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Microstructural changes induced by ultrashort pulsed lasers in microdrilling of fuel nozzles

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Abstract

Microholes for gasoline direct injection (GDI) nozzles were obtained in martensitic stainless steel AISI 440C with conventional micro-EDM and two laser based processes: water-jet guided µs-laser and fs-laser. Since the analyzed drilling methods heavily differ for their thermal input on materials, the three processes were compared from the perspective of the microstructural changes induced in the bulk material after drilling. Moreover, the sharpness of the edges was taken into account as distinctive feature for a comparison among the three processes, being the spray atomization maximized by a cavitation process inside the microhole.
A tailored procedure was optimised to prepare the samples for Scanning Electron Microscopy (SEM) and metallographic analyses. The cross sections of micro-EDM drilled samples revealed the presence of a recast (white) layer of 1-2 µm in thickness even using the lowest spark energy in the tested range. Samples drilled by water-jet guided µs-laser are affected by the same phenomenon, with an even more pronounced effect. Moreover, they showed the extrusion of the melt material along the hole axis under the action of the water-jet conveying the beam. The extremely fast cooling of this layer also makes the machined surfaces prone to cracking. Conversely, metallographic analysis of cross sections of ultrashort pulsed laser drilled samples, showed no modification of the base metal microstructure in the sub-surface regions, thus testifying that the fs-pulsed laser drilling was an almost pure ablation process and not affected by a remarkable liquid phase as for the other two thermal processes. Periodicity and dimensions of laser induced periodic surface structures (LIPSS) generated by ultrashort pulsed laser were characterized by means of Scanning Electron Microscopy. SEM analysis of the microhole edges revealed burrs for the water-jet guided µs-laser while radii of 3-4 µm for micro-EDM and less than 1µm for fs-lasers were measured.

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1. Introduction

At present, Micro-Electrical Discharge Machining (µ-EDM) is well established in the field of drilling of nozzles for diesel and Gasoline Direct Injection (GDI) systems. The ability to produce micro-holes (µ-holes) with high aspect ratio (thickness/hole diameter) of about 5 is a distinguishing advantage of the µ-EDM process. Anyhow this consolidated process is recently facing new challenges [1] which mainly concern the flexibility in changing the hole geometry and the decrease in process time. Another relevant issue in the production of deep µ-holes in the possibility to work with higher efficiency and quality in dry environment thus avoiding pollutants dispersed in the de-ionized water of µ-EDM drilled machines.

Attempts have been made by several research groups and companies to use short pulsed laser drilling (with pulse duration of micro or nanosecond) instead of µ-EDM. However, the hole quality is not able to fulfill the requirements of the industrial standards as laser drilling with short pulses typically produces larger recast and Heat Affected Zones (HAZ) [2]. As a consequence of the remarkable amount of melt involved in the process, the quality and reproducibility of the holes is rather low.

Two laser based techniques alternatives to µ-EDM have recently successfully used for micro-drilling of spray hole [3, 4]. The first one uses a thin water jet to

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convey a low-power laser beam, sufficient to vaporize metals, and to mitigate the thermal effect of µs laser pulses. This water jet guided laser also known as Laser Micro-Jet (LMJ) is now used in a variety of applications like wafer dicing, solar cells, integrated circuits and stencils. More recently, it has been optimized for high precision machining for automotive industry applications, like for drilling fuel injection nozzle and as a result, very competitive speeds and qualities were achieved [5]. The concept is to focus a laser beam into a nozzle while passing through a pressurized water chamber and a details of the principle is described in [3]. The low pressure water jet guides the laser beam by means of total internal reflection at the water/air interface in a manner similar to conventional glass fibers. As the water jet acts as a fluid optical waveguide, only the laser is used for the material vaporization.

The second drilling alternative is a pure laser ablation by means of ultrashort (sub-ps) laser pulses combined with a precise scanning head. For pulses in the order of hundreds of fs the pulse duration is much shorter than the time required for electrons to relax and transfer energy to the lattice. Electrons are excited instantly and in about 1 ps they transfer energy to the positive ions [6]. If the energy is high enough, which is common for ultra-short pulses, the ions get energy to break the lattice bonding, as for a shock pressure wave. Direct solid vapor transition occurs because of insufficient time to transfer energy to the neighboring lattice ions. Heat conduction is thus negligible and HAZ is minimal. Consequently ultrashort laser pulses allow less thermal damage and a nearly melt free ablation, if it is worked close to or under the ablation threshold [7]. According to authors recent experience, ultrashort pulsed laser drilling has demonstrated to be an alternative technique enabling to work in dry environment with lower process time with an even higher flexibility in changing the hole design [4].

1.1 Research objectives

Improving the efficiency of fuel spray atomization is compulsory to meet the strict requirements of the upcoming EU6 limits [8]. This is because a properly atomized fuel spray allows for a more efficient combustion process avoiding wet parts in the engine and a consequent formation of residual particles.

Injection through the spray hole is a complex process which involves the break-up of the fuel jet at the nozzle entrance and a consequent atomization into fine droplets by cavitation phenomena. Atomization of the fuel spray and jet breaking strongly depend on the dynamics of the fluid occurring inside the hole, which is in turn affected by the hole geometry (size, taper angle, radius of curvature at the hole edges) as well as by microscopic details of the hole inner surface. For instance, the morphology of the inner surface of the spray hole influences the interaction of the fuel with the surface, while the sharpness of the edge corner in fuel entry side influences the spray atomization process. Moreover, the eventual formation of recast layers on the inner surface of the hole is extremely critical since it can be detached from the HAZ by the high stresses induced with the cavitation phenomena or simply by erosion of the fuel. This varies the µ-hole and affects the nozzle spray capabilities and the stoichiometry of the combustion. Main focus of the present work is then to characterize spray-holes on AISI 440C GDI nozzles produced with three different technologies µ-EDM (as production process standard reference), LMJ and fs-laser drilling from the perspective of the following parameters:

- morphology of the inner surface;
- presence and extension of recast layers;
- presence and extension of heat affected zones;
- edge sharpness of the drilled hole in fuel entry side.

2. Experimental details

2.1. Material

Martensitic AISI 440C stainless steel is selected to produce GDI nozzles because it combines good resistance to corrosion and wear.

2.2. Drilling techniques

Experiments are carried out on real injector components in order to assess the feasibility of the proposed drilling techniques in a real production environment.

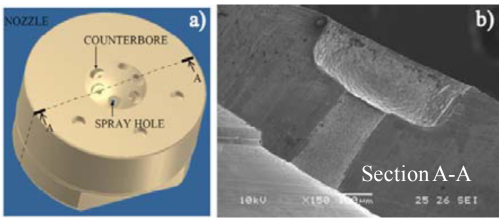

Fig.1: (a) 3D view of a GDI nozzle: spray hole are drilled concentrically with the counterbores, (b) Cylindrical hole geometry achieved at the end of the drilling process.

Concerning the drilling process adopted in the present research for the drilling of cylindrical spray holes with a diameter of 180 µm starting from the flat surface of counterbores previously micromilled as shown in Fig.1 (a) and (b), machining conditions can be summarized as follows.

1. The EDM process is obtained by a Sarix generator SX-200 (SARIX SA, Switzerland) with a total drilling time of 18 s and 10 s for energy levels of 3.25 µJ and 15 µJ with process parameters reported in Table 1. The electrode rotates at 800 rpm while penetrating in the

workpiece. The details of the μ-EDM drilling can be found in [9].

Table 1. Process parameters adopted in μ-EDM drilling process.

Dielectric	De-ionized water
Electrode material	Tungsten Carbide
Electrode diameter [μm]	80
Electrode rot. speed [RPM]	800
Pulse energy [μJ]	3.25, 15
Voltage [V]	100, 150
Peak current [A]	3, 7
Pulse on duration [ns]	60, 100
Frequency [kHz]	150
Polarity	Negative electrode

2. Posalux HP1 laser drilling machine is employed for drilling fuel injector nozzles by LMJ technology. The process time is 4 s. The details of the machine and the working principle of LMJ are provided in [3]. The drilling strategy adopted in case of LMJ makes use of a pilot through hole of about 25 μm which is progressively enlarged by moving the LMJ along a spiral trajectory up to the imposed nominal diameter of the hole. The experimental conditions for LMJ adopted in this work are shown in table 2.

Table 2. Experimental conditions for Laser Micro-Jet (LMJ)

Laser	
Laser type	Industrial Nd:YAG, classical resonator
Transverse mode	Multimode
Polarization	Random
Wavelength [nm]	1064
Average power [W]	18
Peak power [W_{peak}]	450
Pumping source	Diode Pumped
PRF (pulse repetition frequency) [Hz]	2000
Pulse duration range [μs]	20
Pulse energy [mJ]	9
Fluence [J/cm^2]	2866
Specific power [MW/cm^2]	5.7
Process water and gas	
Process water	Demineralized water
Conductivity [μS/cm]	< 0.5
Water nozzle diameter [μm]	20
Water pressure [MPa]	50
Jet tangential speed [mm/s]]	1.3
Cycle time [s]	4
Process gas	Helium (97.5% purity), Filtered air

3. Pure laser drilling is performed with a Raydiance (US) Starfemto R-100 femtosecond fibre laser (details in table 3) which conveys a 3.8 mm unfocused beam in an ARGES (Ge) scanning head (5 axes controlled galvanometer). The scanning head enables to set position, focusing and inclination of the beam giving it a precessional movement around the hole axis. A λ/4 wave plate is used to have circular polarization. A through hole of 50 μm diameter is firstly performed and then enlarged with refining parameters up to the nominal diameter. Pressurized helium (0.7 MPa) is used as processing gas. The cycle time is 2.5 s.

Table 3. Process parameters adopted for the laser micro-drilling process.

Wavelength [nm]	1552
Pulse duration [fs]	800
Spot diameter [μm]	20
Pulse energy [μJ]	50
Pulse frequency [kHz]	100
Tangential speed [mm/s]	75

2.3. Sample preparation

For metallographic analysis, the drilled samples were cross sectioned by a precision saw along a surface parallel to the hole axis and passing through the diameter of the hole. All the preparations step were performed manually like- fine grinding up to a section very close to final observation, the mounting in a hard resin, polishing and final etching of the component with Adler reagent to highlight the microstructure in the area close to the hole surface. For microscopic analysis of the inner hole wall morphologies, the samples were prepared by cutting, grinding it up to the intersection of the hole. For Scanning Electron Microscopy (SEM) observation of inner hole surfaces, the samples were cleaned by ultrasonic cleaning in a water solution containing citric acid.

3. Results and discussion

3. 1 Surface appearance

Samples were cross sectioned longitudinally to open the hole surface to SEM analyses. Fig.2-4 shows the appearance of the inner surfaces of the holes drilled using the abovementioned techniques. μ-EDM drilled holes are characterized by the presence of craters created during the discharge process. The dimension of craters is strictly related to the used energy, as visible in Fig.2.

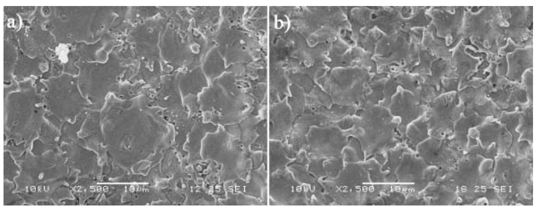

Fig.2: SEM micrographs showing the dimensions of crater in the surface of μ-EDM drilled holes. a) Pulse energy of 15 μJ; b) Pulse energy of 3.25 μJ.

The average diameter is about 5-7 μm and 15-20 μm for pulse energies of 3.25 μJ and 15 μJ, respectively. In addition to craters, some re-deposited particles ejected during the discharge process can be found on the hole surfaces of μ-EDM drilled samples.

The inner surface of LMJ drilled holes shows the presence of a marked longitudinal pattern. This is due by the extrusion of the melt material along the hole axis under the action of the water-jet conveying the beam. Micrograph in Fig.3a shows the superposition of different grooves created by superimposed μs pulses, characterized by pronounced crests. Some microcracks were found, presumably as a consequence of the fast cooling process of the melt layer in contact with the water jet, see Fig.3b. As seen for μ-EDM samples, also LMJ ones showed the presence of spatters of molten material in the hole surface, ejected by the combined action of laser melting and water jet action. In case of LMJ, spatters are higher in number with respect to μ-EDM with the presence of both spherical and elongated particles, as visible in Fig.3b.

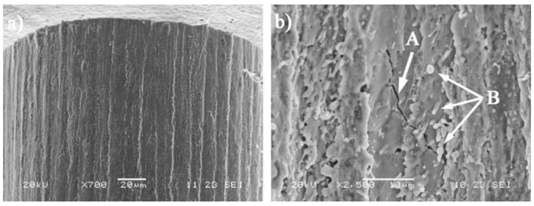

Fig.3: SEM micrographs showing the surface morphology of holes drilled by LMJ. a) general appearance, b) presence of small cracks. Arrow A indicates the crack, arrows B indicate spatters.

Finally, Fig.4 shows the typical appearance of fs-laser drilled holes. It is well known that ultrashort pulsed lasers generate periodic patterns on the irradiated surfaces often referred to as Laser-Induced Periodic Surface Structure (LIPSS) [10], showed in Fig.4 at different magnifications. The complex morphology of LIPSS shares many similarities with other self-organized patterns originating from instabilities, such as aeolian sand dunes or ripples produced by ion-beam sputtering.

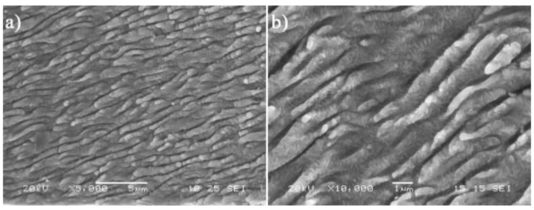

Fig.4: SEM micrographs showing the surface morphology of holes drilled by fs-laser. a) and b) refer to different magnifications. The axis of drilled sample is close to the vertical direction.

The mechanism of ripples formation is still under discussion: the excitation and subsequent ablation by ultra-short laser pulses induce a state of extreme non-equilibrium of the surface [11]. The instability relaxes in a very short time generating the formation of self-organized and quasi-regular surface structures under the driving action of the absorbed electromagnetic field. The morphology of these structures varies with the material properties, the energy density used and the optical setup (polarization, incidence angle, etc.). As instance, in case of linearly polarized laser beams, the orientation is found to be perpendicular to the light polarization with a periodicity often smaller than the laser wavelength [11].

SEM analysis of fs-laser drilled samples showed that typical spatial periods were about 1 μm, in good agreement with the results of the analysis of topography maps acquired by Shear Force Microscope (SHFM) [4] and the length of elongated structure is between 5 and 10 μm. Concerning the surface defects that could be generated by the drilling processes, μ-EDM and LMJ processes have in general the ability to melt and recast all the phases that could be present in the steel base microstructure (martensitic phase, carbide particles, inclusions). On the other hand fs-laser drilling is a non-thermal process that induces ablation of the drilled material. Discontinuities in the chemical composition (such as matrix-inclusion interfaces), showing different ablation energy thresholds can induce discontinuities in the removal process. This in turn, may result in defects. The major highlighted defects were (i) small cracks or matrix/inclusion interface separation, or, (ii) in case of small inclusions in proximity of the surface, their detachment associated to the formation of a "pit".

Fig.5 shows two examples of the highlighted defects. EDS microanalysis performed by SEM gave evidence of Aluminium, Calcium and Silicon oxides inclusions (see Fig.5b), typically coming from steelmaking processes.

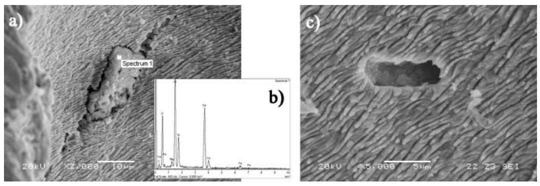

Fig.5: SEM micrograph showing the presence of defects in fs-laser drilled hole surface. a) large inclusion particle emerging in the inner wall surface, b) EDS spectrum acquired from the inclusion in a); c) "pit" .

3.2 Recast layer and heat affected zones

Adler etchant allowed to reveal the microstructure of AISI 440C in the polished and etched cross section of the analysed samples and to highlight the presence of recast layers and heat affected zones. As visible in the optical micrographs (see Fig.6) the base microstructure of AISI 440C is composed by a martensitic matrix with dispersed chromium carbide precipitates with different dimensions. Optical micrographs of μ-EDM and fs-laser drilled samples do not show any visible microstructural alteration in regions close to the hole surface, thus if a recast layer is present its thickness is limited to very few microns. On the other hand LMJ is able to induce a marked effect on base material. A surface layer presenting a heavy modification in the microstructures, increases its thickness passing from about 1 μm in the laser entry side up to about 15 μm in the exit one. This layer is composed by two different parts: a recast layer (A), that appears white in Fig.6, and a heat affected zone (B) brown, the latter being much thinner than the former (in the laser exit side about 3-4 μm against 10-15 μm, respectively).

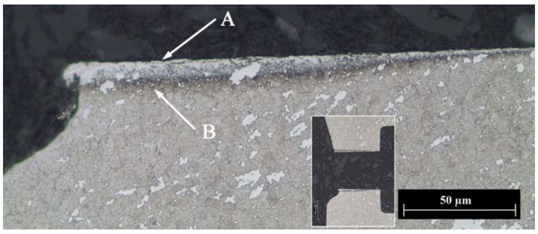

Fig.6: Optical micrograph showing the steel microstructure in a region close to the hole surface of a sample of LMJ drilled hole.

Moreover, during the drilling process the water-jet is able to push the melted layer produced by the thermal input of laser beam along the just created hole surfaces and finally the grooves protrude out from the hole, as shown in Fig.7. The presence of this "crown" in the laser exit side of the hole governs the edge geometry of the fuel entry side, greatly affecting its reproducibility and the possibility of a robust hole-edge control. Furthermore, protruded grooves could be presumably prone to rupture under the high pressure fuel action, because of both their brittleness (due to their structure made of recast material) and their thickness of only few microns.

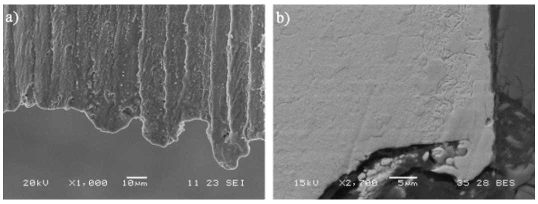

Fig.7: a) SEM micrograph of the hole surface in the laser exit side of a LMJ drilled hole where the protruded material is apparent. b) SEM micrograph showing the cross section of a protruded groove.

High magnification SEM micrographs of the polished and etched sections of tested samples are shown in Fig.8-10 A recast layer of about 1-2 μm in thickness is clearly visible in μ-EDM samples (see Fig.8) having a microstructure different from the base metal. The rapid solidification of the steel layer melted during the EDM process induces a more uniform microstructure, where the morphology of the martensite microstructural features is no longer visible. Moreover, in the edge zone of the cross section of μ-EDM samples it is easy to recognize the shape of craters and their overlapping.

Concerning LMJ samples, SEM analysis confirms the optical microscope observations, i.e. the presence of a recast layer whose thickness increases from the laser entry side to the exit one, see Fig.9. The higher magnification of SEM microscope with respect to the optical one allows for the identification of some cracks in the interface between the base metal and the recast layer, as visible in Fig.9b.

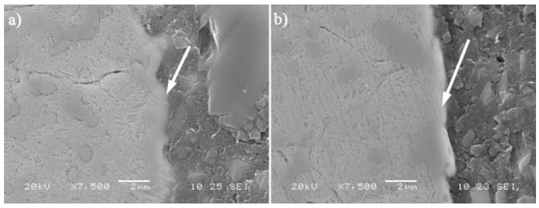

Fig.8: SEM micrograph of section of the μ-EDM drilled hole samples where a recast layer of about 1÷2 μm is clearly visible (see arrows).

Microcracks are not present in all the analysed samples, and their occurrence seem not to be correlated to the recast thickness neither to the microstructural features of the base metal.

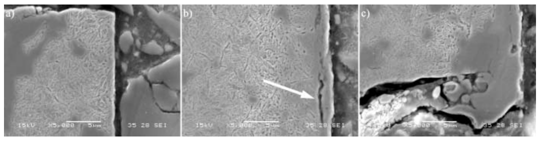

Fig.9: SEM micrograph of a section of the LMJ drilled hole sample. a) laser entry side, b) central region, c) laser exit side.

The sample preparation procedure used in the present work has proven to be able to highlight the fine LIPSS structures also in the cross section of fs-laser drilled samples. In the region close to the hole surfaces their typical periodic structures are clearly visible, see Fig.10. Their height is between 0.2 and 1 μm, and the spatial period ranges between 0.5 and 1 μm. The main finding is that no alteration of the base metal microstructure can be recorded. Martensitic microstructures and Chromium carbide particles are visible up to the hole surface, also in the LIPSS crests, thus testifying that the fs-laser drilling is an almost pure ablation process and it is not affected by a the formation of a liquid phase as for the other two investigated thermal processes.

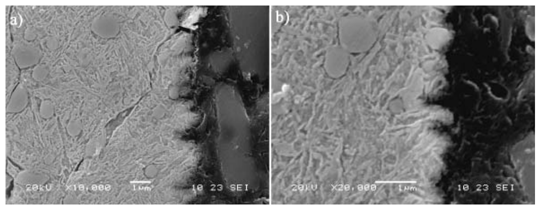

Fig.10: Examples of SEM micrograph of sections of the fs-laser drilled hole samples.

3.3 Edge sharpness

According to fluidynamics simulations, one of the most important parameters driving the performances of fuel injectors is the edge radius of the spray-hole. In fact the fuel atomization increases for sharper edges at the fuel entry side of spray-holes. Thus, a rough assessment of the atomization ability of the tested drilled methods was carried out by measuring the edge radius of drilled spray-holes by means of a image analyser software (Image J). Fig.11 shows SEM micrographs of cross sections of drilled holes where the edge radius measurement procedure was used.

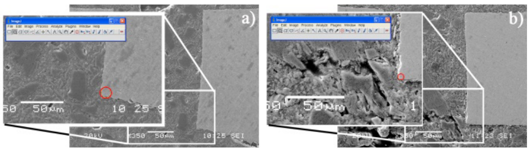

Fig.11: SEM micrographs showing the interpolating technique used to measure the edge radius. a) μ-EDM drilled sample; b) fs-laser drilled sample. Red circles represent the circles that best interpolate the edge profile.

Edge radiuses were measured interpolating the edge profiles with a circle whose radius was appropriately changed. In Fig.11 red circles are the best circles interpolating the edge profiles. The analysis was performed on μ-EDM and fs-laser samples. The presence of protruding crests in all the LMJ samples made impossible the determination of a correct edge radius. The edge radius measurement was possible thanks to the good edge retention obtained by the very careful polishing preparation procedure used. μ-EDM showed edge radius ranging from 2 to 4 μm, while fs-laser samples from 0.5 to 1 μm. The difference is roughly of the same order of magnitude of the recast layer induced by the μ-EDM technique, that represents a dimensional limit in the possible control of surface features.

4. Conclusions

Three different micro drilling techniques have been compared in respect to the superficial, geometrical and microstructural features of the produced injector spray-holes. The following conclusions could be drawn:

- holes drilled by fs-laser are characterized by the smaller dimensions of their features (LIPSS) both in height and in the spatial period. The other techniques present structures with larger dimensions (craters for μ-EDM and grooves for LMJ)
- fs-laser do not show spatters and debris in the inner surface. Conversely, both μ-EDM and LMJ present spatters being much more abundant in LMJ samples;
- Some defects associated with the presence of matrix-inclusions interfaces have been found in fs-laser samples. Also LMJ showed some very fine and small cracks in the re-solidified surface layer, while μ-EDM surface is practically cracks free.
- LMJ is the technique that induces the thicker recast and heat affected layers. Its thickness increases from the laser entry side to the exit one achieving a final thickness of about 15-20 μm. The recast layer visible in μ-EDM samples is limited to the crater thickness (1-2 μm), while fs-laser samples do not present microstructural modification in the base material up to the inner surface.
- Concerning the edge sharpness, fs-laser drilling is the best technique that produces the most controlled edge profile. Their edge radius is less than 1 μm, while that produced by μ-EDM methods ranges between 2 and 4 μm. Edge profiles of LMJ samples are affected by the presence of protrusions, making the designed geometry difficult to be controlled and reproduced.

Acknowledgements

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