. According to Hypertherm (2018), a kerf width equal to 1.1 mm must be adopted, given mainly by the type of cutting (plasma), the sheet metal thickness (5 mm), the gas (oxygen), and the raw material (SAE 1020 steel), besides the upper and lower feed rate limits considered.

Considering the difference between the kerf width and the cutting distance defined for *DDQ1.0* (2.0 mm) and *DDQ2.0* (2.4 mm), as well as heat-affected zones (1.5 mm to 2.5 mm) caused by the active arc thermal energy, the dimensional tolerance is substantially re-

Table 5
Operational cost (OC), raw material waste cost (RMW), and processing time cost (PT) are categorized according to dimensional quality (DQ) values

Instance	Cost	Dimensional quality				
		DQ1.0	*DQ2.0*	*DQ3.0*	*DQ4.0*	*DQ5.0*
pt12_30_3	OC	$2.95	$3.15	$3.46	$3.73	$4.17
	RMW	$1.53	$1.58	$1.63	$1.68	$1.73
	PT	$1.42	$1.57	$1.83	$2.05	$2.44
pt2_23_42	OC	$2.85	$3.09	$3.58	$3.99	$4.64
	RMW	$1.41	$1.49	$1.68	$1.83	$2.00
	PT	$1.44	$1.60	$1.91	$2.16	$2.64
pt10_23_40	OC	$4.42	$4.69	$5.30	$5.54	$6.15
	RMW	$2.80	$2.89	$2.98	$3.07	$3.14
	PT	$1.62	$1.81	$2.32	$2.47	$3.01
J1	OC	$4.61	$4.88	$5.64	$6.24	$7.10
	RMW	$2.86	$2.98	$3.35	$3.66	$3.97
	PT	$1.75	$1.91	$2.29	$2.58	$3.13
pt9_27_3	TO	$5.43	$5.77	$6.29	$6.75	$7.48
	RMW	$2.35	$2.59	$3.01	$3.38	$4.01
	PT	$5.43	$5.77	$6.29	$6.75	$7.48
pt16_26_84	OC	$6.17	$6.46	$6.89	$7.27	$7.87
	RMW	$4.48	$4.58	$4.65	$4.73	$4.79
	PT	$1.69	$1.87	$2.23	$2.54	$3.08
bwmv159	OC	$16.80	$17.35	$17.93	$19.26	$22.32
	RMW	$12.70	$12.99	$13.28	$13.57	$13.87
	PT	$4.10	$4.72	$5.84	$6.80	$8.45
pt1_22_3	OC	$18.64	$19.35	$20.50	$21.52	$23.14
	RMW	$15.18	$15.37	$15.55	$15.73	$15.92
	PT	$3.46	$3.98	$4.95	$5.78	$7.22
pt1_24_60	OC	$56.51	$57.93	$60.15	$62.16	$65.36
	RMW	$50.03	$50.43	$50.81	$51.19	$51.64
	PT	$6.48	$7.49	$9.35	$10.97	$13.72
pt1_24_89	OC	$45.80	$64.35	$68.96	$75.27	$76.68
	RMW	$43.09	$61.18	$65.02	$70.63	$70.90
	PT	$2.71	$3.16	$3.95	$4.64	$5.78
Mean	OC	$16.42	$18.74	$19.99	$21.28	$22.49
	RMW	$13.64	$15.61	$16.20	$16.95	$17.20
	PT	$3.01	$3.39	$4.09	$4.67	$5.70
Mean difference (from *DQ1.0*)	PT		12.6%	36.0%	55.3%	89.2%

duced, resulting rectangles with dimensions smaller than projected, which must be scrapped and recut.

To show the cutting distance impact, Fig. 2 presents three cutting layouts for a generic instance with six rectangles.

The cutting distance of 2.0 mm (*DDQ1.0*) was adopted (Fig. 2a), slightly restricting the area available to the cutting layout, resulting in $H = 78$ mm, with 27.87% of raw material waste. Next, the cutting distance of 2.8 mm (*DDQ3.0*) is considered (Fig. 2b), requiring a change in the cutting layout, constraining the sheet metal area, resulting in $H = 82$ mm, with 31.39% of raw material waste. Finally, a cutting distance of 3.6 mm (*DDQ5.0*) is used (Fig. 2c), further constraining the available area, returning $H = 88$ mm, with 36.07% of raw material waste.

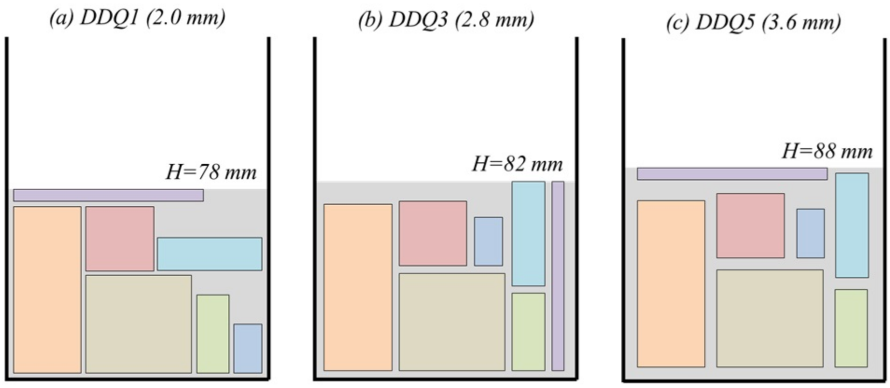

Fig. 2. Example of three packing layouts for cutting distance

With only six rectangles, the restriction given by the cutting distance increases the raw material waste by approximately 10%. However, the minimum distance guarantees the dimensions projected during the cutting operation.

To mitigate the trade-off effect between raw material waste and the guarantee of obtaining the dimension projected, reducing reworks or scraps, an intermediate cutting distance, close to 2.8 mm (*DDQ3.0*), is recommended.

Processing time costs increase proportionally as the feed rate decreases up to the lower limit in *SDQ5.0* (1513 mm/min), given by the active arc time required when compared to *SDQ1.0* (3442 mm /min). The arc is active approximately 70% of the time, increasing inputs, gas, electricity, and labour costs required to cut all rectangles.

For the remaining time, the machine torch is being moved between cuts without the arc being active, where the motor's electrical energy and labour costs are considered. However, the risk of increasing excessively the feed rate, for example, *SDQ1.0* compared to *SDQ5.0*, is associated with the low edges' surface finish level, which may require non-added value activities to improve the edges' surface finish level, being infeasible in practice. For extreme situations, the edges cut may not be complete, especially for thick sheet metals (> 12 mm), because of the short contact time between the sheet metal surface and the active arc.

As with DDQ, intermediate SDQ values are required to the best trade-off between processing time costs and the required edges' surface finish level to avoid reworks or scraps, where a feed rate close to 2477 mm/min (*SDQ3.0*) is recommended.

An acceptable value for DQ, considering the operational cost, is between 2.5 and 3.5, given by a cutting distance between 2.8 mm and 3.2 mm and a feed rate between 1995 mm/min and 2477 mm/min.

Rework or scrap rectangles impact

This section shows the impact of reworks or scraps in the sheet metal plasma cutting process profit, based on a metal-mechanical industrial scale dynamic, considering an operational time equivalent to four hours and the number of sheet metals to be cut in a working day.

The profit (in %) of each test was calculated by dividing the revenue by the expense, being reduced by the potential cost to rework or scrap rectangles. Additional considerations are: (i) The revenue is unique for an instance, with an acceptable value equal to 130% of the average operational cost from all tests, considering the metal-mechanical industrial context; (ii) The expenses are based on the raw material waste cost and the processing time cost individually for each test; and (iii) The rework or scrap rectangles demand (∂) are adopted when SDQ or DDQ is equal to 2.0, using the expense value as a reference.

From all 10 instances, Table 6 shows the average profit for seven tests (8, 9, 12, 13, 14, 17, and 18) relating to a DQ between 2.5 and 3.5, with SDQ and DDQ equal or higher than 2.0, from a zero ($\partial = 0$) to an extreme of 50% ($\partial = 0.5$) rework or scrap rectangles possibility.

For no rework or scrap rectangles demand ($\partial = 0$), the feed rate and cutting distance variation values effect was a difference of 13% between the average profits, being 137% in test 8 (*DQ2.5*: *SDQ2.0* and *DDQ3.0*), showing the scalability of adopting values close to the lower limit for the feed rate, compared to test 18 (*DQ3.5*: *SDQ4.0* and *DDQ3.0*), where the average profit is 124%.

Test 8 allows the cutting of more sheet metals throughout the working day. As an example, for *pt2_23_42*, using the feed rate 1995 mm/min from test 18, 75 sheet metals can be cut, while with the feed rate 2960 mm/min from test 8, 96 sheet metals can

Table 6
Average profit value for tests 8, 9, 12, 13, 14, 17, and 18

Test	SDQ	DDQ	DQ	Rework or scrap demand?	Rework or scrap (∂)			
					0	0.20	0.35	0.50
					Profit			
17	4	2	3.0	Yes	126%	115%	107%	99%
12	3	2	2.5	Yes	133%	122%	113%	104%
9	2	4	3.0	Yes	135%	127%	122%	116%
8	2	3	2.5	Yes	137%	130%	124%	118%
18	4	3	3.5	No	124%	124%	124%	124%
14	3	4	3.5	No	127%	127%	127%	127%
13	3	3	3.0	No	131%	131%	131%	131%

be cut, increasing the operation's production capacity, but with the risk of not reaching the edges' surface finishing level and the projected dimension, which result in additional costs with non-added value activities.

Raw material waste affects the average profit. In tests 8 and 9 (*SDQ2.0*), the cutting distance (*DDQ3.0* to *DDQ4.0*), from 2.8 mm to 3.2 mm, reduced the average profit by 2%. Between tests 12, 13, and 14 (*SDQ3.0*), the average profit was reduced by 6%, with the cutting distance changing from 2.4 mm (test 12) compared to 3.2 mm (test 14).

Compared to test 12, for test 13 and test 14, the edges' surface finishing level and the projected dimension conditions are satisfied. As verified for feed rate, the cutting distance variation interferes the average profit.

In specific, increasing the cutting distance value mainly influences instances with large rectangles proportionally to sheet metal size, as verified for *J1* and *pt12_3_13*, affecting the cutting layouts and compromising the raw material waste cost.

In addition, from *DQ4.0*, the projected dimensions are maintained, but the profit reduces given the distance between the rectangles (up to 3.2 mm) and the reduced number of sheet metals cut (feed rate lower than 1995 mm/min). The average profit value of tests 15, 19, and 23 is 124%, 4% lower than test 18 (*DQ3.5*) when $\partial = 0$. For *DQ5.0*, explored in test 25, the profit is 110%, giving a margin of 10% per sheet metal, which in the industrial metal-mechanical scale is unfeasible to be managed and accepted as the plasma cutting process economic contribution.

Considering the effect of seven rework or scrap variations on the average profit value, Fig. 3 shows trend curves with fourth-degree polynomial regression equations, in equal intervals from 20% ($\partial = 0.20$) until 50% ($\partial = 0.50$).

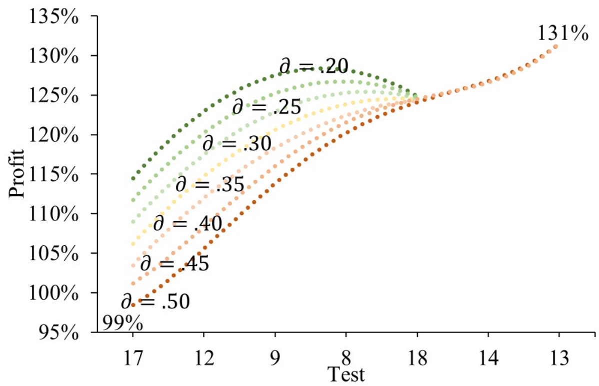

Fig. 3. Rework or scrap demand (∂) trends curve for the average profit value for Tests 8, 9, 12, 13, 14, 17, and 18

In tests 18, 14, and 13, the profit suffers no ∂ interference, given by SDQ and DDQ greater than 2, not requiring reworks or scraps. Even for the extreme possibility, where 50% of rectangles must be reworked or scrapped ($\partial = 0.50$), the expenses for test 13 remain unchanged, considering only the raw material waste cost and the processing time cost calculated when $\partial = 0$. For test 8, the best profit (137%) reduces to 118%, no longer being the most economically attractive situation to be adopted in practice.

Tests 17 and 12 profits with DDQ equal to 2 suffered significant reductions, 27% and 29%, respectively, from $\partial = 0$ to $\partial = 0.50$, confirming the raw material waste impact on the operational cost, as detailed in Table 5.

In tests 8 and 9, the highest profits, not considering the possibility of reworks or scraps ($\partial = 0$), were reduced by 19% in $\partial = 0.50$, given by the SDQ equal to 2, where the feed rate is higher than recommended for the plasma cutting proposed.

Given that the edges' surface finishing level, and the projected dimension, must be satisfied, considering the average profit on industrial scales as a reference, the conditions verified for test 13 (*DQ3.0*: *SDQ3.0* and *DDQ3.0*), with a cutting distance of 2.8 mm and a feed rate of 2477 mm/min, are recommended for plasma cutting the SAE 1020 steel, with 5 mm thickness, kerf width equal to 1.1 mm, and oxygen as ionized gas.

Conclusion

The following arguments show the main perspectives highlighted in the proposed research:

- Based on the relation between the dimensional quality and the operational cost, acceptable values for the cutting distance and feed rate were defined.
- Defining values for cutting distance and feed rate is not trivial, given the scalability of the operational cost variations impact.
- Considering a relatively high sheet metal cutting demand for the instances addressed, a metal-mechanical industry will not be competitive in adopting large cutting distance (>3.2 mm) and slow cutting speeds (<1995 mm/min).
- Short cutting distance (<2.8mm) and fast cutting speeds (>2477 mm/min) require reworking or scrapping rectangles when the dimensions of the four edges are not greater or less than the projected dimension.
- Based on raw material waste and processing time costs, reworks or scraps reduced the profit in a working day by up to 15%.
- The results found cannot be generalized to conditions not tested in the present research.
- As a research limitation, metallographic analyses to inform the sheet metal surface roughness and microhardness were not available. Future research can be conducted to verify, for example, how the plasma cutting affects the sheet metal surface quality.
- Understanding how the exploratory analysis is useful for developing a mathematical model to find the optimal values for both cutting distance and feed rate is an opportunity for future research.
- The replication of exploratory analysis for the laser cutting process, where a smaller cutting distance can be adopted without interfering with the surface finishing level, given by the reduced heat-affected zones on the sheet metal.
- The exploratory analysis can find the cutting distance and the feed rate of other types of machine cutting, sheet metal materials, or any other operational parameter specification.
- The last future research suggestion is to develop a machine learning model able to predict the operational cutting parameters based on, for example, the type of raw material and sheet metal thickness.

Acknowledgments

This work was supported by the Coordination of Superior Level Staff Improvement (CAPES) under Grant [numbers 88887.713376/2022-00] and Brazilian National Council for Scientific and Technological Development (CNPq) under Grant [numbers 406917/2023-0, 312474/2023-7].

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