High efficiency laser-cutting of stainless steel

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Abstract

Standard laser cutting of stainless-steel material is generally performed with nitrogen (N_2) assist gas at pressure as high as 25 bar at the cutting head through cutting nozzle orifice diameter as large as several millimeters. Whereas in free flow, the N_2 gas flowrate is directly proportional to the pressure and quadratically proportional to the nozzle diameter, it can become a large percentage of operation costs for metal fabrication shops. Moreover, in order to allow higher productivity, the industry is raising the average power of lasers in operation thereby proportionally achieving faster cutting speeds. In order to add to this drive for better efficiency, we are offering gas application technologies that will increase laser cutting speed of stainless workpieces and /or reduce N_2 gas consumption at a given laser power. It features a new cutting nozzle tip that operates by contact with the workpiece. When compared to standard laser cutting process, a reduction of N_2 gas consumption by 40% to 60% is observed, while cutting speed increase of 20% to 40% is consistently demonstrated.

Material Considerations

While mild steels are 98% iron, stainless steels have an alloying content of 10 to 20 times higher than mild steel. The top alloying elements include Chrome (Cr) within a 11% to 20% content range, followed by Nickel (Ni) at about 8%: these alloying elements increase weldability and reduce brittleness. When exposed to ambient air, stainless steel rapidly oxidizes into a thin film of Cr_2O_3 diluted in FeO on its surface [1].

$2\ Cr + 3/2\ O_2 \rightarrow Cr_2O_3 + \text{heat}$

This Cr_2O_3 film self-shields the workpiece from deeper oxidation and is also responsible for lesser oxy-cutting effect contribution to the laser-cutting process when assisted with gas containing O_2. Because Cr_2O_3 has a higher melting temperature than iron, this protective film of Cr_2O_3 rapidly solidifies around droplets of molten metal during cutting and sticks as stalactites to the bottom edge of the kerf, thus creating dross (fig.1).

As for the other major alloying element, in the presence of O_2, oxidation of nickel creates a black film coated on the cut edge, which will generate porosity when welded. To avoid the above oxidation caused defects, neutral nitrogen assist gas is predominantly used for laser cutting of stainless steel, particularly for a reduction of dross formation.

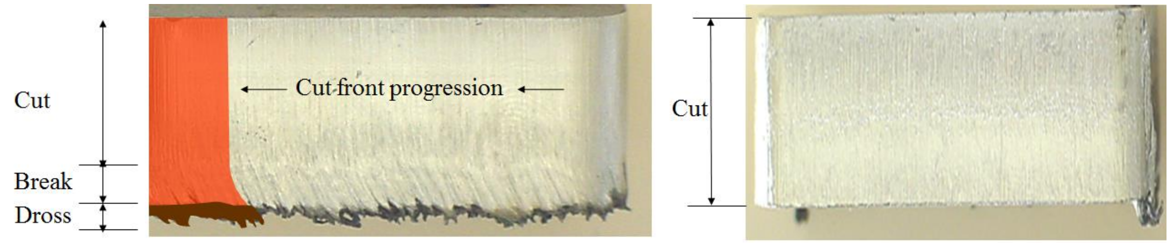
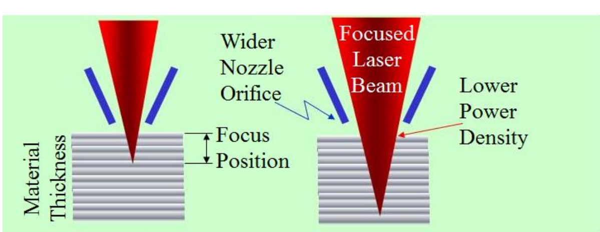


Figure 1: Cut edge quality can be characterized by three zones: cut, break and dross zones (left); the black film visible in the break and dross zones is indicative of the heightened presence of oxygen at the bottom of the kerf. The best quality cuts have a high cut-to-break ratio and minimum burr (right).

Process Considerations

To achieve dross-free cut quality, the focus point is preferably sunk underneath the material's surface to bring more heat density towards the bottom of the kerf. The deeper it is sunk in thick gage material, the more defocused it is at the top surface of the material, and thus the slower the speed becomes. As a consequence, the nozzle orifice diameter must be enlarged to accommodate a wider defocused beam; and increasing the nozzle diameter is also quadratically increasing the gas consumption flow rate through the nozzle (fig. 2). Laser operators can optimize the set-up according to their wanted compromise between speed, quality and gas consumption. Note that for most gases, supersonic flow rate regime is achieved when P is greater than about 1.9 bar.



Gas dependent constant — Pressure — Nozzle Diameter — Temperature

$$\text{Flow Rate} = \alpha \times P \times D^2 \times T^{1/2}$$

			Nitrogen Flow Rate	
Temperature	Pressure*	Nozzle Diameter (mm)	SCFH	l / min
300 K	8 bar	1	165	78
		1.5	371	174
		2	660	310
		2.5	1031	485
Temperature	Pressure*	Nozzle Diameter (mm)	SCFH	l / min
300 K	16 bar	1	312	147
		1.5	701	329
		2	1246	586
		2.5	1947	915

* Pressure read on gauge (add 1 bar for the the absolute pressure)

Figure 2: To minimize dross formation, the focus position is sunk deeper in the material thickness, to bring more heat density towards the bottom of the kerf (left). This results in a wider laser beam cross-section, a lower power density at the top surface of the workpiece and requires a wider nozzle orifice. In free flow conditions, the gas flowrate increases quadratically with nozzle orifice diameter. With supersonic regime ***Flow rate*** *expressed in SCFH (1 SCFH = 0.0282 Nm3/h) when absolute pressure in the nozzle is P in bar, nozzle diameter is D in mm and ambient temperature in the nozzle is T in Kelvin; then gas dependent constant□□ = 297 for N_2, □ = 317 for O_2, □ = 313 for Air.*

The N_2-assisted fusion laser cutting process main set-up parameters are illustrated in fig. 3. The concentrated laser beam and the assist gas stream both exit through the same nozzle tip's orifice. The focused laser beam delivers a flux of very high heat density into a small workpiece area: that is more heat input than it can dissipate by conduction, convection or radiation. Consequently, the temperatures rises beyond fusion and vaporization threshold and the N_2 assist gas stream evacuates the molten and vaporized material through the kerf.

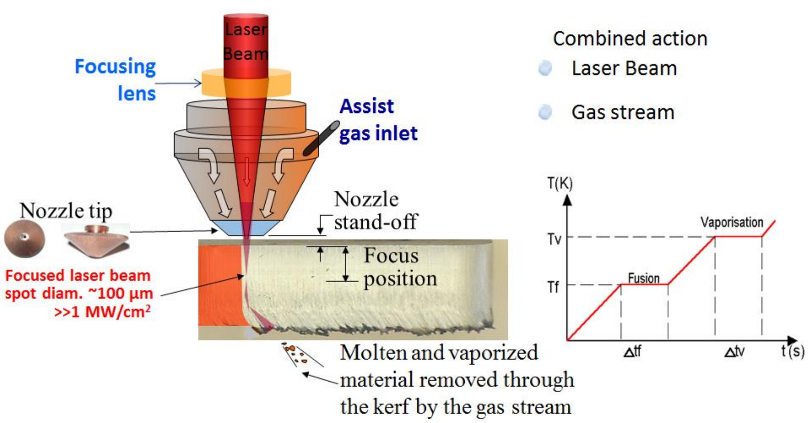


Figure 3: Laser cutting fusion process main set-up parameters for each material and thickness are: laser power, focal length, nozzle orifice diameter, nozzle stand-off, focus position, gas type and pressure and cutting speed.

Compared to O_2-assisted laser cutting, N_2 assisted laser cutting consumes a larger amount of gas that represents a substantial proportion of operating cost for a laser cutting shop (fig. 4).

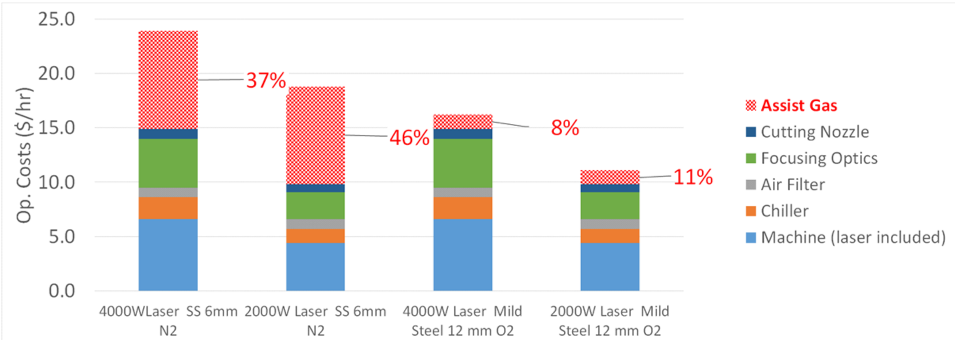


Figure 4: ***Hourly cost itemization example for laser cutting with N_2 vs. with O_2.***
When the laser power increases, that portion decreases and piece cost decreases even further due to increase in cutting speed. Nevertheless, in N_2 assisted laser cutting, the gas represents a predominant portion of operating costs (labor excluded).

Pressure Considerations

Typical pressure for N_2-assist laser cutting can go as high as 25 bar just upstream the nozzle. In order to account for pressure drops, the laser OEMs require 35 bar and up supply pressure at the entrance of their machine. Several gas supply modes are available depending on the volume consumption pattern (fig. 5).

In compressed cylinders volume range, those pressures are easy to supply. However for customers requiring a switch to a more cost effective bulk liquid cryogenic N_2 supply, then standard bulk tank can only deliver up to 15 bar: they need to be coupled with a pressure booster to deliver up to 40 bar.

Figure 5: Gas modes of supply for N_2-assisted laser-cutting. Packaged gases are individual or bundles of compressed cylinders with typical operating pressure ranging from 150 to 300 bar when full. Skid tanks are onsite high pressure tank containing liquid cryogenic N_2 with typical operating pressure of up to 40 bar. Bulk supply consists of either a large cryogenic high-pressure tank with typical operating pressure of up to 40 bar, or a large cryogenic standard 15bar pressure tank coupled with a pressure booster system totaling to a typical operating pressure of up to 40 bar. Onsites consist generally of membranes or PSA generators of N_2 coupled with a compressor and a buffer tank.

Since metal fab shops find themselves needing up to 35 bar, a pressure booster or higher cost high pressure bulk tank have to be installed; this raises considerably the capex for the installation. The following is a technology that enables tremendously higher efficiency in consumption of assist gas and also has the potential to eliminate the need for pressure booster or high pressure tank capital expenditure.

Laser Touch Nozzle Technology

With the conventional state of the art laser cutting process, the nozzle tip is set about a millimeter above the workpiece, and should by design never come in contact with it. Due to the non-uniformity of workpiece surfaces, the nozzle stand-off distance above the workpiece is regulated by a capacity sensor and a Z-axis servo-drive and the numerical control of the machine. Maintaining that nozzle stand-off steady, insures Repeatability & Reproducibility of the laser cutting performance. Numerical simulations confirm that with conventional nozzle and process, 90% of the assist gas is wasted away from the kerf and thus ineffective for the cutting process (fig 6).

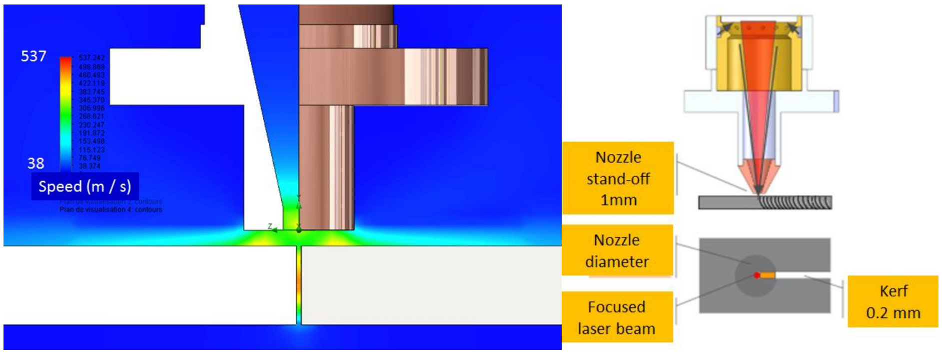


Figure 6: Numerical gas dynamics simulations illustrates how the vast majority of the assist gas escape through the lateral sides of the nozzle and never makes it to the kerf.

Let us remember that the laser cutting process is the only thermal cutting process where the cut kerf width is smaller than the nozzle diameter; this made possible the development of a new gas jet optimization solution in the kerf, including the development of a new nozzle that comes into contact with the workpiece under the effect of assist gas pressure and brings gas only in an active place; in that way, the kerf becomes an extension of the nozzle (fig. 7).

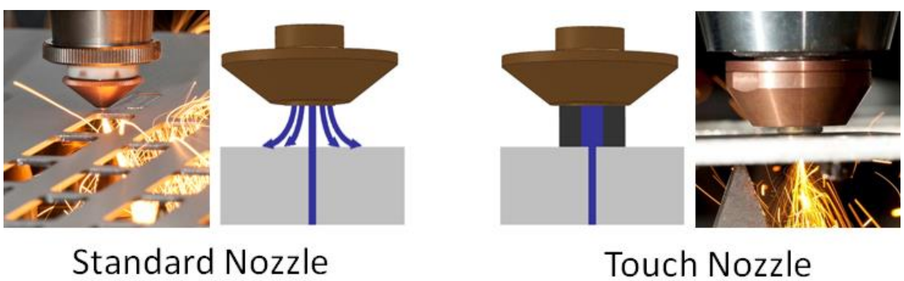
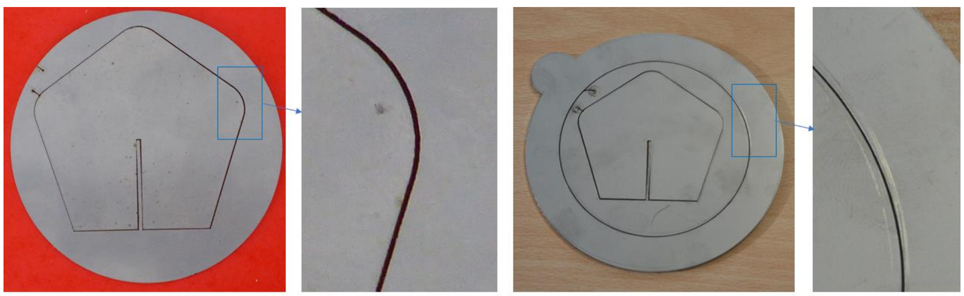


Figure 7: Typical nozzle orifice diameter is of the order of 1 to 2 millimeter. The corresponding nozzle stand-off is of the order of a millimeter in standard laser cutting (left). In such configuration only a minority portion of the assist gas flows through the kerf; the rest is wasted through the sides on the workpiece surface. The new nozzle has a moving brass element that slides down to touch the workpiece and thus preventing assist gas lateral waste escape.

Technical challenge

The technical challenge is that this nozzle has to be compatible with the use of capacitive sensors for nozzle height control. Thus we needed to find an insulating material ideal for the capacitive sensor utilization and compatible for long-term use. Ceramic materials are too fragile and too abrasive to the workpiece surface, whereas polymers have a too short lifetime in a high temperature environment.

For industrial use, the choice of a brass contact mobile part has been validated in terms of thermal resistance, low hardness abrasiveness for steel workpieces. Because brass is an electric conductor, this choice imposes to electrically isolate the element in contact with the rest of the nozzle with an adequate material.
In order to limit the action of the gas pressure on the mobile part in contact with the workpiece, a spring has been calibrated to allow the brass element to slide down only in soft kiss-contact with the workpiece; and so avoid scratches on the workpiece (fig. 8).



With spring optimization Without spring optimization

Figure 8: soft kiss contact of the laser touch nozzle makes a difference on the workpiece surface.

A specific study on the functioning of the capacitive sensor made it possible to highlight the parameters to be taken into account.

$\varepsilon 0$:Relative Permittivity of Vacuum (8.85 pF/m)
εr : Relative permittivity of the material (Air 1.004)
S : Surface of the nozzle next to the sheet (m^2)
d : Distance from the nozzle / sheet (m)
C : Capacity (pF/m)
r2 :max radius (m)
r1 : Min radius (m)
l : length of the coaxial capacity (m)

$$Cplane = \varepsilon 0 \varepsilon r \times \frac{S}{d}$$

$$Ccoax = 2\pi \varepsilon 0 \varepsilon r \times \frac{l}{\ln \frac{r2}{r1}}$$

Understanding this operation has made it possible to define the ideal family of materials to ensure optimal sensor operation. It is important to use an insulating material of low relative permittivity between 1 and 4. Above this range, the sensors no longer regulate. The optimization of the material was made from a numeric tool (CES Selector) to find the best compromise depending on the relative permittivity, temperature resistance, mechanical strength and manufacturing cost.

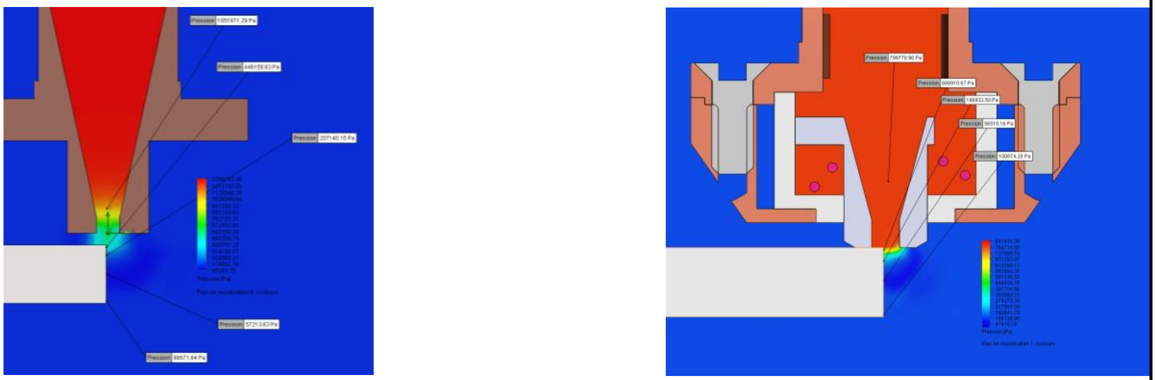


Figure 9: Trials have shown that too much gas pressure in the kerf can cause a plasma generating the loss of the cut. A nozzle geometry has been defined to reduce the pressure in the kerf when the nozzle is in contact. The important parameter is the gas pressure at half height in the kerf. Thanks to an automatic retractable mobile part which limits risks of collisions, the lifetime of the nozzle is increased (fig 10) and unscheduled production stops are prevented.

Figure 10: Top Detail appearance of the touch nozzle after 7 hours of cut

How to optimize cutting parameters?

One of the unique advantages of the Laser touch nozzle is the working pressure which facilitates optimization of the main cutting parameters. According to the evaluation criteria, searching for the optimum focal point position and cutting speed can be facilitated by using the cutting area tool methodology (fig. 11). When the cutting area tool methodology is used, an optimum can be defined according to the highest tolerance focus point parameter and cutting speed. Cutting speed increase are consistently demonstrated (fig. 12) at equal cut edge quality as illustrated in fig 13.

Figure 11: Example of results when using the cutting area tool methodology Results at 4 kW : SST 304L : 3 , 5, 8 & 10 m.

LASER MACHINE	Make and Model	
LASER RESONATOR	Make and Model	
BEAM SHAPE		
MATERIAL	Stainless steel	
THICKNESS	3.0	mm
LASER POWER	4	kW
NOZZLE DIAMETER	6.0	mm
NOZZLE HEIGHT	0.5	mm
ASSIST GAS PRESSURE	7	Bar
ASSIST GAS CONSUMPTION	7.0	Nm3/h
FOCAL LENGTH	200	mm

Δ	No Burrs
o	A few Small Burrs
X	Sharp Burrs
XX	Not cut

Cutting Speed (mm / min)	Focus Position (mm)												
	-0.5	-1.0	-1.5	-2.0	-2.5	-3.0	-3.5	-4.0	-4.5	-5.0	-5.5	-6.0	-6.5
12,000					XX	o	o	o	Δ	Δ	Δ	XX	
12,500						o	o	Δ	Δ	Δ	o		
13,000						o	o	Δ	Δ	Δ	o		
13,500						XX	o	Δ	Δ	Δ			
14,000							Δ	Δ	Δ	Δ			
14,500							Δ	Δ	Δ	Δ			
15,000							Δ	Δ	Δ	XX			
15,500							Δ	Δ	Δ				
16,000							XX	Δ	XX				
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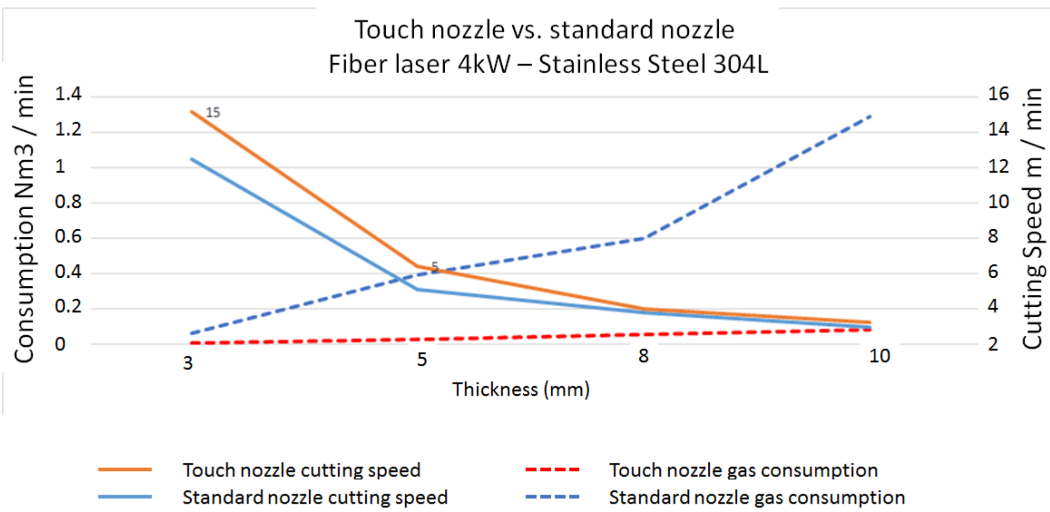

Figure 12: Compared with standard nozzle and conventional laser cutting, the laser touch nozzle consistently results in lower gas consumption and higher cutting speed at comparable cut quality (fig. 13).

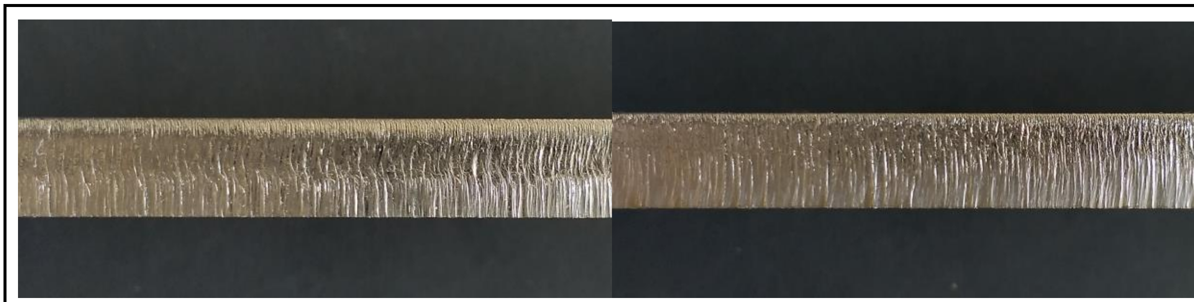

Figure 13 Cut edge quality comparison: (left) Standard nozzle ; Stainless steel 5 mm ; Cutting speed 3,5m/min - fiber laser 4kW.
(right): LASER NOZZLE-TOUCH ; Stainless steel 5 mm ; Cutting speed 5m/min - fiber laser 4kW

Summary

Trials on different laser cutting machines makes and models have shown a significant N_2 gas saving and cutting speed increase at up to 10 kW on stainless steel and mild steel at constant cutting quality.

Typically a gas flow reduction at up to 40% and cutting speed increase at up to 20% give finally a 50% gas saving in production.

A lower gas pressure (7 bar) can also bring value in terms of gas installation saving when a high pressure tank or booster are no longer needed.

Another advantage can be useful in terms of number of nozzle models, only one is enough to cut all thicknesses and simplify nozzle alignment with the focused laser beam.

These improvements with the laser touch nozzle technology are achieved with fiber lasers as well as with CO_2 lasers.

References

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