Cliff Darrow

The Fundamentals of Gouging with Plasma

Abstract: The purpose of this document is to present the fundamental mechanics of gouging with plasma. While plasma gouging is not a new concept, little has been presented on subjects such as nomenclature, how the gouge is actually produced, and the relationships between process parameters. This paper seeks to present this information to help aid in gouging process design.

Keywords: plasma gouging, gouge, process variables of plasma gouging, mechanics of gouging

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Introduction

Welding came into its own in in the 1930s leading up to World War 2. Born out of a need to fuel the war effort, firms that supplied equipment rich in welded features needed to find more efficient ways of manufacturing. It was during this era that welding processes and welding engineering saw significant levels of evolution. As specifications drove engineers to design better products, more strength and durability in welded joints was required. By necessity, innovation in welding followed suit. By applying engineering principles and experimental techniques, technologists learned a great deal more about materials, interactions, and processes. Previously a collection of tools and techniques driven by tribal knowledge, welding evolved quickly from a trade to a science. Though much more sophisticated than earlier efforts, welding still required both preparation and repair. In order to address this process step, the need to gouge away material was identified. Early methods consisted of mechanical means of removing the material (i.e. grinding and chipping). Carbon arc gouging was then developed by Myron Stepath in the 1940s using the welder itself and a carbon electrode to melt metal. Over time this became the default method to gouge.

However, it is only in the last decade that plasma gouging has come into its own in terms of a viable solution. Even so, industry wide adoption of plasma over other technologies has not taken hold on a large scale. The reason for this can be largely attributed to a lack of understanding in both how the technology works and hence, how it can be adapted to applications based solutions. In order to help bridge this gap, this paper aims to present the following information on gouging nomenclature, mechanics of plasma gouging, and the basic relationships between performance parameters.

Nomenclature

Within this context, there are two basic uses for gouging: Weld preparation and weld repair. While there are a myriad of other applications for gouging, the focus of this paper will be on gouging as it relates to welding applications. Some basic nomenclature is defined below:

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Common terminology

- *Gouging*: The controlled removal of material from a workpiece by a thermal or mechanical process. The gouge can be any shape depending on the application, but is typically a recess in the workpiece.
- *Workpiece*: the part or welded body of parts that is being gouged.
- *Plasma Gouging*: The use of a plasma process to partially melt the workpiece and pneumatically remove the unwanted material to create a gouge.
- *Back Gouging*: The removal of a temporary root pass weld from a butt seam or joint to enable proper penetration of the final weld(s).
- *Profile Ratio*: A unitless ratio that expresses a width to depth relationship of the gouge profile shape.
- *Linear Travel Speed*: The speed at which the gouging process travels along a linear path. This parameter is commonly measured in inches per minute (IPM) or centimeters per minute (CPM).
- *Slag*: The material that has been gouged from the workpiece; first molten and then solidified.
- *Offset Torch Angle*: A secondary torch angle in the vertical plane between the torch centerline and the gouge centerline. Typically used to gain a wider gouge by introducing a vector component transverse to the gouge centerline.
- *Tangent Surface*: A flat surface created by the gouging process that is tangent to the curve at the base of the gouge profile.
- *Tangent Surface Angle*: the angle of the surface tangent to the curve at the base of the gouge profile shape as measured from the top surface of the material that is gouged.
- *Torch to Work Piece Distance*: The effective working distance as measured between the electrode tip and the work piece surface. In most shielded plasma applications, this measurement can be taken from the outside of the nozzle tip.
- *Root Curve*: The curved section of a gouge profile, occurring in the base of the gouge.
- *Positive feature*: A feature that exists in space not surrounded by other material.
- *Negative feature*: A feature that exists in space surrounded by other material.
- *Transfer Height*: Electrode tip to work piece distance during when the arc transfers from the nozzle to the work piece.
- *Arc Stretch*: The ability of the arc to extend to a pre-defined maximum amount.
- *Material Removal Rate*: The unit amount of metal removed per unit amount of time.
- *Symmetry factor*: A unitless ratio of 0 to 1 that expresses the symmetry of a gouge profile shape relative to the theoretical centerline of the gouge.
- *Profile shape*: The shape of the gouge cross section, commonly associated with weld preparation specifications (ex. "U", "V", or "J")
- *Linear surface profile*: A patterned geometric feature that runs in a linear sense along the gouge path as a result of molten metal solidification at a given frequency. These features typically resemble ribs or scales.
- *Surface roughness*: A measurement of surface texture that quantifies deviations of the real surface from its ideal form.
- *Lead-in Region*: The region of the gouge as measured from the point of arc transfer to the beginning of full profile.
- *Lead-in angle*: An angle tangent to the curve of the lead-in region.

Definition of an ideal gouge

An *ideal gouge* is relative to the application. What may be ideal for a given situation may be unsuitable for another. In general terms, the *goodness* of a gouge can be evaluated by determining if the correct amount of material has been removed in a controlled manner by the operator. Shape may or not play a vital role in the process. More specifically, the removal of the material can be characterized in two ways: *positive feature removal* or *negative feature removal*. Below are some common applications that illustrate the difference.

Typical Positive Feature Removal Applications:	Typical Negative Feature Removal Applications:
Casting sprue removal	Back gouging
Seized bolt or nut removal	Excavation of weld defect
Removal of other protruding surface feature (such as a fillet weld)	Spot weld removal

Positive feature removal is fairly straight forward. In most cases, the goodness is directly related to the highest speed at which one can remove the feature while protecting the workpiece from collateral damage. In positive feature removal, there is no requirement for a profile shape.

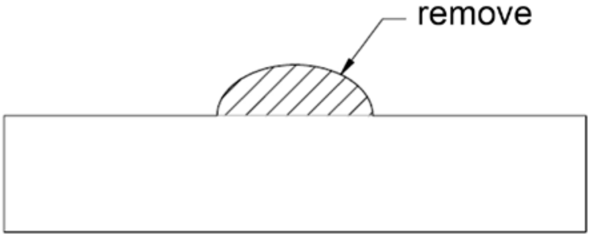

Fig. 1. Example of positive feature removal

Negative feature removal can be more complex depending on the application. In many cases, the profile of the gouge is more important than the rate at which one can remove material. The profile (cross sectional shape of the gouge) must reveal enough access for the subsequent weld. Of course, this can be highly situational depending on the orientation of the workpiece thereby making it difficult to define an ideal gouge without a context. However, a few general assumptions can be made regarding the characterization of a gouge profile:

- The width of the gouge should always be greater than the depth of the gouge.
- The profile should be as close to symmetric as possible.
- The ratio of the width to depth of the gouge can be expressed as a unitless ratio.

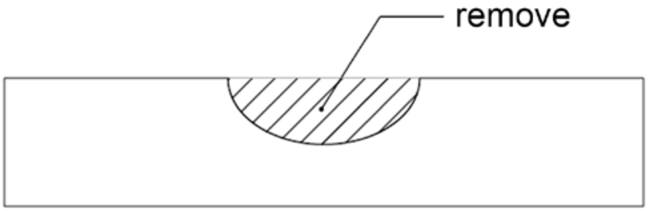

Fig. 2. Example of negative feature removal

Furthermore, there are other features of the gouging process that are of importance:

- Slag buildup should not affect the parent material and should be easily removed.
- The surface texture of the gouge should be relatively smooth such that it does not present adverse conditions to the subsequent welding process.
- If the gouging process results in hardening of the surface, then removal of the hard surface material will be required.

Additionally, it is noted that cutting tools can be used to gouge and gouging tools can be used to cut. Therefore, a distinction between a cut and a gouge can be defined as such: *A gouging process removes any amount of material from a body or bodies regardless of shape or rate such that piercing or severing of that body does not occur. Conversely, a cutting process is defined by piercing and or severing of a body or bodies.*

Lastly, figure 3 details the anatomy of a negative feature gouge. This would be a typical gouge used for weld preparation or removal. The suitability of the geometric condition of a gouge is highly situational and can vary depending on the application. Nominal dimensions and other specifications can be found in a variety of welding specifications such as those published by AWS, ASME, and ISO.

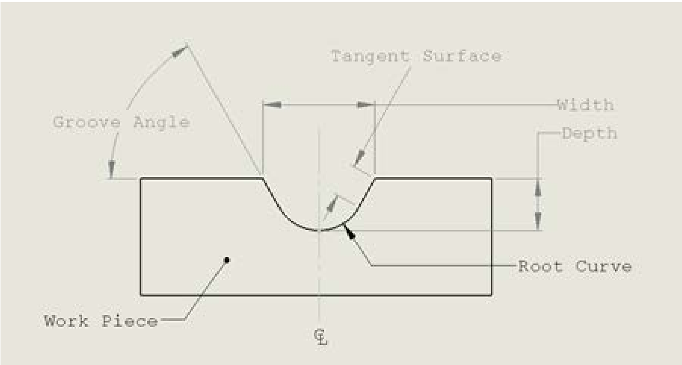

Fig. 3. Anatomy of a typical negative feature gouge

Mechanics of Plasma Gouging

Plasma is essentially a super-heated, electrically conductive, ionized gas. First developed in the late 1960's as a cutting technology, plasma has long since gained mainstream acceptance as a viable cutting alternative to oxy fuel, laser, electro-discharge machining, or waterjet. More recently, plasma gouging has begun to move to the forefront of the industrial mindset. Plasma can be used effectively for a variety of common gouging applications that have traditionally been reserved for legacy technologies such as carbon arc gouging (CAG) or mechanical grinding. At a system level, plasma shares several key features with CAG. Elements such as high current arc melting and high airflow are common between both CAG and plasma. Figure 4 presents a basic diagram of a typical high frequency start plasma system.

Unlike CAG or grinding, plasma consumables do not directly interact with the work piece. As a result, there is no contamination of the parent material by consumable material. Speeds are comparable depending on the application.

To illustrate the primary difference between cutting and gouging with plasma, the mechanics can be viewed simply. Like other fluid systems, the plasma can be constricted in its cross sectional area to increase its velocity and resultant energy density. Typical velocities in the nozzle bore reach super-sonic speeds, though this parameter can vary significantly depending on the bore design. In theory, as the plasma stream becomes more constricted and velocity increases, the higher its cutting capabilities are in terms of material thickness, speed, and kerf minimization. The inverse is true with gouging. Less constriction will result in less air velocity but a higher volumetric flow rate. This will limit the cutting action. Figures 9 and 10 illustrate a simplified cold flow CFD analysis showing the differences in the velocity profiles of

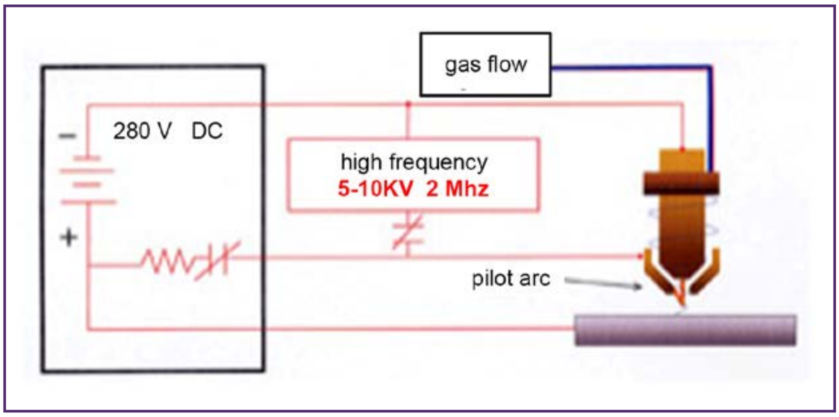

Fig. 4. Plasma gouging system diagram.

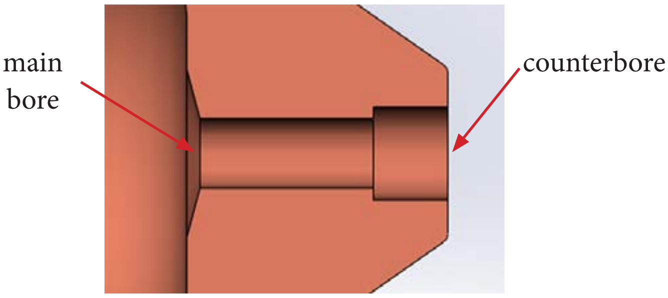

Fig. 5. Typical plasma cutting nozzle bore

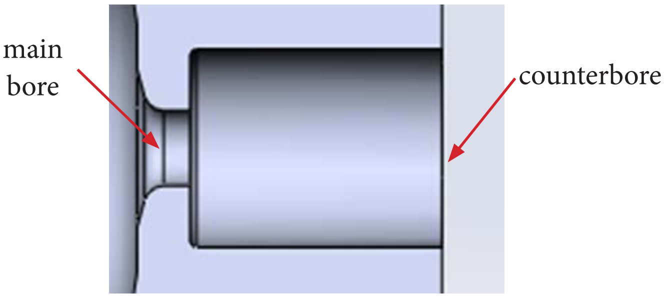

Fig. 6. Typical plasma gouging nozzle bore

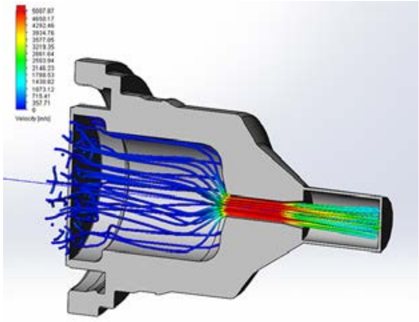

Fig. 7. Cold flow CFD analysis of a plasma cutting nozzle

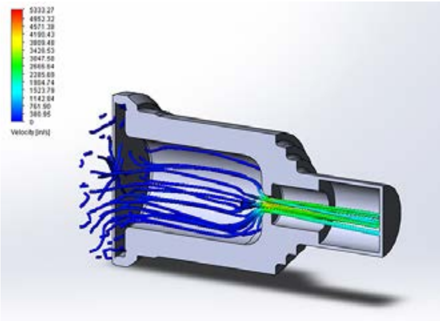

Fig. 8. Cold flow CFD analysis of a gouging nozzle bore

each respective nozzle bore. In a gouging design, a diffuse plasma stream coupled with high shield gas flow rate provides the correct combination of elements to produce partial melting and effective subsequent clearing of slag. To accomplish this, the plasma gouging nozzle bore diameter will be greater than 2 times the diameter of a cutting nozzle bore, while much shorter in length. Additionally, there will be a sizable counterbore in the nozzle to encourage relaxation of the flow. Lastly a shield gas at high flow rates is necessary to evacuate the molten material to reveal the gouge.

In figures 7 and 8, the same input and output parameters were used for each simulation (pressures, temperatures, densities). While not reflective of a true plasma stream profile (i.e. a helical vector field in the nozzle cavity), the contrast is obvious. Note that the difference of respective velocities is roughly 40%.

Process Variables of Plasma Gouging

There are many process variables that influence the features and characteristics of the gouge. Naturally, these relationships play a large role in understanding how to match plasma gouge features to applications. Note that many of these relationships are inversely proportional. Table 1 relates general input process parameters with gouge output features. A key influencing factor on the gouge shape is system amperage. As the amperage increases, so will depth of the gouge in a proportional fashion. Figure 9 shows a plot of the relationship between amperage and gouge depth between 35A and 50A. In this example, a fixed gouge width of ½” is created at a static speed while the amperage is increased by steps to influence the depth of the gouge.

Another key process parameter that influences the shape of the gouge is the angle of the torch relative to the work piece. While a primary angle

Table 1. Process input/output parameters

	OUTPUTS						
INPUTS	**width**	**depth**	**groove angle**	**tangent surface area**	**surface texture**	**transfer height**	**arc stretch**
amperage increases	*decreases*	*increases*	*increases*	*n/a*	*n/a*	*increases*	*increases*
linear travel speed increases	*n/a*	*decreases*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
TWPD increases	*increases*	*decreases*	*decreases*	*n/a*	*n/a*	*n/a*	*n/a*
primary torch ang. increases	*decreases*	*increases*	*increases*	*n/a*	*n/a*	*n/a*	*n/a*
secondary torch ang. increases	*increases*	*n/a*	*decreases*	*increases*	*n/a*	*n/a*	*n/a*
nozzle bore diameter increases	*increases*	*decreases*	*n/a*	*n/a*	*n/a*	*decreases*	*n/a*

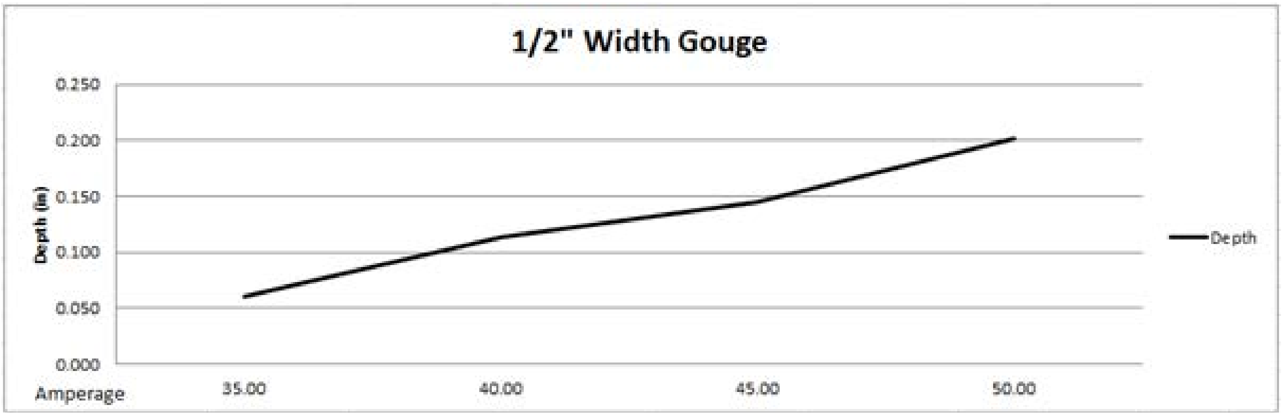

Fig. 9. Relationship of Amperage to Depth of Gouge

is used to gain a basic gouge shape, a second angle can be introduced to increase the width of the gouge. This is known as *Offset Angle Gouging*. In this case, the torch is rotated about the "*z*" axis such that it is positioned at an offset angle "α" relative to the vertical plane of the centerline of the gouge. When $\alpha=0$, this is referred to as straight-line gouging. As α increases, the gouge will widen.

However, as α approach 90°, the gouge profile will tend to an asymmetric shape. Furthermore, there will be a pronounced tangent surface feature on the near side of the gouge. This feature will exhibit a flat face as well as a groove angle relative to the top surface of the work piece and angle of the torch. Figure 10 illustrates concept of *offset angle gouging* as viewed from the top. Figures 11 and 12 detail experimental results related to gouge width and tangent surface features as a function of offset torch angle. In conclusion, a wider gouge can be accomplished by using the offset angle gouging technique. Optimum profile shapes can be gained by experimentation, the maximum allowable tangent surface being determined to suit the application.

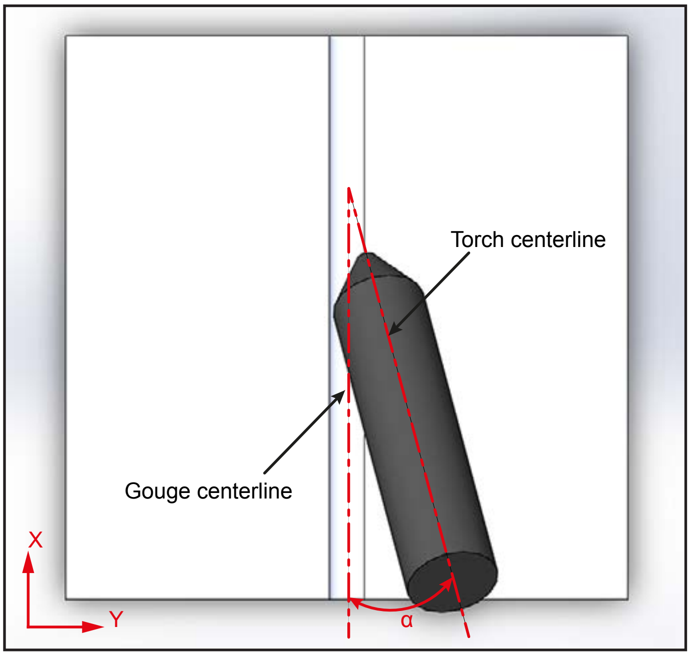

Fig. 10. Offset angle method of gouging, top view (Z direction)

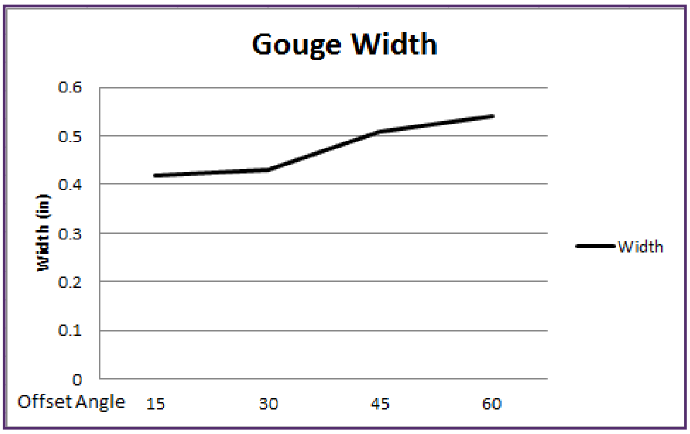

Fig. 11. Relationship of torch offset angle to gouge width

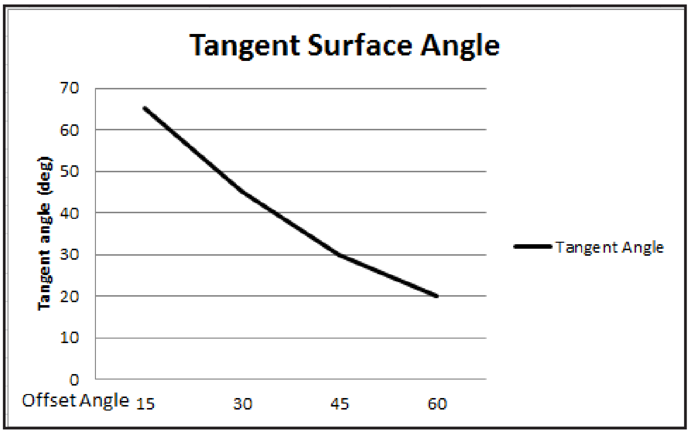

Fig. 12. Relationship of tangent surface angle to offset angle

Additionally, the effect of the torch to work piece distance (TWPD) can be cited as a key influencing factor of the shape of the gouge. In essence, the closer the torch consumables are to the workpiece the deeper and narrower the gouge will be. This is due to the fact that the energy density will be higher as it reaches the work piece with a smaller TWPD. Conversely, the further the plasma travels without the aid of an impinging device (i.e. a nozzle), the more diffuse it will become. To reiterate, the relationship of arc constriction to distance traveled to the work piece is the enabler of plasma gouging. This working distance is commonly referred to as arc stretch. Varying the arc stretch has a direct effect on the gouge profile shape and the ability to remove material.

However, all plasma systems place a limit on arc stretch as a function of arc voltage. This is mainly attributable to the duty cycle associated with the power supply and its ability to manage heat and energy loads on the system components. Therefore, when the arc reaches to its maximum, the power supply will automatically break the circuit and the arc will disconnect from the work piece. At this maximum distance, the operator should be able to achieve a theoretical maximum width gouge at minimum depth for a given amperage and primary torch angle. Figure 13 shows how the torch to workpiece distance "x" can be measured.

Examples 1, 2, and 3 in figure 14 show the variation of profile shape that is typical when varying the TWPD. It should also be noted that similar effects can occur (though to a lesser extent) by varying system amperage and linear travel speed. Width "X", Depth "Y", and groove angle "θ" as well as the scaling factors will vary significantly by make of system and its associated system parameters.

Lastly, some discussion of the starting transition region of the gouge is required. This region can be referred to as the *lead-in region*. When gouging with plasma, the process requires some linear distance to reach its full depth. Since arc attachment occurs at the surface of the work piece and is somewhat diffuse, a delay in full penetration is to be expected. Variations in system make and process parameters will vary this effect. Furthermore, the angle tangent to the curve of the lead-in region is typically about 1/3 of the primary torch angle, depending on process parameters. This effect is most evident in mechanized applications when a starting shim is used. Figure 15 shows a theoretical cross section of a gouge illustrating the geometry of the lead-in region. Again, variations in system make and process parameters will vary this effect.

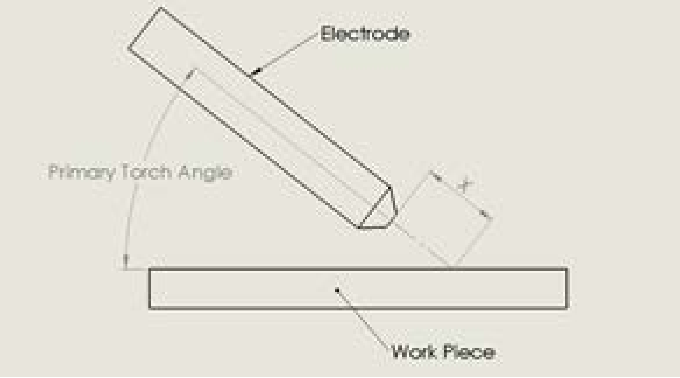

Fig. 13. Torch to work piece distance

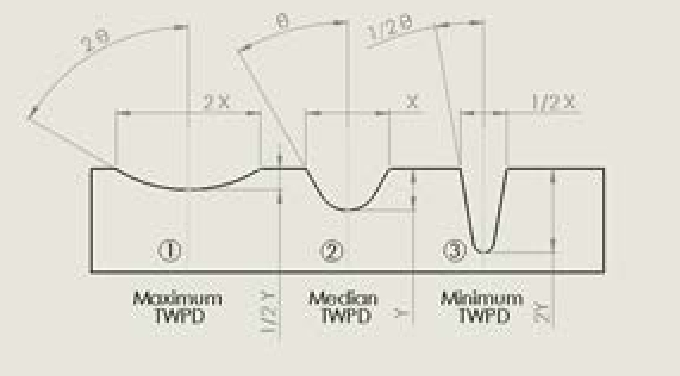

Fig. 14. Typical gouge profile shapes as a function of TWHD

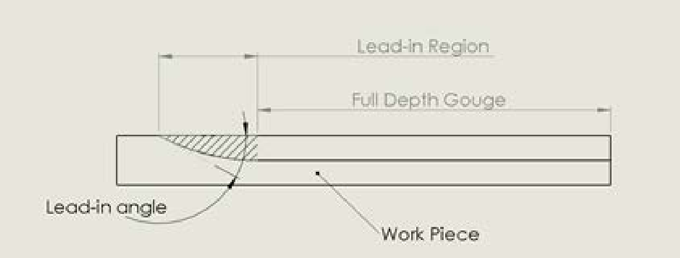

Fig. 15. Cross section of gouge lead-in

Conclusion

In today's welding and fabrication markets, the operator has many choices when it comes to selecting a gouging solution. Established technologies such as carbon arc gouging or grinding are still today's preferred solutions for many operators. However, new trends in end user feedback suggest that gouging with plasma offers a safer, more efficient and cost effective way to make a gouge. Standard and best practices for plasma gouging are only now starting to develop. In order to address this need, this paper has presented the basic relationships between these key process parameters:

- amperage,
- torch positioning ,
- torch motion.

With a basic understanding of how these process parameters interact, an end user now has the building blocks to design a plasma gouging process to address specific applications. Moreover, the specific characteristics of the gouge profile and process can be referred to by nomenclature. As plasma becomes more user-friendly and repeatable, it is likely that it will be well positioned to become the new standard method of gouging.