The Graping Phenomenon: Improving Pb-Free Solder Coalescence Through Process and Material Optimization

Authored by: Tim Jensen

Abstract

As small surface-mount components such as 0201 and 01005 packages have entered volume assembly, manufacturers are observing increased instances of poor solder coalescence during reflow. The root cause is the change in oxidation behavior at very low volumes of deposited paste. A solution is required, both to restore a high-quality appearance to solder joints and to maintain customer confidence. Comprehensive analysis of factors, including material selection, print process settings, reflow profile, and factory-floor practices, highlight a number of measures that engineers may apply to solve this issue cost-effectively without impairing satisfactory reflow of other components on the board.

Introduction

Flux performance is a critical factor determining the quality of solder joints produced during an SMT reflow process. In addition to the flux chemistry, other factors influence fluxing performance, including solder particle size, deposit volume, and reflow profile. If a given set of conditions conspires to reduce the effectiveness of fluxing, the result is seen in terms of increased soldering defects such as poor wetting, solder balling, voiding, and incomplete solder coalescence.

Among these, incomplete coalescence is observed in an increasing proportion of assemblies, particularly with increasing adoption of ultra-small component packages such as the 0201 and 01005 outlines. This defect is commonly referred to as "graping." Solder spheres near the outside of the joint do not fully coalesce into the main bulk of the solder during reflow, producing an irregular surface finish similar to a cluster of grapes. It is possible that graping may also affect solder joints of chip scale packages (CSPs), but the problem is difficult to identify in these cases.

Cross-sectional analysis suggests that solder joints, where graping is evident, for the most part display normal electrical and mechanical integrity. However, assemblers should take steps to prevent graping for at least two reasons: firstly, customers tend to assume that abnormal appearance indicates a defective joint and will view graping as a sign of poor quality. Secondly, and of equal importance to assemblers, AOI equipment cannot be educated to ignore such characteristics in solder joints and will therefore report

TIM JENSEN

Tim Jensen, Product Manager, PCB Assembly Materials, Indium Corp., has spent over a decade troubleshooting and optimizing SMT process lines. He works closely with Indium's Technical Service, Research & Development, and Sales Teams to ensure that Indium continues to offer cutting edge products to meet unique challenges in the electronics assembly industry. Tim is an SMTA-Certified SMT Process Engineer.

email: tjensen@indium.com

Full biography: indium.com/corporate/bio/tim_jensen.php

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these joints as being defective. This will lead to a high rate of stoppages, failures, and demands for rework, with a noticeable effect on productivity. The higher the graping count per board, the greater the reduction in productivity.

In addition, some instances of poor coalescence have been recorded in the main bulk of the solder joint. Identifying a solution to graping is expected to eliminate this type of defect also.

To reduce or eliminate graping, it is first necessary to acquire a full understanding of its causes. Table 1 shows the various mechanisms known to affect the frequency of graping.

Reflow	Printing	Materials	Processes
Ramp rate Soak time Peak Temperature Air Flow in Reflow Oven	Stencil Thickness Aperture Size Transfer Efficiency	Solder Paste Oxidation Resistance Powder Size PCB Surface Finish and Solderability Component Finish and Solderability	Contaminated Incoming Air Time Between Print and Reflow Aperture Clogging Paste Time on Stencil Poor Paste Handling or Storage

Table 1 – Causes of graping.

In addition to laboratory work, experimentation has also been carried out at various production sites, and has shown that graping can be provoked or eliminated by fairly straightforward process adjustments.

It is also worth noting at this point that solutions to graping have been relatively slow to emerge, partly because the effect can be difficult to record and quantify using existing instruments such as microscopes or cameras. Moreover, there are currently no moves to establish an industry-wide consensus or standards describing acceptable levels of graping or rates of occurrence in volume production.

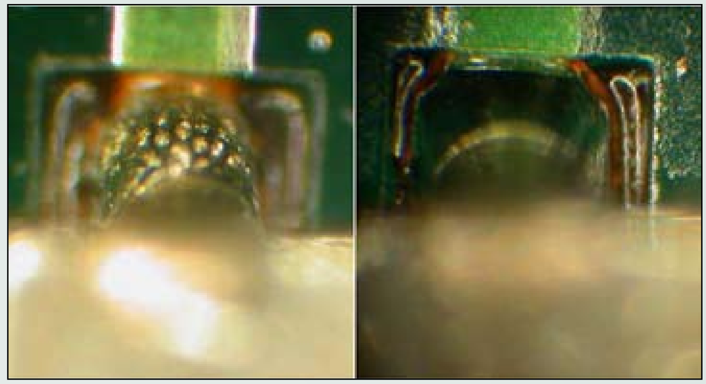

Figure 1 – The solder joint on the left exhibits graping while the one on the right has no graping.

Observations 1: Exterior appearance of graped joints

Figure 1 compares reflowed solder deposits displaying graping, next to those where graping has not occurred. The photographs clearly show the effect on the outer surface of the solder deposit, producing an appearance similar to a cluster of grapes. This effect has been observed on a variety of component types, but is more severe with smaller components.

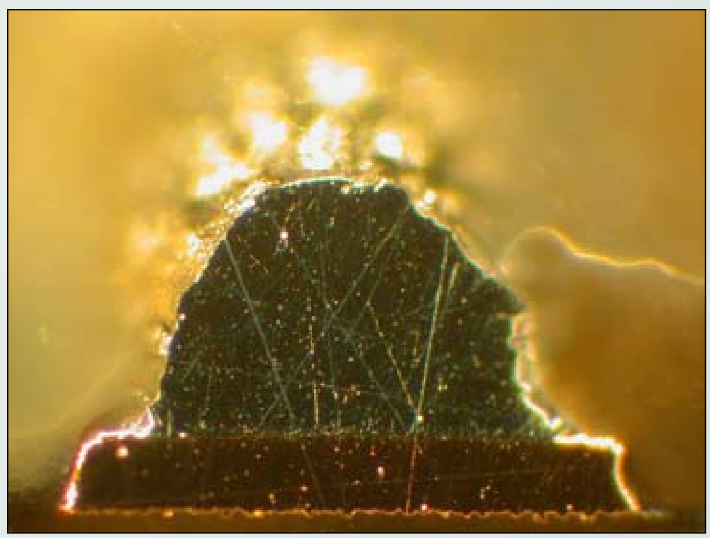

Figure 2 – Cross section of joint with graping.

Observations 2: Structural integrity of graped joints

Figure 2 shows cross-sectional views of joints where graping has been observed. While the small number of non-coalesced particles can be identified around the outside of the joint, the main bulk of the joint and the inter-metallic areas display close to ideal characteristics, demonstrating that graping does not necessarily indicate poor electrical or mechanical integrity.

Causes of graping

The fundamental cause of graping is an oxidation on the surface of the printed solder paste deposit. Because of this oxidation, the outer particles do not fully coalesce when the board reflows. Since oxidation will only occur on the outer surface of the paste deposit (which is in contact with oxygen from the oven blowers), it can be easily explained why smaller deposits exhibit more graping. If we consider an example of square apertures in a 5-mil thick stencil, it is clear that as that aperture increases in width the surface area of the printed deposit will also increase. However, it is essential to also consider that flux volume is 50% of the total solder paste volume. In Figure 3, you can see that as the square aperture width increases, the flux volume increases at a greater rate than the surface area. The result is that larger solder paste deposits have a greater overall fluxing capacity to overcome the surface oxidation.

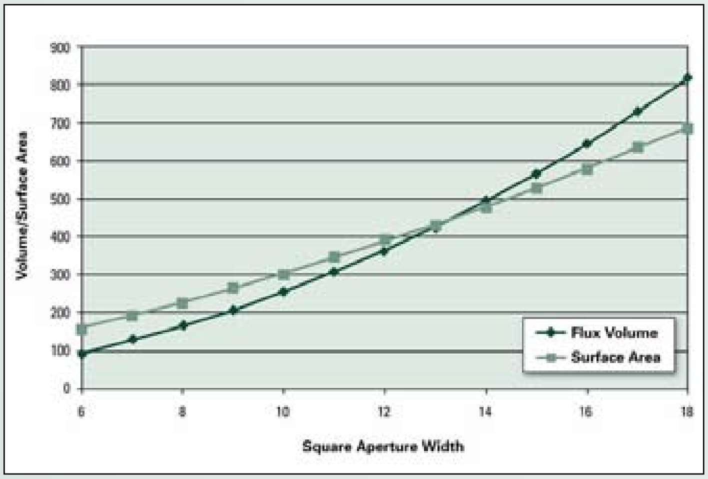

Figure 3 – Flux volume relative to surface area.

It is also essential to note that the flux within the solder paste also must remove the oxidation from the component terminations and pad surface. Therefore, the more heavily oxidized those are, the less flux remains available to remove the surface oxide on the solder powder.

By experimenting with various reflow profiles, with particular reference to the duration of certain regions of the profile, we have found that a faster ramp from ambient to peak reduces rates of occurrence of graping. This can be demonstrated with no change in peak temperature.

Hence, reducing the time to liquidus in the reflow profile and maximizing solder paste transfer efficiency appears to provide an effective response to the graping phenomenon. From these observations we understand the following series of mechanisms to be the underlying causes of graping:

- When a large deposit of solder is present, the flux can withstand a long profile because the ratio of surface area to overall flux volume is small.
- When no component is present – even when the deposited solder volume is small - the flux remains intimate with the solder and promotes adequate reflow.
- When a component is present, the flux within the solder paste must remove the oxides from the lead or termination. There is also a tendency for flux to wick up the component. The consequence is that there is less total fluxing available to protect and remove oxides from the powder surface.

The fact that graping reduces if the profile is shortened supports these suggestions, in addition to the observation that smaller components requiring smaller paste deposits suffer from higher instances of graping. On the other hand, reducing the profile length may increase voiding. [1]

Further observations are that BGA devices and large capacitors experience less graping, and that no graping is experienced when no component is present - even when the deposit volume is equivalent to that for an 0201 passive device. It is also worth noting that graped joints have shown slightly more mini-voids than joints without graping. The mini voids may be attributed to trace instances of incomplete coalescence throughout the solder joint.

Recommendations to Eliminate Graping

Stencil Printing

An investigation of solder paste printed with different aperture sizes shows that the larger paste deposit exhibits less graping. In this study, a 5-mil laser cut stencil was used to print solder paste onto a test board with various pad and aperture sizes using two different solder pastes. Figure 4 shows that as the pads increased in size, the occurrence of graping decreased. The apertures for this study were 1:1 with the pads.

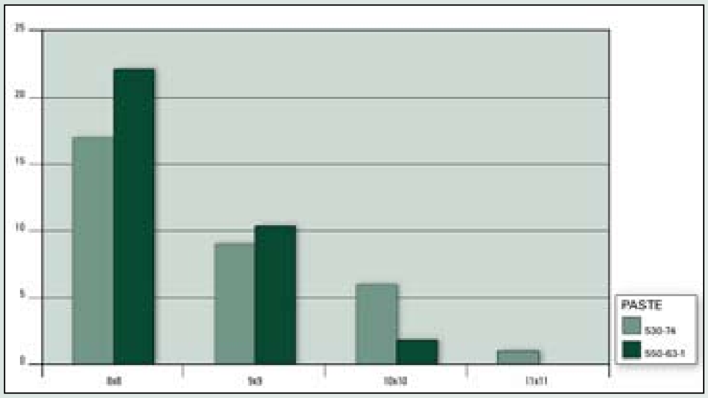

Figure 4 – Graping relative to aperture size.

The data shows the number of incidences of graping out of 24 opportunities per board when reflowed on a more challenging slow ramp profile (0.6°C/sec). This data helps to validate the theory linking graping to the ratio of surface area to flux volume.

In addition to larger apertures, additional testing suggests that the transfer efficiency of the solder paste also can play a key role. If we test using a 10x10-mil aperture in two stencils of 5-mil and 4-mil thickness, the printed deposit from the 5-mil stencil should have an overall better coalescence capacity (flux volume/deposit surface area). This is evident in Figure 5, in which the flux volume/surface area for a 4-mil stencil is always lower than that of a 5-mil stencil. Based on that information, one would surmise that using a 5-mil stencil should always give a lower incidence of graping. However, experimental data suggests that this is not true.

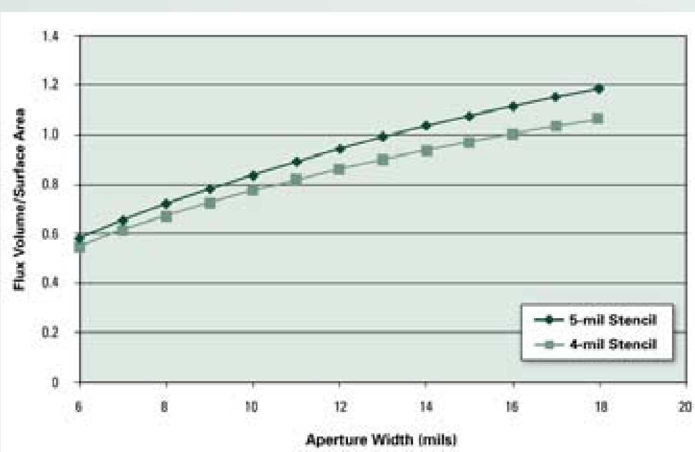

Figure 5 – Graping potential vs. aperture width.

Figure 6 shows that when 2 different solder pastes were tested for graping, the 4-mil stencil consistently exhibited a reduced occurrence of graping as compared to the 5-mil stencil. The reason for this is believed to be related to transfer efficiency. It is likely that even though the 5-mil stencil has a greater theoretical volume, the actual volume printed is probably less due to more clogging in the aperture. The partial aperture clogging also results in an irregular shaped deposit. This irregular shape also means a greater surface area than a brick shaped deposit.

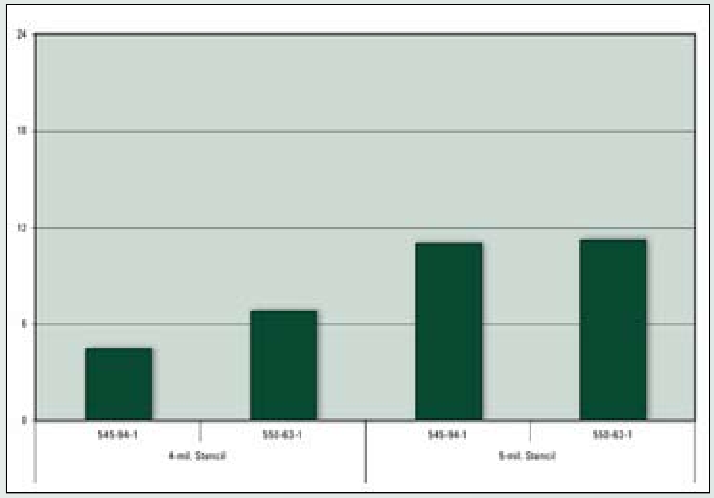

Figure 6 – Graping relative to stencil thickness.

The optimum aperture dimensions for 0201 and 01005 components are, obviously, smaller than for larger components and pads for IC packages including QFPs and BGAs, even for fine-pitch packages. Hence, these apertures display the lowest area ratio and therefore the lowest paste transfer efficiency. Possible responses may be to establish the largest practical aperture size for 0201 and 01005 termination pads, without inducing bridging defects. Alternatively the stencil thickness may be reduced, to bring the area ratio back within the IPC recommended limit of 0.66. There are, however, some natural limits on the reduction that may be applied. The thinner stencil may compromise the design of apertures for larger components, where a comparatively high volume of solder is required to withstand the higher mechanical stresses resulting from the increased bulk of the device.

Stepped stencils may provide an effective solution for assemblies requiring extremely large deposits for components such as connectors or large electrolytic capacitors, as well as ultra-small deposits for 0201 or 01005 passives. However, these will not always be a practical option. For example, in very small assemblies, such as cell phone handsets, close component spacing precludes the use of a stepped stencil technology.

Reflow profile optimization

Surface oxidation and fluxing capacity are the two primary factors affecting the occurrence of graping. Optimization of the reflow profile can affect both. Oxidation occurs at a greater rate at elevated temperatures. Therefore, the longer time that the PCB is in the oven prior to reflow, the more the component terminations, pads, and solder particles will oxidize. This imposes extra demands on the flux in the solder paste as it has to clean off that oxide.

Results from customer production sites show that graping can be reduced or eliminated by adjusting the reflow profile: in particular, by ramping directly to peak temperature instead of implementing a long pre-soak. At one customer site, setting an ambient-to-peak time of five minutes produced graping, while reducing this period to 3.5 minutes nearly eliminated it. This was validated through experimentation which is shown in Figure 7. The figure shows that for every solder paste tested, a faster ramp rate reduced the occurrence of graping on small pads.

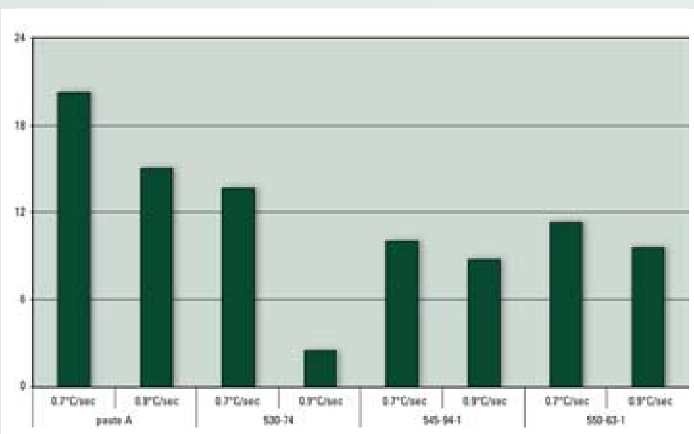

Figure 7: Graping relative to ramp rate in oven.

However, there are a number of reasons why process engineers have tended to extend soak times when working with lead-free materials. The primary reason is that a longer soak time eliminates a higher proportion of volatiles prior to solder going liquidus. Flux constituents volatilizing above the melting point of the solder can create conditions for large voids to form within the resultant solder joint. In practice, many engineers use the longest possible soak time to attempt to reduce voiding to the lowest levels they can.

Since assemblies with 0201 and 01005 components (which are more prone to graping) typically also have via-in-pad CSPs, reflowing these correctly may challenge optimization of the profile with respect to voiding and graping.

It is also likely that air flow rates within the oven could affect the occurrence of graping. High air flow rates are often used as this gives good thermal transfer and minimizes any temperature gradient across the board. However, high air flow rates would also increase oxidation of pads, terminations, and powder. While this statement is fundamentally sound, experimentation would be necessary to validate the significance of air flow rates on graping. The primary question to answer would be: Could air flow rates be changed enough to have a positive impact on graping while still providing sufficient convection to minimize thermal gradients?

Reflowing in nitrogen may reduce the potential for graping through the reduced oxidation that occurs during the preheat and soak portion of the profile. There are cost implications to this approach as well as an increase in tombstoning of passive components. [2]

Another aspect to consider is that process engineers will appreciate the maximum freedom when optimizing the reflow profile. This may be necessary for a number of reasons, including the need to reflow other, much larger components, to improve yield when working with a multi-layer board of high thermal capacity, or to reflow assemblies that may already have a heat sink attached. Hence, process engineers need more than one technique as effective armament to deal with graping.

Engineers need more wide-ranging solutions at their disposal, to be able to optimize printing and reflow processes not only to minimize graping but also to guard against the gamut of potential assembly defects ranging from soldering flaws to burning of components and other damage due to excessive temperatures. This can include boiling of electrolyte in capacitors, leading to increased ESR and shorter operational lifetime, or distortion of plastic-bodied components such as connectors.

Process Optimization

Utilizing best practices for handling and use of PCBs and components minimizes the potential for other factors to influence graping. Since oxidation of parts and boards could influence graping, their storage conditions and age should be examined. There have also been unsubstantiated reports of graping being influenced by the component or board supplier. While this statement would need experimentation to validate, it seems possible that the processing conditions of the components and boards could affect the solderability of the surface and therefore impact graping.

The storage and handling of the solder paste is also critical. For example, solder paste that is exposed to elevated temperatures during storage may see an increase in viscosity and loss of activity which will result in poor printing and reflow. Therefore, poor storage may increase the occurrence of graping.

As mentioned earlier, the print process is critical for minimizing graping. In addition to the factors already mentioned, DOEs should be conducted for the solder paste being used to determine the set-up which provides the most consistently high transfer efficiency. Figure 8 shows a contour plot performed on one particular solder paste comparing transfer efficiency relative to print speed and transfer efficiency. With this solder paste, it is evident that slower speeds are ideal for small area ratios which would be more prone to graping. Another printer set-up variable that is often overlooked is the separation speed at which the board drops away from the stencil following the print stroke. Very fast separation speeds may be better for small apertures, but a DOE should be conducted on the particular solder paste being used.

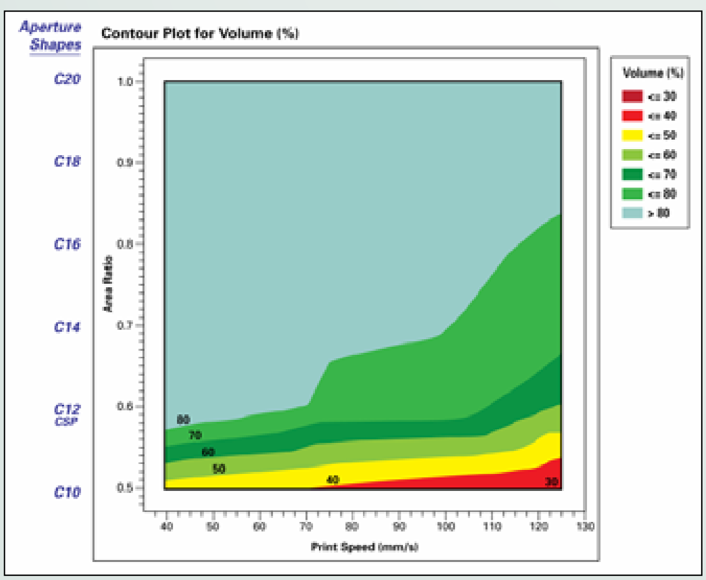

Figure 8 – Transfer efficiency relative to print speed and aperture size.

Choice of materials

Choice of materials can be shown to have an appreciable effect. Production processes have demonstrated reductions in solder joint graping by specifying a paste with enhanced oxidation characteristics. Lee suggests that when searching for the best non-graping performance combined with the highest paste-volume transfer and minimum volume variability, it must be remembered that paste properties typically impose a trade-off between anti-oxidation performance and printability.[1] Solder pastes with a higher content of rosin and other solids content are generally going to protect the powder better but limit the rheology of the material and sacrifice print consistency and response to pause printing.

General recommendations

On the basis of experimental results presented in this paper, combined with data and experience from actual customer sites where graping has been witnessed, it is possible to begin to assemble a set of tools on which process engineers can draw in order to achieve an optimal solution. Since the reflow profile must be optimized to meet a variety of requirements, engineers may not be completely at liberty to re-optimize the profile for anti-graping. In particular, eliminating a soak period may induce other defects such as voiding.

Acknowledging that engineers may come up against practical limitations on the extent to which the reflow profile can be modified, we believe that focusing on screen printing stencil design parameters and aperture characteristics, as well as process settings, is an important element of any anti-graping strategy. Optimization of these aspects must prioritize paste volume transfer efficiency, to ensure the highest volume of flux per surface area of solder particles.

A set of guidelines can be established, for engineers using pastes featuring particle size of type 4 or smaller, in order to minimize or eliminate instances of graping:

- Maximize aperture dimensions within known stencil design rules, to ensure the maximum deposited paste volume
- Optimize aperture profile to ensure maximum paste release (e.g. trapezoid aperture)
- Use electro-form or electro-polished stencils

• Set the highest possible separation speed, to maximize paste release

• Consider small changes to reflow profile: principally, use the shortest practicable soak time, without incurring voiding

Technology Developments for the Future

It is relatively simple to design a solder paste with improved oxidation resistance to help reduce the occurrence of graping. However, by improving that oxidation resistance, the trade-off is typically a decline in printability. Indium Corporation has focused on developing a solder paste technology that combines a high level of graping resistance while still maintaining exceptional printability.

It is also important to note that, as yet, a clear-cut definition of a graped joint has not been agreed upon within the industry. Before any of the applied techniques recommended can be deemed satisfactory, a consensus needs to be established and suitable definitions of a graped joint need to be ratified by respected industry bodies such as the IPC.

References:

1. Lee, Ning-Cheng, “Is it really impossible? Combining superior anti-oxidation and superior printing,” EPP Europe, December 2007, pp 20-21.
2. Schake, Jeff, “Mass Reflow Assembly of 01005 Resistor Components,” Proceedings from APEX 2007, February 2007, Los Angeles, CA.

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