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CHIP BEHAVIOR ON ORTOGONAL MACHINING WITH APPLICATION OF HIGH PRESSURE CUTTING FLUID JET BY FINITE ELEMENTS METHOD

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Abstract. *As machining operations we understand the ones those give shape to a piece of work or grant dimensions or else a combination of these features and as a result, produce chip. Chip can be defined as a portion of the material, removed by the tool, and it is characterized for having an irregular geometric form. Many improvements have been made in recent decades relative to cutting tools and machining strategies, granting better performances and greater life to the tools. In processing materials considered as hard to cut like Titanium or Nickel alloys an acceptable performance has not been reached yet. One of the processes of improvement in machining that deserves attention is the Machining with High Pressure Jet Assistance(HPJA) which will be studied in this work. Until now, many experimental works were done to understand the phenomena caused by the jet, phenomena like increase of tool life and reduction of efforts. The problem is how to know the better machining conditions to use on each kind of material, what pressure of jet is the better one and what more we can expect from the jet assistance. The experimental work have limitations and consume a lot of time to research many materials. So in this work a dynamic analysis of the machining process with Jet Assistance will be made through a finite elements method (FEM) simulation to detect mechanic and thermal parameters caused by the jet on the system by modifying the position of the nozzle and the point of impact of the jet on the interface.*

Keywords: *Chip, HPJA, FEM.*

1. INTRODUCTION

As machining operations we mean those that by giving the piece the form, or the size or finish, or any combination of these three goods, produce chip. We define chip as the workpiece material portion removed by the tool, characterized by presenting irregular geometric shape (Oliveira, 2005).

The characterization of the chip formation when machining pure steel is classified as segmented formation and continuous fomation. The characterization of the training is regarded as the deformation of the chip and in the case of the segmented chip, training is expressed as the frequency of segmentation, targeting and the degree of deformation itself (Qibiao et al., 2012).

Many improvements have been made in recent decades with regard to cutting tools and machining strategies intended to improve operational performance. In the process of materials considered to be difficult to cut such as titanium and nickel alloys, there is still no final solution in order to obtain a good performance (Courbon et al., 2011). Ezugwu (2005) indicates that many emerging technologies have been developed to increase the overall efficiency of the process, for example, combined machining laser, cryogenic cooling or assisted machining by high pressure jet (HPJA).

The HPJA machining deserves special attention due to the fact that this installation not be expensive, making it affordable for most of the metals. The question that remains as to which pressure to use in each case, what would be the ideal pressure to obtain the best possible result with a particular type of material to be machined, and what effect this pressurized cutting fluid is actually exercising in the piece of work and on the tool.

This study will investigate the effects of pressurized cutting fluid in the chip, workpiece and cutting tool. The entire system performance will be analyzed under the varying position of the jet nozzle exit and also to the impact point on the chip-tool interface.

Influence of the jet on the up-curl radius, side flow angle and side curl radius of the chips has been observed by Kaminski et al. (2000). The authors emphasized the advantage of using a small nozlzle diameter and a high fluid pressure to force the chip sideways and thus control the chip flow.

Mazurkiewicz (2000) studied HPJA in steel cutting using high pressures up to 280 MPa via an external nozzle. By comparing the results to dry cutting and conventional cooling, it was proved that the jet assistance could reduce friction by inducing a sliding condition along the tool–chip interface, produce shorter chips, permit the use of higher cutting parameters, and nevertheless reduce the cutting forces. Comparable trends such as better chip breaking and an improved productivity are exposed by Braham-Bouchnak et al. (2010) when machining a duplex stainless steel at relatively low pressure (25 MPa) but higher flow rate.

Thermal aspects have been concerned in the work of Kaminski and Alvelid (2000). Cutting temperature was shown to be decreased of ~40–45% when machining alloyed steel with coated carbide.

Habak et al. (2006) and Ezugwu et al. (2007) investigated the surface integrity in turning of AISI 316L and Ti–6Al–4V respectively. In both studies, the use of a HPJA minimized undesired hardening effect of the material during the machining process. This effect was amplified when increasing the coolant pressure. Dominant hardening of the machined surface was on the other hand reported after machining with conventional cooling. Regarding residual stresses, Habak et al. (2006) especially showed that surface tensile stresses can be reduced compared to dry cutting.

Even if FE simulations of the cutting process are getting more and more invaluable, Shet et al. (2003) and Vosough et al. (2004) are the only authors known for the development of a numerical model describing the possibilities of the HPJA.

The work of Shet et al. (2003) was based on a Lagrangian formulation in which the water jet was injected directly at the tool–chip interface through a small hole on the rake face. Chip separation has been modelled through a nodal release technique. The study has been focused on the effect of water jet hole position and pressure in machining of AISI 4340 steel. They confirmed that, when a high-pressure jet is injected into the tool–chip interface through the tool, substantial reductions in the interface contact pressure and shear stress, the tool–chip contact length, the temperature in the cutting zone, and the residual stresses in the finished workpiece could be observed. It has been shown that the jet hole position is an important factor.

As for Vosough et al. (2004), a FE simulation using the updated Lagrangian formulation was used to study the turning of a titanium alloy under HPJA, especially the consequences on the residual stresses in the machined workpiece. The jet was injected at the tool–chip interface via an external nozzle. It was found that the jet increases the amount of residual compression stress in both cutting and feed directions. Effect of the jet pressure has not been investigated.

Based on this brief state of the art, it appears essential to add a numerical approach to deeply investigate this new technology. No models are at present known to simulate the HPJA in turning of an Inconel 718 nickel alloy on a whole pressure range (50–130 MPa). Consequences on local variables such as temperatures and stresses fields in the different shear zones as well as sliding velocities along the tool–chip interface are thus completely ignored.

This work aims at completing the experimental study already carried out by Bertoncini (2007) by comparing the trends from an Arbitrary Lagrangian–Eulerian (ALE) numerical model to the experimental ones on an identical pressure range. Experimentally unreachable variables are extracted and studied to reinforce the knowledge on this assistance method and provide additional analysis regarding the effect of the pressure level. Mechanical impact of the jet and thermal cooling are especially dissociated, and the contribution of each effect is analysed.

2. RELATED EXPERIMENTAL STUDY

2.1 Context

A previous survey (Bertoncini, 2007) aimed to investigate the application of HPJA, Minimum Quantity of Lubrificant (MQL) and normal application with no pressured fluid on orthogonal machining of the hard-to-cut steel alloy SAE J775.

The point of interest is the HPJA machining with the application in chip-tool interface. The experiments were done varying some machining parameters like cutting speed, feed rate and depth of cut (ap) showed on Table 1.

A TiCN coated carbide tool ISO TNMA 160408 was chosen. The tool in question has been chosen without chip breaking, so that such a device does not mask the effects of cutting fluid applications, both the tool wear as in the form of chips generated. As the chosen tool does not contain chip breaking and also because the material is high hardness, a toolholder that generates a negative rake angle was selected.

There are five output variables on the experiment: tool wear, piece of work roughness, machining force, relative tool temperature and shape of the chip.

test	V_c (m/min)	f (mm/volta)	a_p (mm)
1	200	0,2	0,75
2	200	0,2	0,5
3	200	0,15	0,75
4	200	0,15	0,5
5	200	0,1	0,75
6	200	0,1	0,5
7	172	0,2	0,5
8	172	0,1	0,5

Table 1 – Machining parameters of preliminary tests.

2.2 Metodology

From an experimental point of view, even if the influence of the jet parameters has been inspected in the past, no study had systematically investigated the relationships between the HPJA process parameters and the machining performance responses. One blank line must be included above and below each equation.

The first step was thus to determine the regions of operability, which set the boundaries of the process parameters for different lubrication conditions (pressure/flow rate), by using the tool–material pair (TMP) methodology (Afnor, 1994). The assessment of HPJA machining performance was then conducted via the response surface methodology (RSM), which integrated a Design Of Experiments (DOE) and a regression modelling technique for the identification of empirical models. The determination of significant model degree and parameters effects was based on the analysis of variance. Chip formation, cutting forces, tool–chip contact length, surface finish and tool temperature were mainly concerned.

Once the jet on the tool-chip interface works as a chip breaker, the main expectation of the experiment is to find a position on the tool rakeface to inject the fluid and the angle of injection for finding the position which gives more life to the tool.

For the present study the jet is guided by two angles C and D. The C angle is formed between the passive plan and the reference plan of the rakeface and the D angle is formed between the reference plan and the work plan. The Fig. 1 shows how the angles are disposed.

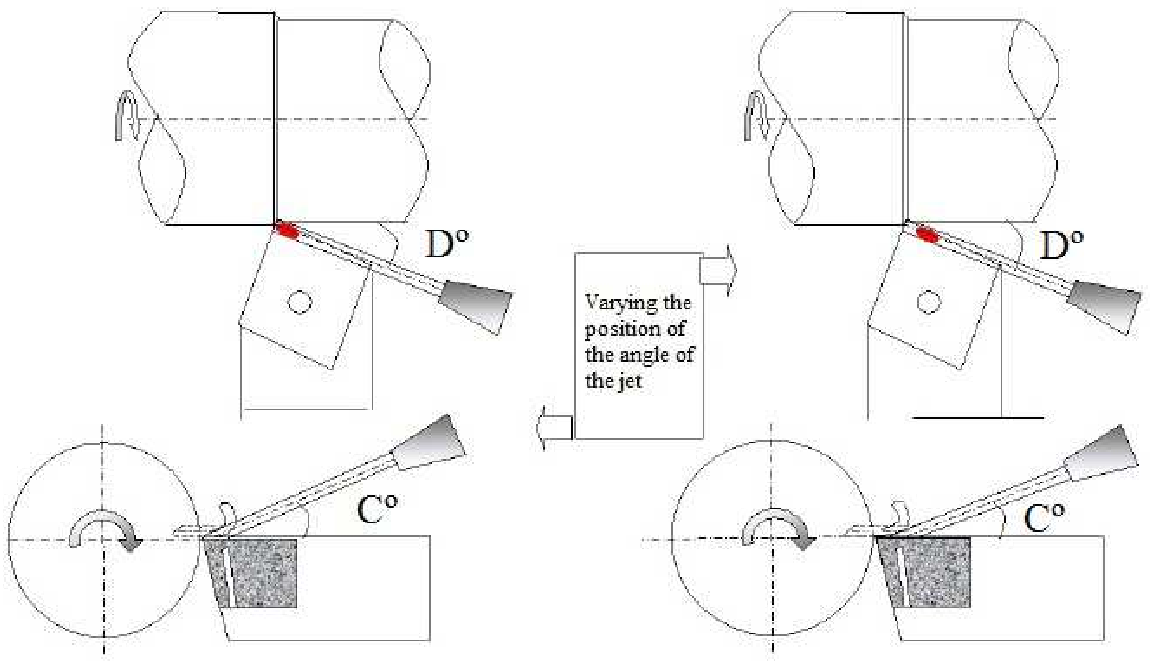

Fig. 1 – Different positions for the angles C and D of the jet.

The pressure used on the experiments was 2,94 MPa and the diameter of the nozzle 1,0 mm because that shows to be a diameter that don't let the jet disperse. The distance of 22 mm ensures that there won't be radial variations and also won't be diameter variations on the jet (Courbon et al, 2009).

Angle C is tested for the values of 10º, 20º, 25º and 30º and angle D only for 20º.

2.3 Main findings

The present methodology showed a considerable influence of the HPJA on the cutting process. Excellent chip breakability and reduction of machining forces as well. The results for the tool life are showed on Fig. 2.

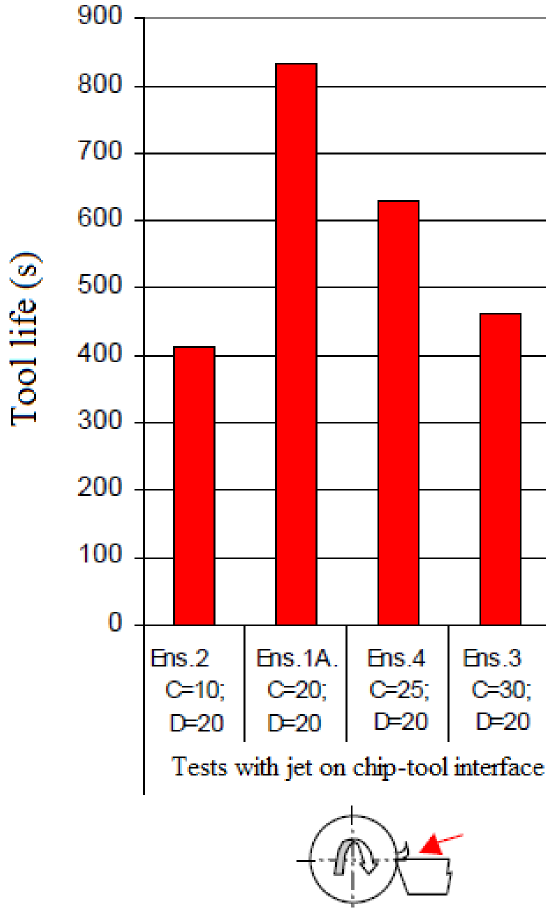

Fig. 2 – Tool life on varying the C angle.

The conclusion was that the best value for angle C is 20º and the point of impact of the jet 1 mm before the toll tip grants better chip removal and also a smaller and better size for the chip helix. All of this facts added to the reduction of the machining force gives for the tools a bigger life.

3. NUMERICAL MODEL

3.1 – Initial formulation

Based on the work done by Bonnet et al. (2008b), a 2D orthogonal cutting model has been developed using an ALE approach in the commercial code ANSYS/Explicit on Workbench(v15.0). As emphasized by Movahhedy et al. (2000), strength of both Lagrangian and Eulerian methods can be combined with this approach. The chip formation occurs by continuous plastic flow of the material around the tool. It especially makes the process simulation possible without the need of a separation criteria such as a critical stress state achieved at a specified distance ahead of the tool tip (Shet et al., 2003) or a damage evolution parameter for the elements deletion (Mabrouki et al., 2008). The density of the mesh around the tool tip need not be very high, and thus the process is computationally efficient. This approach however does not enable to model chip serration process.

According to the fixed cutting conditions (f = 0.2 mm/rev and ap = 2 mm), authors assumed that the value of the depth of cut is large compared to the feed rate. Consequently, plane strain hypothesis has been considered. The model consists of both deformable workpiece and cutting tool. Both solids are meshed using 4-node plane strain thermally coupled quadrilateral elements (CPE4RT). Predefined chip morphology as well as tool geometry, mesh density and order of magnitude of the element size are described in Fig. 3.

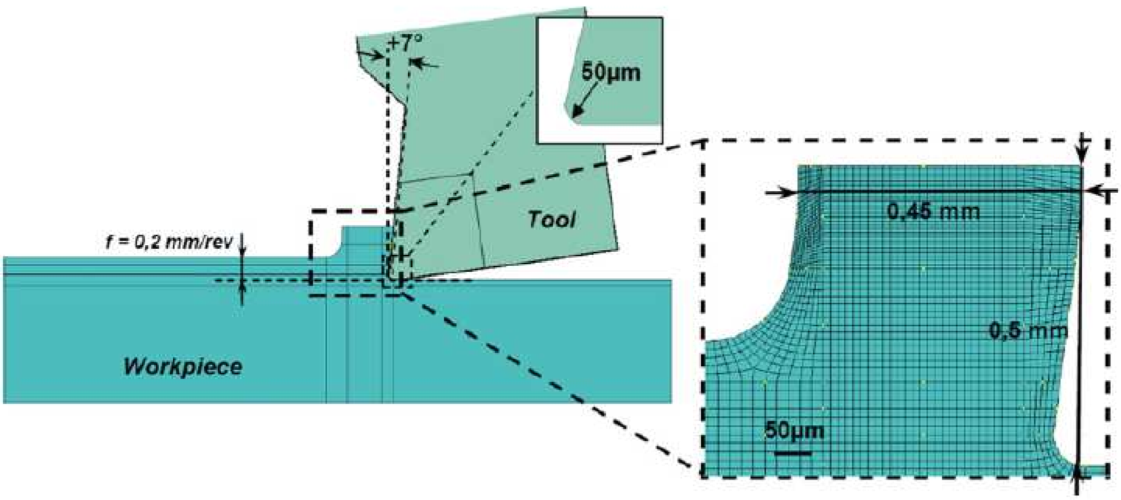

Fig. 3 – Geometry of the work piece and cutting tool (Courbon et al., 2009).

To model the thermal–visco–plastic behavior of the workpiece material, the original Johnson–Cook empirical law (Eq. (1)) has been used as it has proved its suitability in modelling the cutting process. The parameters for this widely used and main constitutive model have been set thanks to the experiments conducted by Uhlmann et al. (2007) (Table 3) on an annealed Inconel 718.

$$\sigma_{eq} = \left[A + B(\varepsilon_p)^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_f - T_0}\right)\right] \qquad (1)$$

where A [MPa] is the yield strengh, B [MPa] is the hardening modulus, C is the strain rate sensitivity coefficient, n is the hardening coefficient, m the thermal softening coefficient, $\dot{\varepsilon}$ p [s−1] the plastic strain rate, $\dot{\varepsilon}$ 0 [s−1] the reference plastic strain rate, T_f [ºC] the melting temperature (ºC), T [ºC] the current temperature (ºC), and T_0 [ºC] is the room temperature. Finally, in order to model the important thermo-mechanical coupling existing in the cutting process, the Quinney–Taylor coefficient which indicates the fraction of plastic work converted into heat has been considered. A constant value of 0.9 has been set as it is usually considered in the machining literature (Shet et al., 2003).

The present simulation used a master slave kinematic contact method for the friction model and associated Eq. (2) for the mechanical behavior.

$$\mu_{adh} = K_1 V_{ls} + K_2 \qquad (2)$$

with V_{ls} the local sliding velocity in m/min, K_1 = −0.0042 min/m and K_2 = 0.3821. It should be emphasized that this friction model has been identified under dry conditions. By using it, authors put forward the hypothesis that the fluid may not influence the tribological behaviour of the tool–chip interface (Courbon et al., 2009).

The mechanical effect of the jet on the chip can be defined by Eq. (3).

$$v = \eta_n \sqrt{\frac{2P_n}{\rho}} \qquad (3)$$

with η_n the nozzle efficiency coefficient, P_n nozzle overpressure and ρ water density. The input velocity is much smaller than the output one and can be neglected. Nozzle efficiency coefficient for averaged nozzle design is typically around 0.85 (Momber and Kovacevic, 1998).

4. RESULTS

From tests made at the machining laboratory we could validate the numerical model corresponding to the sort of turning method used in this work. The tests were done varying the point of impact of the fluid on the interface and varying the C angle, showed in Figure 1, at a few varyations on cutting speed, depth of cut and feed rate.

As showed on Fig. 4 the total machining cutting force was reduced by changing the angle of impact of the jet.

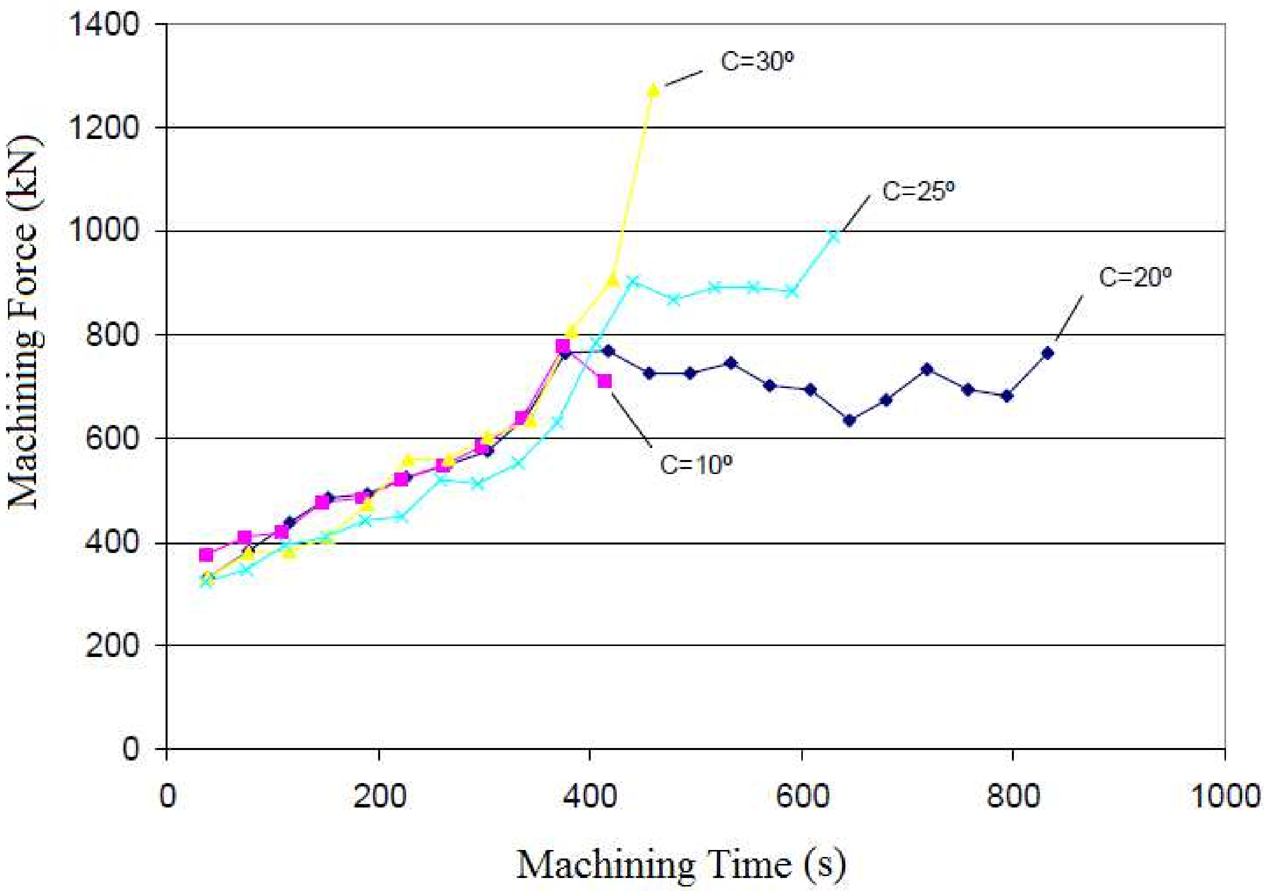

Fig. 4 – Machining Force by varying the point of impact.

Varyng the C angle on the simulation we could get the results close to the ones on our experimental work but the numerical model is still in development. As can be seen in Fig. 4, we realize that in the first four hundred seconds of process the Machining force stays equal for all the angles tested, and after that period the differences start to appear, showing that even in the numerical model (which is still in progress) the value of 20º to the angle C is the best to reduce the machining force efficiently. That fact must be associated to the fact that this angle of 20 degrees makes the hydraulic wedge formation easier and the chip break more easily.

Another parameter that showed to be important and should be validated on the current numerical model presented in this work is the point of impact of the jet. We tested the results on machining force and tool life by pointing the jet accurately at the tool tip and after that at 1 millimeter of distance from the tool tip and then 2 millimeters. The result was that the jet applied at 1 mm of distance from the tool tip provides a better protective layer in the tool surface reducing the friction between the chip and the tool, and that provides lower machining forces, increasing the tool life.

At the start of this work we attempted to use the commercial code ANSYS/Explicit on Workbench(v15.0) but it showed way too difficult to program when we tried to indroduce the fluid jet as loads applied orthogonaly to the chip surface and then we found difficulty on programming the Jonhson-Cook equation. So the solution was change to a new and more appropriated commercial code called DEFORM 3D v. 5.0.3.61.23 (Service Pack 3) that contains many equations, like the Jonhson Cook, and resources for machining simulations. The simulation is still in process.

5. CONCLUSION

Following the numerical model described above we should be able to verify that varying the point of impact of the fluid and the angle of the jet, the tool life can be improved. Results on our experimental work will be used to validate our Finite Elements simulation where we expect to see decrease on the cutting forces and chip helix diameter.

We still need to do more experimental tests and their respective Finite Elements simulations with more accurate point of impact of the jet, different pressures of jet and different materials to improve and expand the validity of that reduction in the machining force and in the increase of the tool life reached on our experimental tests.

The simulation must be able to show if the distance of 1 millimeter from the tool tip is accurately the best to form the protective layer because on the experimental work it is almost impossible to get a 0.1 mm of precision for example, due to the dispersion of the jet.

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