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## A comparison of resistance spot weld quality assessment techniques

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### Abstract

Resistance Spot Welding (RSW) is used in many different manufacturing industries to join sheet metal components due to its quick cycle times, low cost, ease of implementation and adaptability to different joint configurations and materials. However, quality variation in spot welding can affect both the functionality and safety of products. Therefore, the quality assurance of spot welds is vital in many industries. Spot weld quality is assessed in several ways, ranging from physical weld nugget measurements, to ultrasonic inspection and mechanical strength testing.

This paper investigates four commonly used weld quality testing protocols: tensile shear, a chisel test, ultrasonic inspection and peel strength testing. We present a range of spot welding data to demonstrate the variability of the results and assess the correlation between nugget diameter (the industry standard) and the strength of the joint. This study highlights the benefits and limitations of each quality assessment technique, and limitations associated with using one metric to infer the outcome of another. Comparisons are made between the industry standard, measurement of weld nugget diameter, and each additional testing protocol. This provides insights into the validity of each test for assessing joint quality in industry.

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### 1. Introduction

Resistance Spot Welding (RSW) is commonly chosen for high volume sheet metal joining processes due to the high speed at which strong joints can be created. RSW can be used to join a number of different sheet metal materials ranging from all types of steel, to aluminium [1], and magnesium [2]. The automotive industry requires high volume sheet metal joining and quality control is paramount for customer safety. Structural components of cars are joined by

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RSW, and so the structural integrity of the vehicle is closely related to the strength of the resistance spot welds. Therefore, knowing the quality of spot welds is essential to assuring the safety of vehicles leaving the production line.

To address this, many studies in the literature have focussed on topics such as characterisation of the process [3], characterisation of the joint [4], the effects of different surface coatings [5] and alloys in high strength steels [6].

Resistance spot welds are formed at the interface between two or more pieces of sheet metal, commonly known as the faying surfaces. Copper electrodes press the sheet metal components together and a high welding current is used to fuse the metal components. The electrical resistance at the faying surface is usually the point of highest resistance and generates sufficient heat to fuse the sheets together. The progression of nugget growth in steel RSW was characterised by Dickinson et al. in which the process is split into 5 distinct stages, using the resistance measured across the workpiece during welding [7]. The stages, in order are: surface breakdown, asperity softening, temperature increase due to resistive heating, melting, complete nugget growth and mechanical collapse due to heat and clamping pressure. The nugget diameter is commonly used to quantify the quality of a spot welding process given its links to the process outlined by Dickinson et al.

Once welded, the area surrounding the joint is known as the Heat Affected Zone (HAZ). The HAZ is an annealed region around the weld and in steels is often the point of failure making it an important part of the spot weld. The characteristics of the HAZ can be significantly different depending on the material and alloy that is welded.

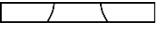
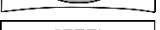
This paper draws on significant weld testing experience and data, collected from industry and in the lab to investigate button diameter as a quality metric and its relationships to other measures of quality. From these comparisons, insightful conclusions can be made about the different weld quality tests outlining which test is appropriate under different conditions.

## 2. Failure Modes and Mechanisms

Spot welds most commonly fail in one of two broad categories; interfacial failure – failure at the interface between the sheets (or faying surface), or by pull-out failure – failure where the spot weld (or part of) is removed from one of the sheets. When a spot weld fails in pull-out, the weld is pulled from one side of the sheet metal component producing what is known as a weld ‘button’, see Fracture Mode 1 below. When a spot weld fails by interfacial failure, no measurable ‘button’ is left on either sheet, see Fracture Mode 7 below. In steel RSW the weld should be stronger than the base material [8] and as such, failure through the weld is considered substandard. In the case of steel RSW, interfacial failure is often the result of an issue in the welding process that causes the weld not to form. It has been well documented that spot welds that fail in interfacial failure absorb less energy to failure than welds that fail by pull-out failure [9,10]. This is particularly important for joints that are designed to be subjected to dynamic loading.

The diameter of a spot weld, that has failed in pull-out failure is known as the ‘button diameter’, which is considered a representation of the true diameter of a weld nugget before it is destroyed [11]. This distinction between the button diameter of a destroyed joint and the nugget diameter of the welded joint is used throughout this paper. The button diameter is quick and easy to measure once a spot weld has been destroyed and is used in industry as the standard quality metric to infer the nugget diameter and subsequently its strength [11]. There are several intermediate fracture modes that have been identified between total button pull-out and total interfacial failure. Sometimes, the joint will fail initially in one region and then transfer to brittle fracture or crack propagation in the weld producing different failure mechanisms [12]. The different failure mechanisms identified in (AWS 8.9M-2012) [13] are presented below.

Spot weld failure is clearly complex given the number of possible failure mechanisms identified by the AWS. The consequences for joint strength and energy absorption of the different failure modes has not been comprehensively studied and it is therefore difficult to compare welds that fail by different mechanisms by the resultant button diameter alone. A weld that fails through complete button pull-out is likely to absorb more energy before failure and achieve a higher shear strength than welds that fail by interfacial failure. However, welds that fail by the mechanisms from 2-6 have not been well characterised. Spot welds that fail by failure modes 1, 2, 4, & 5 have buttons that can be measured and perhaps compared, however it is unlikely that the relationships to weld strength are the same for each failure mode. Welds that fail by failure modes 3, 6, 7 & 8 do not have measurable button diameters and therefore cannot be compared using this metric.

Failure Mode 1:	Button Pull – Complete Button Pull-out	
Failure Mode 2:	Partial Thickness Fracture with Button Pull – Partial Thickness Fracture with partial Button Pull-out,	
Failure Mode 3:	Partial Thickness Fracture – without Button Pull-out,	
Failure Mode 4:	Interfacial Fracture with Button Pull-out and Partial Thickness Fracture,	
Failure Mode 5:	Interfacial Fracture with Button Pull-out – No Partial Thickness Fracture,	
Failure Mode 6:	Interfacial Fracture with Partial Thickness Fracture – No Button Pull-out,	
Failure Mode 7:	Interfacial Fracture – no Partial Thickness Fracture or Button Pull-out, and,	
Failure Mode 8:	No Fusion – no spot weld has formed.	

The multitude of materials used by automotive manufacturers adds to the complexity of the challenge. In steels, the increasing use of different surface coatings and alloying elements results in different behaviour when the material is melted and quickly cooled as it is in RSW. Additionally, aluminium alloys can respond differently when subjected to the heating and cooling in spot welding and the response to heating and cooling of the material when welded can greatly affect the hardness profile across the weld. This can increase the prevalence of different failure modes in different materials [14].

### 3. Weld Quality Tests

#### 3.1. Chisel and Roller Peel Tests

The most common destructive testing techniques used in industry are the chisel test and peel test [11,15]. In a chisel test the chisel is forced between the sheets adjacent to the spot weld, providing increasing pressure to the nugget until it fails. Quantitative measures can be taken from this test including: average button diameter, sheet indentation, circularity of the spot weld, failure mode and evidence of expulsion. Often the measurements from this test are used to infer the quality of the joint and the state of the process, however this becomes challenging when welds fail by different failure modes.

Destructive peel tests are conducted by peeling one side of the sheet metal away from the other, often using a roller, which subjects the weld to a different loading condition to the chisel test. The same information can be recorded for a spot weld from peel test under a different loading condition. In a peel test, the load is heavily concentrated on one side of the spot weld and typically promotes failure in the HAZ which may make welds that would have otherwise failed in a different failure mode easier to compare. However, because this test focusses heavily on the HAZ, the peel strength of the weld is not only governed by the nugget diameter.

#### 3.2. Weld Strength Tests

Several destructive testing setups can be used to find the strength of a resistance spot weld. Most common are the tensile-shear, U-tension and peel tests [11]. These tests use a tensile testing machine to determine the strength of the joint under quasi-static loading conditions and allow for button diameter measurements to be taken after failure.

Tensile-shear tests measure the shear strength of a weld, and in the case of a steel spot weld most often produces button pull-out allowing a button diameter to be measured [10]. Measuring the tensile-shear strength of the joint allows the full range of spot weld failure mechanisms and joint quality to be compared with one metric. Additionally, the energy absorbed by the joint before failure can be compared for spot welds that fail by different failure mechanisms from this test. Unfortunately, due to the requirements on sample size and dimension, and the time taken to complete the test, tensile-shear tests are seldom used to monitor weld quality in industry. Tensile-shear testing can sometimes stretch the nugget and consequently the button that is removed from the sheet, making it difficult to compare to those from different destructive testing methods. Peel tests can also be conducted in a testing machine to measure the peel-strength using a fixture (shown in Figure 1 b) that pulls the weld around rollers of a predetermined radius until failure. Peel tests provide similar metrics to the tensile-shear test but tend to measure the peel strength of the HAZ rather than the spot weld itself. Peel tests often result in button-pull failures [16].

### 3.3. Non-Destructive Testing

Not all spot welds that leave the production line can be subjected to destructive testing. To address this, several non-destructive alternatives exist for inferring the quality of spot welds. These include ultrasound [17], infrared thermography [18] and eddy current thermography [19]. Most commonly used in industry is the ultrasound testing technique. During ultrasonic testing, an image of the nugget is generated based on the response of an array of ultrasonic transducers which measure waves that are reflected from the faying or back surface of the sheet metal [20]. The image produced can be used to measure the nugget diameter of the spot weld without destroying it. Unfortunately, due to the time taken to complete a test, ultrasound testing cannot feasibly be completed on all spot welds in industry.

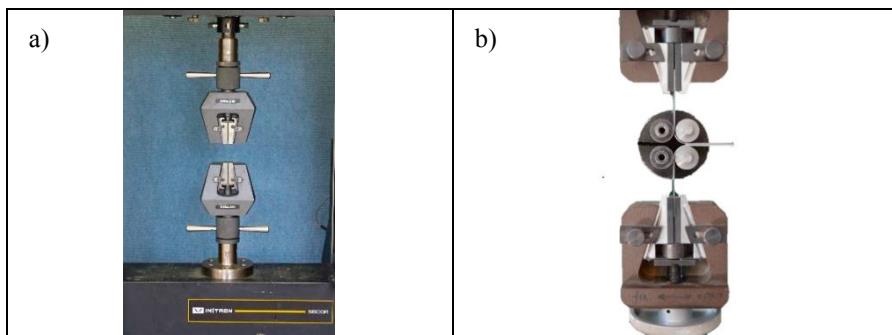


Figure 1: a) Instron 4505 universal testing machine b) Peel-testing setup for Instron 4505

## 4. Weld Quality Data

Of the techniques described above, button diameter is the most common metric in industry for assessing weld quality, measured by ultrasound or destructive testing. The measured button diameter is used to infer the joint strength and amount of energy it can absorb before failure. To critically analyse the button diameter as a quality metric, the relationship between the strength of spot welds from two different destructive tests was compared to the resultant button diameter after failure. The materials investigated were zinc-coated mild steel, a boron-steel, and a 5xxx series aluminium alloy. Resistance spot welds were subjected to tensile-shear and peel-strength tests in an Instron 4505 universal tensile testing machine (Figure 1 a). The button diameter of all welds was measured after destructive testing by measuring the maximum and minimum button diameters with Vernier Callipers ( $\pm 0.005$ ) and calculating an average [15]. The button diameter of welds that experienced interfacial failure could not be measured and are represented on all graphs as a button diameter of 0 mm. To obtain a strength value during peel testing, a roller peel testing setup was used allowing the tensile testing machine to apply a peeling load to the resistance spot weld while measuring tensile load and displacement (Figure 1 b).

Finally, a comparison of ultrasound measurements of nugget diameter to the measured button diameter after destructive testing was completed to understand the issues associated with using ultrasound to provide a measurement

of weld quality. All ultrasound measurements were taken by a trained professional in an industrial factory. Button diameters were then measured with Vernier Callipers after a chisel test for comparative purposes.

#### 4.1. Nugget Diameter as a Metric for Tensile-Shear Strength & Peel Strength

The strength of a spot weld is likely to be affected by a multitude of different properties, process parameters and testing factors including: failure mode, weld nugget size, material types (homogenous or heterogenous stacks), the severity of the HAZ, surface coatings, grain structure, porosity, the cooling rate of the joint after welding, any contaminants on the surface, loading condition, the extent of fatigue it has endured before testing, the alignment of the spot weld to the base material, and expulsion. However, not all these factors necessarily have the same effect on the button diameter as the strength of the joint. The cooling rate, severity of the HAZ, porosity, extent of previous fatigue and alignment of the spot weld are all examples of factors that may have detrimental effects on the strength of the weld but may not necessarily change the button diameter. With the number of potential confounding parameters likely to affect the strength of the joint that may not result in changes to the measured button diameter, it is increasingly difficult to rely on button diameter as the primary quality metric for resistance spot welds.

Figure 2 a) shows the correlation between tensile-shear strength and the measured button diameter of 821 zinc-anneal steel spot welds with a sheet thickness of 1.1 mm. Variation in weld quality was achieved by electrode wear and electrode-sheet misalignment. For the data collected, the button diameter measured after tensile-shear testing shows moderate correlation to tensile-shear strength, with a wide range of strength values recorded for similar button diameters. Variation in shear-strength of the welds with smaller button diameters is likely to be due to different failure mechanisms affecting the strength and resultant button diameters. Welds in this region are more likely to have failed by mechanisms 2, 4 & 5 where a button diameter is produced but is not the only failure mechanism of the joint, compared to welds that have failed by failure mechanism 1 (complete button pull-out).

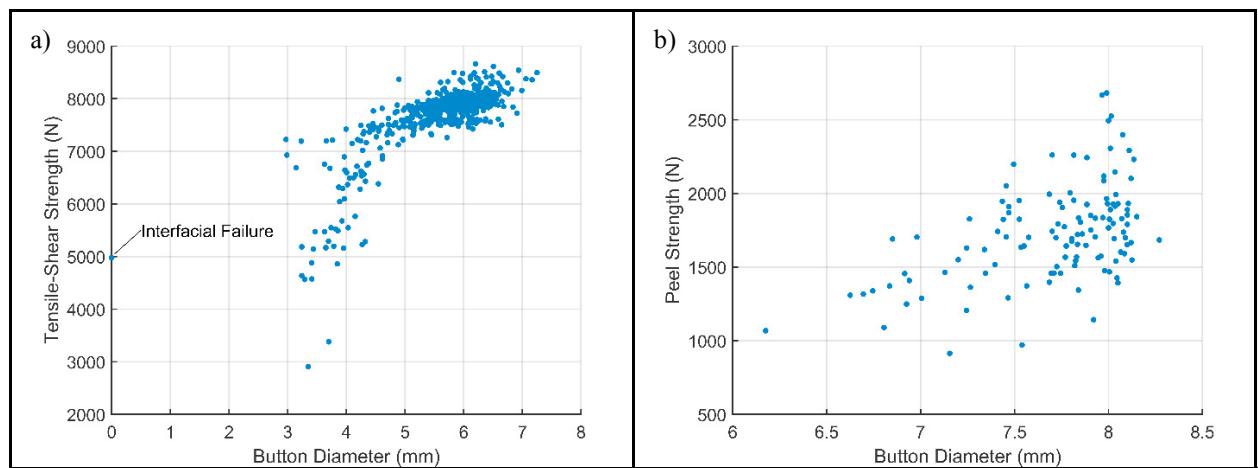


Figure 2: Zinc-anneal mild steel 1.1 mm, a) Tensile-shear strength vs. button diameter, b) Peel strength vs. button diameter

The correlation between the tensile shear strength and measured button diameter is moderate for welds above a certain button size, however once welds fall below this threshold the relationship is not as strong. The threshold is close to the empirically derived and widely accepted minimum button diameter of  $4\sqrt{t}$  (where  $t$  is the thickness of the sheet), which for this material is 4.2mm [13]. The relationship between the shear strength and nugget diameter should be clear, given a larger cross-sectional area should withstand higher shear loads, however with smaller and under-formed welds, failure modes 2-7 are more likely due to variation in button shape and size.

One spot weld failed by interfacial failure and has been represented as having no measurable button diameter (0 mm). This represents a challenge when using the button diameter to infer weld strength as the weld has no measurable button diameter but had a measurable tensile-shear strength comparable to welds with a 3-4 mm button diameter.

Although the strength is comparable to a button pull-out failure of 3-4 mm it is known that the energy absorbed before failure is likely to be significantly less than a comparable weld that failed by failure mode 1 [10].

The correlation between peel strength and button diameter shown in Figure 2 b) was not as strong for the same 1.1 mm zinc-coated mild steel. This is most likely because the peel test concentrates the load on one side of the weld at the HAZ rather than the weld itself. The results of the test are likely to be highly correlated to the strength of the HAZ which may explain the variation in peel strength that is not correlated to button diameter. Variation in weld quality for this data was achieved by electrode wear and part gap between the sheets.

#### 4.2. Non-Destructive Measurement of Nugget Diameter for Inferring Joint Quality

Ultrasound is often used to assess weld quality in industry and can be used to measure the nugget diameter of the weld without destroying it. Measurements from ultrasonic C-scans of the nugget diameter were compared to the measured button diameter from a chisel test which was conducted in a teardown lab in industry, Figure 3 a). Variation in weld quality was achieved by electrode-sheet misalignment. Several of the welds were created with electrode-sheet misalignment, a common fault in industry, which results in uneven sheet indentation. This causes problems for ultrasonic measurement of the nugget diameter and leads to inaccurate measurements of the nugget diameter [21]. However, electrode-sheet misalignment in RSW does not necessarily result in smaller nugget sizes and so the correlation to the measurements taken with ultrasound is poor. Due to the way that an ultrasonic C-scan measures the nugget diameter of a spot weld, factors that affect the failure mechanism such as weld nugget to base material alignment, minor porosity, contaminants or inclusions on the faying surface or in the nugget may not be well characterised. When a weld is destructively tested after non-destructive assessment, these factors affect the correlation between ultrasonic nugget diameter measurements and button diameter.

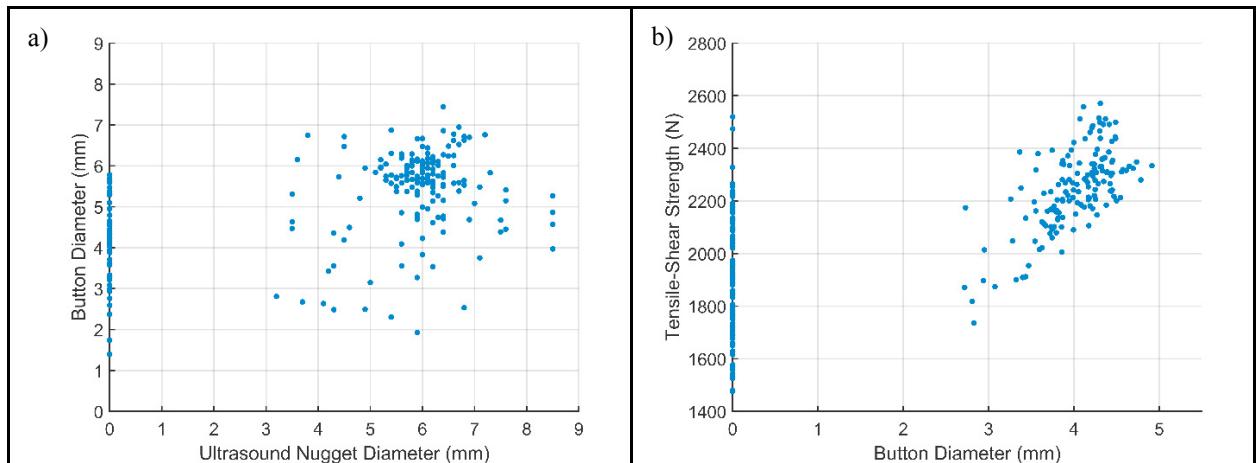


Figure 3: a) Steel ultrasound nugget diameters vs. button diameter, b) Tensile-shear strength vs. button diameter for 1 mm aluminium AA5052

#### 5. The Consequences for Aluminium Spot Weld Quality Assessment

In steel RSW comparing welds with different failure mechanisms has not been a significant challenge because welds commonly fail with button pull-out, which is demonstrated in Figure 2 a) and b). Typically, producing pull-out welds in steel is not considered challenging as the process is well understood and the occurrence of interfacial failure is usually limited to severe process faults. However, with the automotive industry's move towards aluminium passenger vehicles [22], the issue of comparing welds with different failure modes is likely to be more significant.

The high resistance oxide layer, porosity and electrode wear in aluminium RSW mean that process faults leading to interfacial failure are more common than in steel. Additionally, the behaviour of some aluminium alloys during

heating and cooling can mean that the hardness profile across a weld's cross section is much less likely to result in button pull-out failure even if the weld is of high quality [14], and so standards developed in steel RSW may no longer be applicable. Due to these reasons aluminium spot welds are much more likely to experience failure modes 2-8. This means lower dynamic strength and additional challenges when trying to compare a wide range of spot weld quality with button diameter measurements alone.

Figure 3 b) shows a comparison of the tensile-shear strength and the resultant button diameter after destructive testing of aluminium resistance spot welds with variation in weld quality attributable to electrode wear alone. The correlation between the measured button diameter and tensile-shear strength is slightly better than the correlation in steel, Figure 2 a), for welds with a measurable button diameter. However, a significantly higher proportion of the aluminium welds failed with complete interfacial failure (more than 40%), represented in the figure with a button diameter of 0 mm. A significantly higher proportion of these welds failed in a failure mode which does not produce a measurable button diameter, although many of them may have an acceptable tensile shear-strength.

## 6. Discussion

The measured button diameter showed moderate correlations to the tensile-shear strength for button diameters larger than  $4\sqrt{t}$  for steel and aluminium spot welds, while the correlation to peel strength was not as strong, most likely due to variation in the strength of the HAZ. The two testing techniques load the weld nuggets differently, affecting fracture behaviour and the button diameter measurements. These differences make it challenging to use a manual chisel or peel test to infer the tensile-shear or peel strength of a weld.

The nugget diameter measured by ultrasound showed little correlation to the measured button diameter from a chisel test for the data collected, however, the data was collected under conditions that are known to be challenging for ultrasound. Several spot welds failed ultrasound and were given no measurable nugget diameter. This issue was caused by irregular nugget shapes or misalignment of the nugget with respect to the sheet surface from which the measurement was taken. All welds that failed ultrasound failed subsequently through button pull-out when subjected to a chisel test, showing that the ultrasound measurement did not correlate strongly to button diameter under extreme circumstances. From the data presented it has been shown that the quality assessment of resistance spot welds is complex and difficult to represent with nugget or button diameter measurements alone. A summary of the conclusions that can be drawn from the data presented is shown below:

- **Tensile-Shear Strength** - Moderate correlations were found between button diameter and tensile-shear strength above  $4\sqrt{t}$  for steel and aluminium. Button pull-out was found to be common for tensile-shear tests in steel, but less common in aluminium. Using the results from a chisel test to infer the tensile-shear strength of a spot weld in steel may be ok for button diameters above  $4\sqrt{t}$ , however it is difficult to quantify the full range of quality of aluminium spot welds as many fail in pure interfacial failure, which can be a function of both gauge and alloy.
- **Peel Strength** - The correlation between button diameter and peel strength was not strong due to variation in the HAZ. Button pull-out was common in the peel test due to the loading condition. Using a chisel test to infer the peel strength of a spot weld does not consider the strength of the HAZ and may result in an unreliable measure of weld quality.
- **Ultrasound Test** - In challenging circumstances there was little correlation between the button diameter measured from a chisel test and the measurements of nugget diameter from ultrasound.

## 7. Conclusion

The quality of resistance spot welds is inherently difficult to measure and quantify. The concealed nature of the spot weld means that the weld cannot be visually inspected and so it must be destructively or non-destructively tested to determine its strength or diameter. Due to the number of different materials used, the possible failure modes and the multitude of factors that can affect joint strength, the relationship between button diameter and other measures of weld quality is not always strong. This has been shown by its limited correlation with two different strength measurements from data collected in industry and in research labs. Additionally, the most common non-destructive quality testing technique used in industry, ultrasound, was not found to be strongly correlated to button diameter under

challenging circumstances. The button diameter of a spot weld does however provide an easy and repeatable metric for monitoring the quality of a spot welding process, giving an understanding of the effects of process changes on nugget growth. Clearly, a very small spot weld will not produce a strong joint and a larger spot weld is more likely to produce a stronger joint, however, given the data presented and the factors discussed, spot weld button diameter does not necessarily characterise joint quality adequately.

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