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Comparative Study of Joining Processes of High Conductivity Electrolytic Tough Pitch Copper used in Automotive Industries

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ABSTRACT:

In this paper the effects of conventional Gas Tungsten Art Welding (GTAW) process with constant current and pulsed current and Friction Stir Welding (FSW) process on Electrolytic Tough Pitch (ETP) copper which is used as bus bars and rotors in automotive industries are investigated. Autogenous welding was carried out on 4mm thick 99.9% pure ETP copper using GTAW process with constant and pulsed current. Another set of plates of size 300mm×75mm×4mm were welded using FSW process. The tensile strength, micro hardness and micro structure of the joints were studied. The studies indicated that FSW joints were having better strength and hardness than GTAW joints with constant current and pulsed current due to the formation of fire equalled grains.

KEYWORDS:

Electrolytic tough pitch copper; Gas tungsten arc welding; Friction stir welding; Heat affected zone

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1. Introduction

Automotive industry is an ever green and fast growing industry. But the current problems in this industry are the fuel consumption and emission. Fossil fuel is fast depleting and also the price of the fuel remains uncertain and keeps on increasing in the long run. So electrical propulsion becomes the option at this situation. Electrical hybrid vehicles are fast up coming in the market. These vehicles use induction motors for the propulsion. Rotor and end rings are components of this induction motor. Replacing an aluminium rotor with a copper rotor will increase the advantage of induction motor. Copper rotor bars and end rings reduce electrical losses and leading to smaller and more efficient motors. Copper with high conductivity makes it highly suitable for Squirrel case (rotor bar and end rings) in induction motors. Electrolytic Touch Pitch (ETP) copper is a having this property and used for this purpose. When it comes to carrying high current necessary to power heavy equipment, rail and subway cars or reducing weight for latest aircraft or hybrid vehicles, bus bars bring unique advantage to the transportation industry.

Bus bars are made of high conductivity copper. Normally these bus bars are joined by bolting, clamping, riveting, soldering or welding. Amongst these five processes, welding has got the advantage of better strength and uniform conduction of electricity. ETP-C11000 is a 99.9% pure copper with high electrical and thermal conductivity. This copper is also superior in its ductility. ETP copper contains oxygen up to 0.04% in the form of cuprous oxide. This intentional residue reduces the adverse effect on electrical conductivity of traces of impurity metals. This is a high conductivity copper which as in the annealed condition having a minimum conductivity of 100% IACS value (International Annealed Copper standard). Apart from finding its main application in the electrical industry as bus bars, switch gears, stator terminals, conductors etc., it also finds application in architectural, automotive and mechanical industries. In the recent times due to the enormous growth of electronic industry, the use of high conductivity copper also has grown in multi-fold. This has raised the need for fabricating copper in to different shapes using metal forming, welding, cutting and machining process. When it comes to welding, copper is difficult to weld due to its high thermal conductivity and thermal expansion. Pure copper exhibit poor weldability for oxy-acetylene and GMA welding processes.

Copper exhibits good weldability for Gas Tungsten Arc Welding (GTAW) and Plasma Transferred Arc (PTA) Welding and also exhibiting good brazeability. In these conventional welding processes difficulty arises due to the high thermal conductivity, thermal expansion and melting of the metals. Defects such as porosity, hot grade hydrogen embrittlement arises due to high temperature required for melting and distortion due to high thermal expansion. The welding speed has to be maintained at a lower level due to high thermal expansion of copper which results in distortion and residual stresses. Friction Stir Welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly and versatile. As melting of metal is not taking place in FSW like in fusion welding process, most of the problems caused by melting and recasting of metal can be avoided [1]. In this process the Heat Affected Zone (HAZ) is very narrow and the joint contains no cast metal microstructure. Extensive investigations on aluminium and its alloys using FSW have been reported [2-11]. Whereas very little literature is available for other non ferrous metals and steel. In automotive industries, FSW can be used not only to join copper but also other metal alloys like aluminium alloys and magnesium alloys.

2. Experimental work

The purchased 4mm thick rolled copper plate was made sure that it is 99.9% pure ETP copper by obtaining its chemical composition by spectro-analysis. The results of the composition are given in Table 1. Having ensured that it is the right material, the plate is cut into the required dimension of (300×150mm) by band saw cutting machine. The plates were finished to its final dimension using a milling machine. Autogenous welding (without filler rod) was performed on the copper plates using GTAW process with constant current (CCGTAW) and pulsed current mode (PCGTAW). Initially trials were performed to find the optimized parameters which produce defect free welds. Once these parameters were arrived welding was performed on the plates which were machined to the specified dimensions using CCGTAW and PCGTAW. Similarly trial welds are performed on the FSW process to find optimized welding speed, tool rotation speed and axial force. Initially defects such as tunnels, cracks and holes were observed. After many trials, parameters which produced defect free weld were arrived. The optimized parameters were - axial load: 5 kN, tool rotational speed: 1050 rpm and transverse speed: 15 mm/min. Plates with final dimension of 300×150×4 mm were friction stir welded using the optimized parameters. The welding conditions and optimized process parameters presented in Tables 2 and 3 were used to fabricate the joints for further investigations.

Table 1: Chemical composition (mass%) of base metal

Elements	%	Elements	%	Elements	%
Cu	99.9	Zn	0.0061	Mn	0.01
		Fe	0.0067	P	0.04
		Al	0.072	Be	0.001

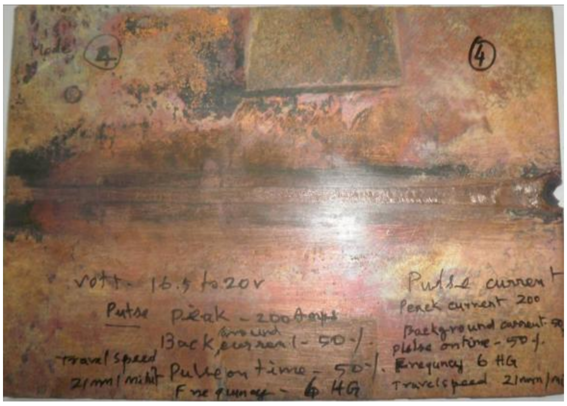
Table 2: Welding conditions and process parameters for GTAW

Parameter	CCGTAW	PCGTAW
Tungsten electrode dia.	2.4mm	2.4mm
Current	200 A	200 A
Voltage	19.5 V	16.5 V – 20 V
Welding speed	21 mm/min	21 mm/min
Shielding gas	99.9% Ar	99.9% Ar
Gas flow rate	14 lit/min	14 lit/min

Table 3: Welding conditions and process parameters for FSW

Parameter	Value
Tool rotational speed	1050 rpm
Axial force	4 kN
FSW tool material	Super HSS
Shoulder dia.	13.5mm
Pin dia. & length	4.4 mm & 3.5 mm

The GTMA joints were fabricated using Lincoln welding machine (USA) with a capacity of 400A. FSW joints were fabricated using an indigenously developed RV Machine Tools FSW machine. The fabricated joints are shown in Fig. 1. The welded joints were sliced using power hacksaw machine and machined to the final dimensions using a milling machine. Smooth un-notched and notched specimens were prepared as per the ASTM E8M -04 specifications. The tensile tests were conducted using an electro-mechanically controlled universal testing machine having a capacity of 100 kN (FIE India, UNITECH 94001). The dimensions of the notched and un-notched specimens were shown in the Fig. 2. The yield strength, ultimate tensile strength and fracture strength were recorded directly from the machine. Notched specimens were prepared to evaluate the notch tensile strength and notch strength ratio of the joints.



a) CCGTAW

b) PCGTAW

c) FSW

Fig. 1: Fabricated welded joints

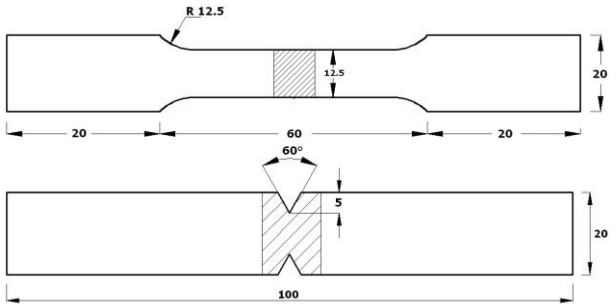


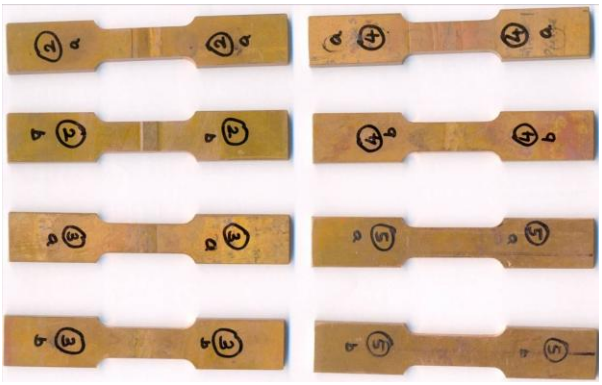
Fig. 2: Dimensions (mm) of un-notched(top) and notched(bottom) tensile test specimens

3. Results and discussion

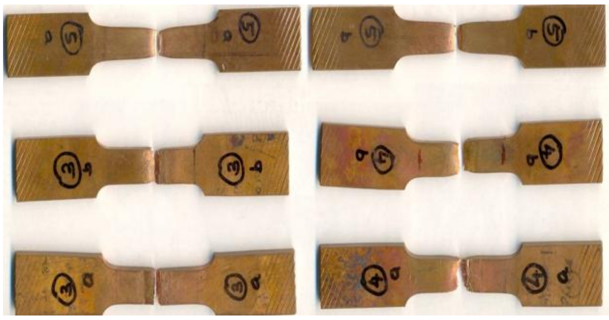
3.1. Tensile properties

Two specimens were prepared and tested for each welding method. The photographs of the specimens before and after the tests are shown in Figs. 3 and 4. The average of the experimentally evaluated values is presented in Table 4. The base metal recorded a yield and tensile strength of 186 MPa and 233 MPa respectively. There is a considerable increase in the tensile strength even after the base metal starts yielding. There is 25% increase in tensile strength of the base metal. This indicates pure copper is a ductile material. Of the three welded joints CCGTAW joints show the lowest yield and tensile strength of 143 MPa and 188 MPa respectively. This indicates there a reduction of 24% in the strength values due to CCGTAW process. FSW joints produced the highest yield strength and tensile strength of 174 MPa and 210 MPa among the three welding process. Though these values are 90% of the strength of base metal, it is 11% and 22% higher than the yield and tensile strength of the CCGTMA process. PCGTAW welded joints have shown moderate yield and tensile value of 147 MPa and 191 MPa which are higher than CCGTAW process and lower than FSW process.

The base metal has shown an elongation and reduction in cross sectional area (RCSA) of 49% and 68% respectively. These high values indicate that the base metal ETP copper is a very good ductile material. CCGTAW joints show the lowest elongation and reduction in cross sectional area of 24% and 31% respectively. This indicates that there is a 51% reduction in ductility due to CCGTAW process. FSW joints show the highest elongation and reduction in cross sectional area of 42% and 63% respectively. Though these values are lower than those of the base metal, the ductility values are 75% higher than CCGTAW joints. This indicates FSW process retains the ductility property of the base metal than CCGTAW and PCGTAW. Notch strength ratio (NSR) is the ratio between tensile strength of notched specimen and that of un-notched specimen. The NSR value of the base metal is greater than 1. This suggests that ETP copper is not sensitive to notches and it falls into the notch ductile material category. Among the three welded joints, FSW joints have shown the highest NSR value of 1.1 other than the base metal. This suggest that FSW welded joints are less sensitive to notches than the CCGTAW and PCGTAW welded joints which have shown NSR values of 1 and 1.08 respectively. In summary, the traverse tensile strength of ETP copper is reduced by welding processes. Among the three welded joints, FSW joint show superior tensile properties compared with CCGTAW and PCGTAW joints. Almost all the tensile specimens fail in the weld region and it suggests that weld region is the weakest region compared to the other regions.



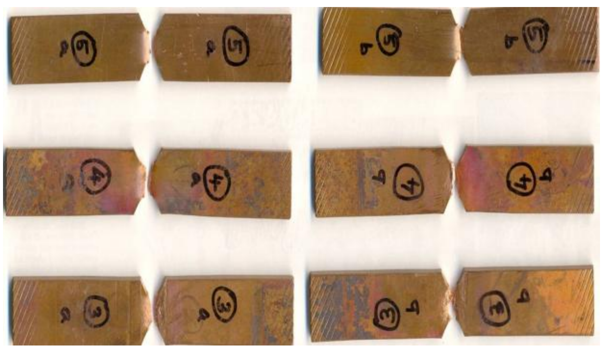
a) Before testing



b) After testing

Fig. 3: Un-notched tensile specimens

a) Before testing



b) After testing

Fig. 4: Notched tensile specimens

Table 4: Traverse tensile properties of welded joints

Property	BM	CCGTAW	PCGTAW	FSW
Yield strength MPa	186	143	147	174
Ultimate tensile str. MPa	233	188	191	210
Elongation %	49	24	30	42
Reduction in cross section area %	68	31	61	63
Fracture strength	65	44	39	75
Notch tensile str. MPa	232	188	191	231
Notch strength ratio	1.14	1	1.08	1.1
Joint efficiency %	---	81	82	90

3.2. Hardness

Vickers micro harness testing machine (Shimadzu) HMV-2T with magnification 400X was employed. Micro hardness was measured at different zones namely weld zone, TMAZ, HAZ and the base metal at a gap of 1mm with an applied load of 50 gms for a time period of 15sec and are reported in Table 5. The hardness of the base metal (rolled and annealed) is 118 Hv. The average of hardness values at different points in the weld zone of CCGTAW, PCGTAW and FSW are 75 Hv, 70 Hv and 113 Hv respectively. It is evident that the weld regions show lower hardness than other regions. FSW shows the highest hardness value in the weld which is 96% of the base metal. The hardness value in the TMAZ of FSW is 92 HV. The average of the hardness values of HAZ of CCGTAW, PCGTAW and FSW are 78, 81 and 96 respectively. The hardness value in different zone of PCGTAW is slightly higher than CCGTAW. Whereas the hardness values in different zones of FSW are higher than the other two welding process.

Table 5: Hardness survey across the weld

Joint type	Location			
	Weld metal	HAZ	TMAZ	BM
CCGTAW	75	78	---	118
PCGTAW	70	81	---	118
FSW	113	96	92	118

3.3. Microstructure

The specimens for microscopic examination were cut to the size which comprises the weld metal, HAZ, thermo mechanically affected zone (TMAZ, only in the case of FSW) and the base metal (BM) regions. Then the specimens were polished using different grades of emery sheets till a mirror finish is obtained in a Bainpol- FT disc polishing machine. Initial polishing was done on Bainline Belt Linising Machine to ensure the flatness of the specimens. Final polishing was carried out on a velvet cloth disc using alumina powder mixed with water as the medium. Having made sure enough polishing is done from the glassy appearance of the specimen, they are etched using a solution consisting of 50ml water, picric acid 2 gms and Hcl 5ml. The etchant was applied using cotton swab and some time (5 minutes) is allowed for etching to take place. For macroscopic examination Macroscope–Z equipment fitted with Samsung SDC - 313B camera was used. Fig. 5 presents the macrographs of welded joints. When the macrographs of CCGTAW and PCGTAW welds are observed, it is clearly visible that the grains have grown many times in the weld zone and in the HAZ. When the macrograph of FSW is observed, the ‘U’ shaped stir zone or nugget zone is clearly visible. This zone only gets stirred up during the FSW process and results in very small fine equi-axed grains.

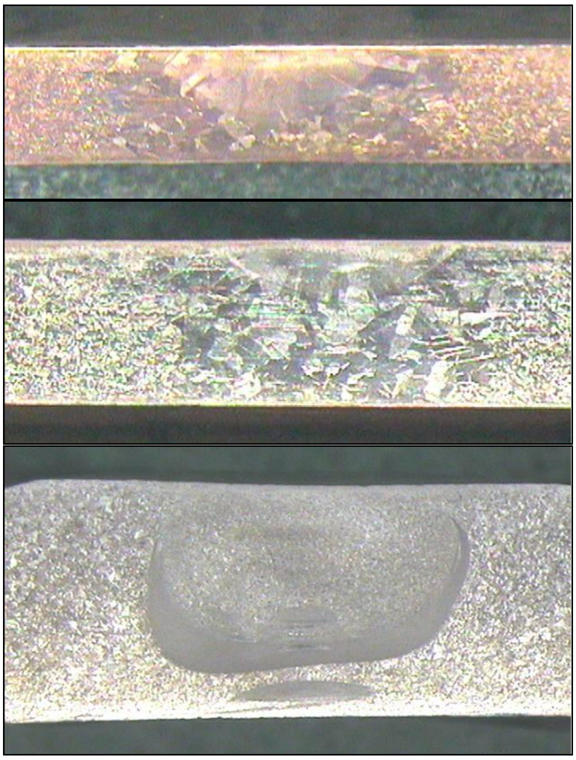


Fig. 5: Optical macrographs of CCGTAW (top), PCGTAW (middle) and FSW (bottom) joints

Metallographic examinations were carried out using equipment supplied by Media Image Technologies consisting of Meiji –Japan/MIL 7100 microscope and metal vision MVLX1.0 software to analyze the structure. Optical micrographs of the joints in the weld metal are shown in Figs. 6 and 7. When the base metal ETP copper is hot rolled from its cast form, the eutectic structure is completely destroyed. The microstructure of the hot rolled copper contains many small grains. Parallel straight lines extending across many of the grains are called annealing twins. They appear after metal has been mechanically worked at a high temperature called annealing. The interdendritic network of cuprous oxide particles was destroyed by hot rolling. The grains of the base metal are smaller in size and measures are average size of 20μm.

There exists a clear boundary between the weld zone and the HAZ. The grains in the weld zone are bigger in size compared to the size of the grain in the HAZ. The average grain size in weld zone is 115μm and the average grain size in the HAZ is 90μm. This is evident when the micrographs of the different zones are examined. In the case of PCGTAW, the grains in the HAZ are bigger that the HAZ of CCGTAW. But the grain size in weld zone and HAZ are slightly smaller than that of CCGTAW. The optical micrograph shows that the grain size is maximum in the weld region of the CCGTAW. So the CCGTAW tensile specimens failed in the weld region exhibiting minimum tensile strength. The grains in the weld zone of the PCGTAW also have grown enormously compared to the grain size of the base metal. But the grain size in the weld zone of PCGTAW is slightly bigger than that of the CCGTAW. This is the reason for the slightly higher tensile strength of PCGTAW joints. The grain growth in the weld zone and HAZ is due to the heat input. Higher the heat input, higher will be the grain size and correspondingly lesser will be the strength.

Fig 5: Optical micrographs of base metal (top) and different zones of CCGTAW (middle) and PCGTAW (bottom) joints

On the other hand, FSW process is a solid state process in which there is no melting of metal and the possibility of grain growth is prevented. In FSW, the frictional heat is generated between the tool shoulder and the base metal causes the material beneath the base the rotating tool to attain plastic state. The axial force applied through the rotating tool causes the plasticized metal to extrude around the tool pin in the vertical direction to get consolidated in the back side when the tool moves forward. Both the stirring and extrusion causes the elongated grains to fragment into smaller grains and this replaces the original base metal grains structure into a very fine equi-axed grain structure in the stir zone. The FSW process produced finer grains in the weld region compared to CCGTAW and PCGTAW. The grains are uniformly distributed throughout the matrix. The grain size of the HAZ almost matches with the grain size of the base metal and the grain size in the stir zone is very much smaller than the base metal. When the micrograph is observed, the interface between stir zone and TMAZ is clearly visible. This TMAZ is possible only in FSW. The grain size in the TMAZ is slightly bigger than nugget zone and smaller than the HAZ. These three different zone of FSW exhibit different micro hardness levels due to their different grain sizes.

FSW gives rise to a large plastic flow in the stir zone, which causes the introduction of many dislocations and grain subdivision by the dislocation boundaries to evolve fine grained microstructure. The dislocations and fine grains contribute to the strengthening of the stir zone. The decrease in grain size increases the strength with significant reduction in ductility. On the other hand heat generation by plastic deformation provides the driving force for recovery, the annihilation of the dislocation and sub grain growth, resulting in marginal reduction in hardness compared to the base metal. However, the formation of fine, equi-axed grains and relatively higher hardness and ductility are the reasons for superior tensile strength of FSW joints compared to GTAW constant current and GTAW pulsed current welded joints.

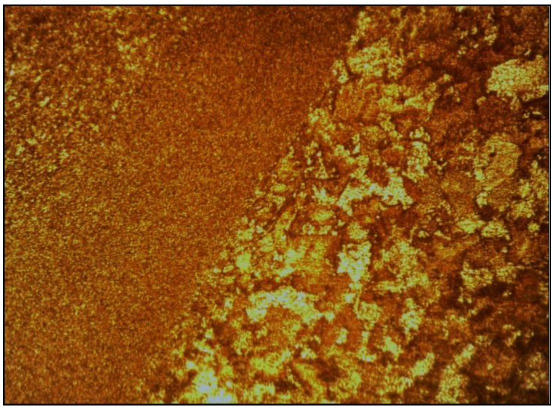


Fig. 6(a): Optical micrograph of different zones of FSW joint

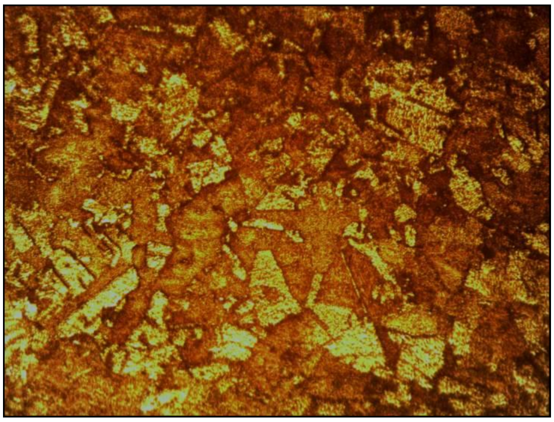


Fig. 6(b): Optical micrograph of FSW Joint - HAZ

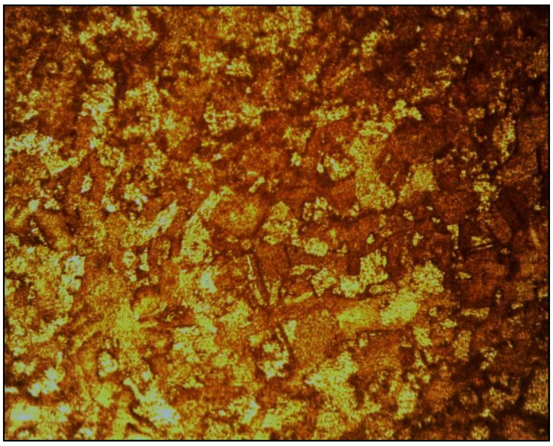


Fig. 6(c): Optical micrograph of FSW Joint - TMAZ

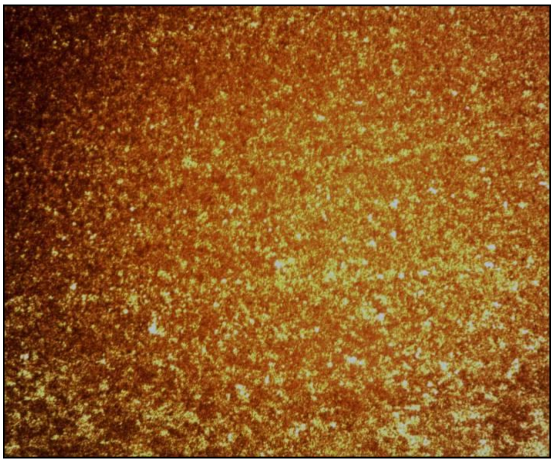


Fig. 6(d): Optical micrograph of FSW Joint - Stir zone

4. Conclusion

In this investigation, the tensile and hardness properties were evaluated and the following are concluded:

- GTAW welded joints have resulted in abnormal grain growth due to the heat input in turn lost its tensile strength and hardness.
- All the three welded joints are not sensitive to notches and the ETP copper material fall in the category of notch ductile material.
- Of the three welded joints, the FSW joints exhibited higher strength values.

The formation of fine equi-axed grains and relatively higher hardness of weld region and HAZ are the reasons for superior tensile properties of FSW joints compared to CCGTAW and PCGTAW joints.

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