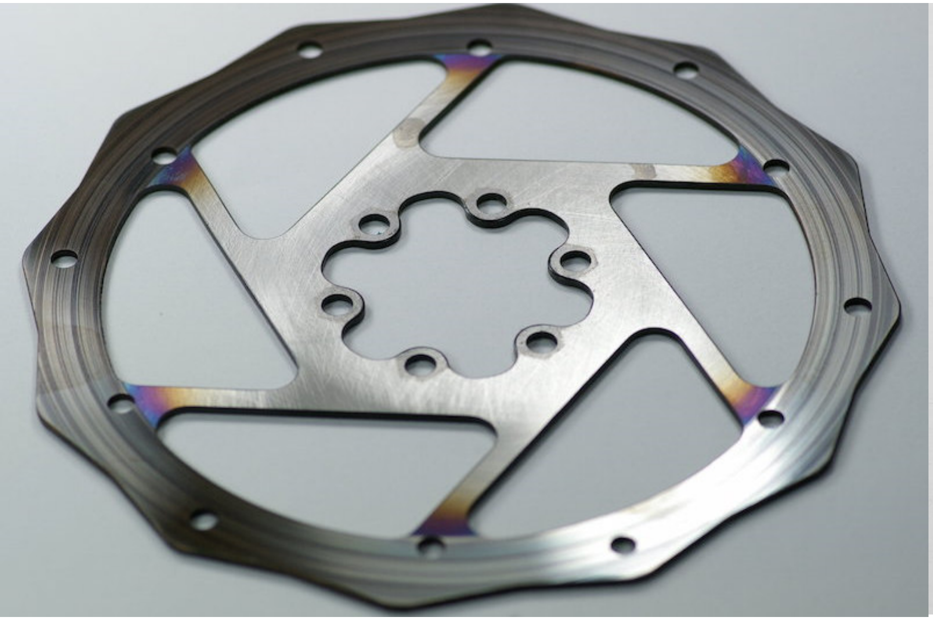
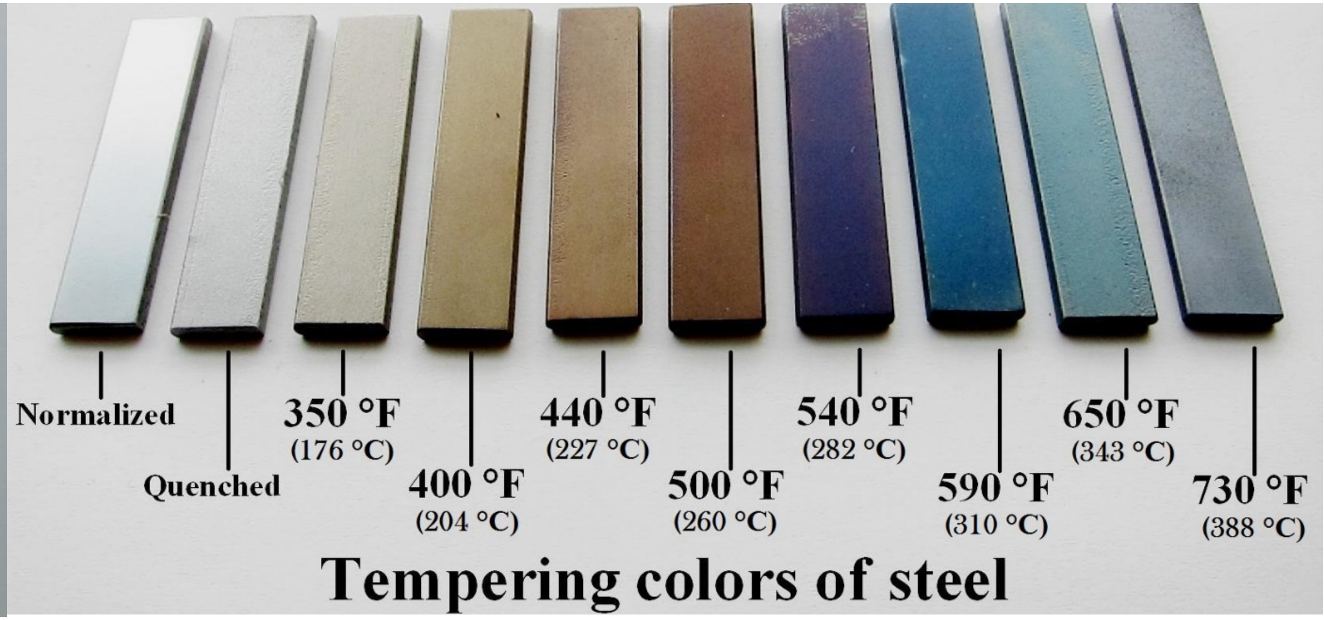
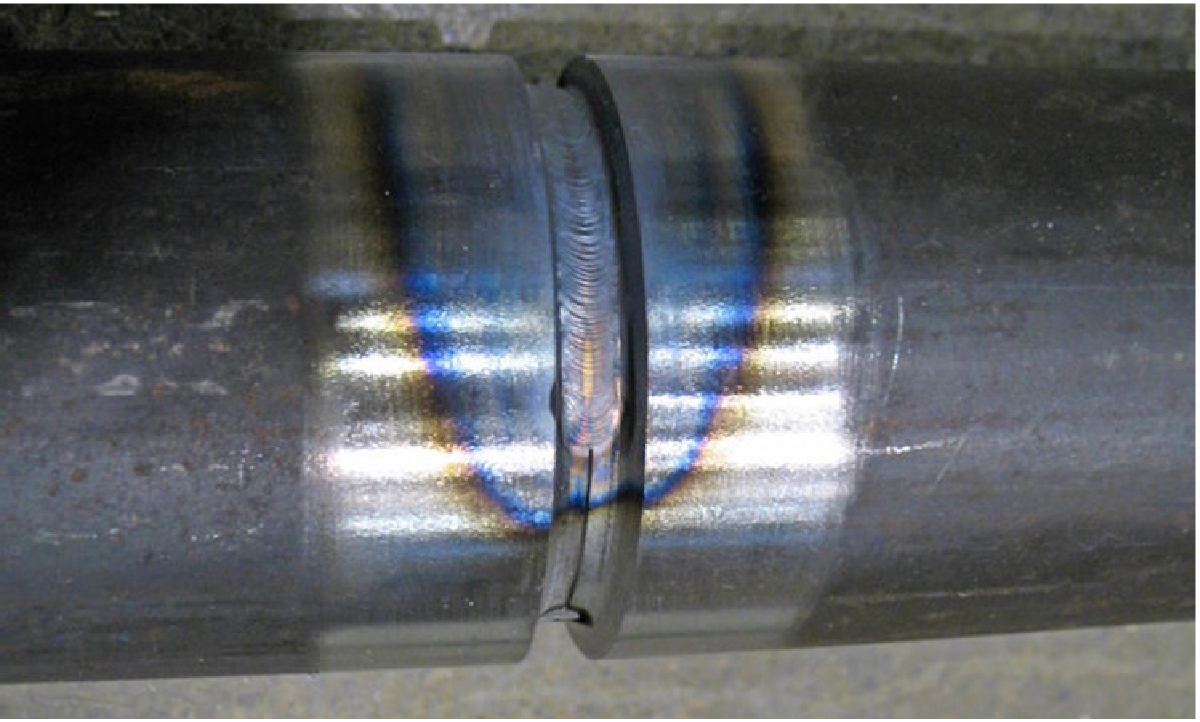





# Heat-Affected Zone Stainless Steel



**Prepared by: DSc Dževad Hadžihafizović (DEng)**

**Sarajevo 2023**

# Heat-Affected Zone Stainless Steel – An Overview

When working with stainless steel, it is important to understand the concept of a Heat Affected Zone (HAZ). This zone refers to the area of metal that has been heated and cooled during welding. The HAZ can be very difficult to predict and can cause unexpected changes in the properties of the metal. Let’s explore what this means for working with stainless steel.

## PROPERTIES OF STAINLESS STEEL

Stainless steel is an alloy that consists primarily of iron, chromium, and nickel. It is known for its high resistance to corrosion and its ability to retain strength at high temperatures. These properties make it an ideal material for many applications, such as food processing equipment, medical devices, and chemical tanks.

## HEAT AFFECTED ZONE

During welding, heat causes changes in the microstructure of the metal in the immediate vicinity of the weld area. This area is known as the Heat Affected Zone (HAZ). In this zone, the grain structure of the metal changes due to exposure to intense heat during welding. This change affects not only its mechanical properties but also its corrosion resistance and weldability. As a result, it can be difficult to predict how a specific HAZ will affect a given project.

https://blog.thepipingmart.com/metals/heat-affected-zone-stainless-steel-an-overview/

## PREVENTING UNWANTED CHANGES IN PROPERTIES

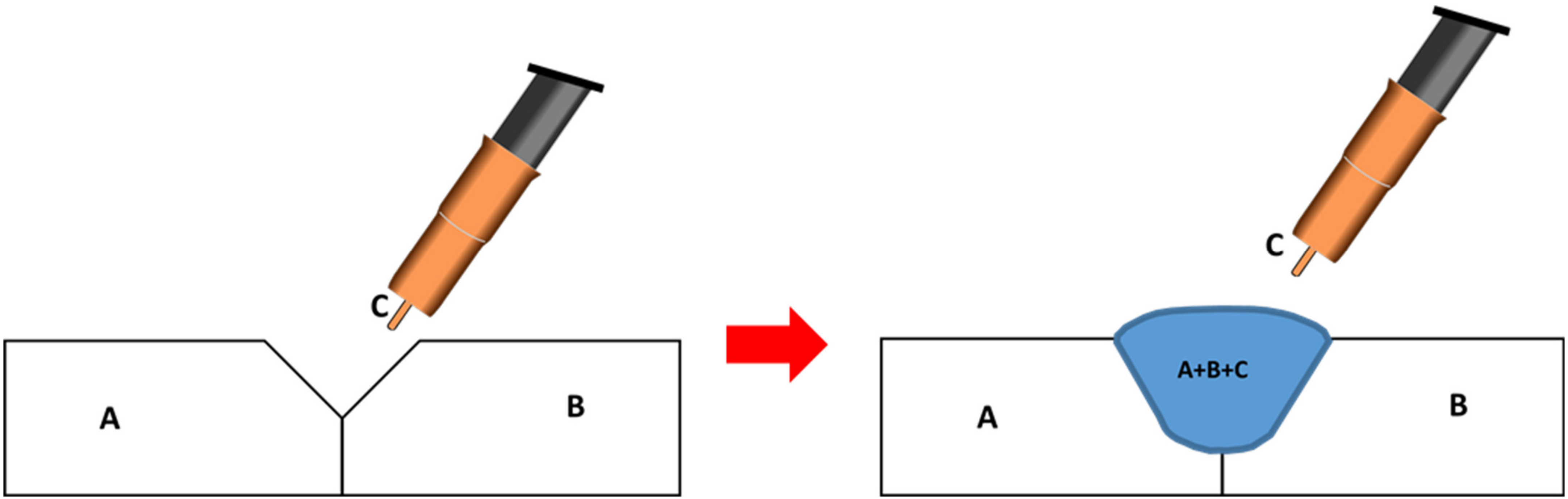
In order to prevent unwanted changes in properties due to welding heat, there are several measures that should be taken when working with stainless steel. First and foremost, proper preheating techniques should be used prior to welding whenever possible; this helps reduce thermal shock when cooling down afterwards. Additionally, proper post-weld heat treatment should be done immediately after welding; this helps relieve stress from any residual thermal cycles within the metal itself. Finally, careful consideration should be given when selecting filler metals; certain filler materials may contain elements that will interact negatively with stainless steels at elevated temperatures or lead to unwanted microstructural changes upon cooling down.

## CONCLUSION:

Working with stainless steel involves understanding what happens in its Heat Affected Zone (HAZ). The HAZ is an area near a weld where extreme temperatures cause changes in mechanical properties as well as corrosion resistance and weldability. To avoid unexpected results due to these changes in properties, while working with stainless steel, it is important to take precautionary measures by properly preheating before welding and doing post-weld heat treatments afterwards if necessary—as well as carefully selecting filler metals that won’t interact negatively with stainless steel at elevated temperatures or lead to unwanted microstructural changes upon cooling down. By following these guidelines, you can ensure successful outcomes when dealing with HAZs on your next stainless steel project!

## The Importance of the Heat Affected Zone (HAZ)

When we weld we generate enough heat in the welding arc to melt the filler metal and base material. Or just the base material is we are welding autogenously (as in GTAW without filler). The edges of the base material melt and combine with the filler metal to create what is called the composite zone. It's called composite because it is a composition of the base material(s) and the filler metal as seen in the image below.



The heat affected zone (HAZ) is the area adjacent to the weld that was heated high enough to affect its microstructure but not enough to melt it. By undergoing microstructural changes the HAZ has different mechanical and physical properties than the weld and the adjacent base metal. These changes can be significant and even cause failure in the form of fracture, corrosion or other problems.

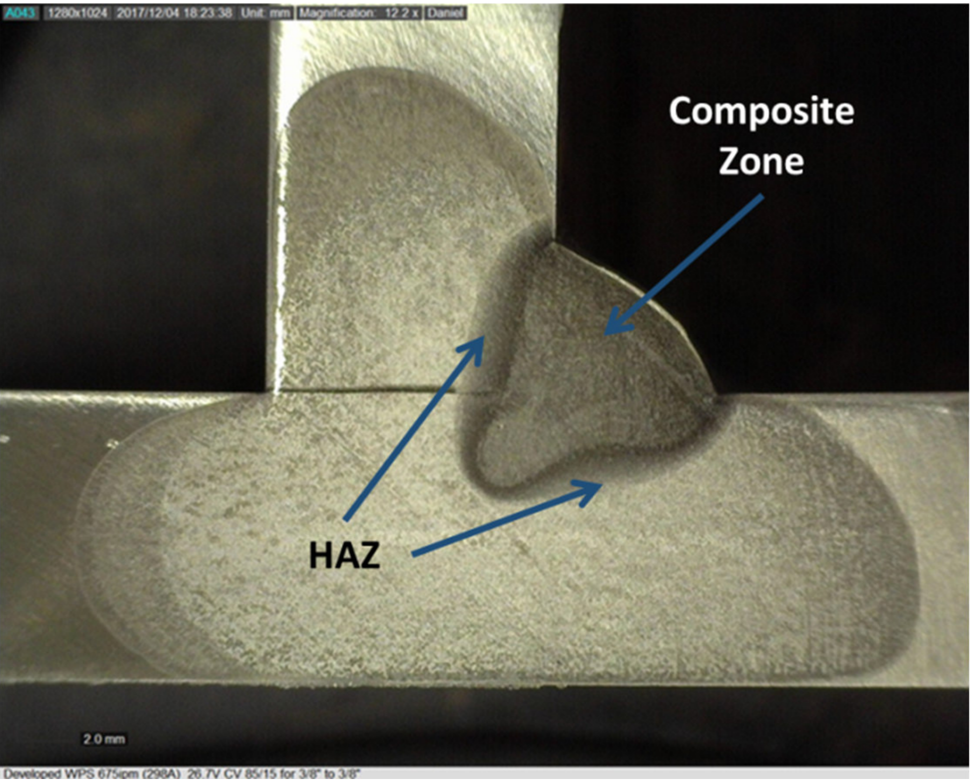
The base material and the thermal cycle (heating and cooling due to welding) as well as any post weld heat treatment (PWHT) are the determinant factors in how the HAZ changes. There are different potential issues with the HAZ depending on whether you are welding on mild steel, medium-to-high carbon steel, aluminum, stainless steel, or other base materials.

https://weldinganswers.com/what-is-post-weld-heat-treatment-pwht/

To explain the importance of the HAZ we'll focus on carbon steel. The image below clearly shows the composite zone with the HAZ surrounding it. The HAZ is the darker shade around the weld and the unchanged base material is the lighter color adjacent to the HAZ.

The problem on steel is that if we have a rapid enough cooling rate martensite will form. Martensite is a hard and very brittle solid solution of carbon in iron. It is desirable in some cases because it is extremely hard, but at the same time may exhibit poor ductility. So it is good for tools, but not so great for structural steel.

The faster the cooling rate the more martensite will form. So to avoid, or at least reduce martensite, we need to slow the cooling rate. This is why we use preheat when welding on thick steel sections (regardless of carbon content) or with medium to high carbon steels (such as 4140 or 4340).




**Why is Preheating Necessary?**

https://weldinganswers.com/why-is-preheating-necessary/

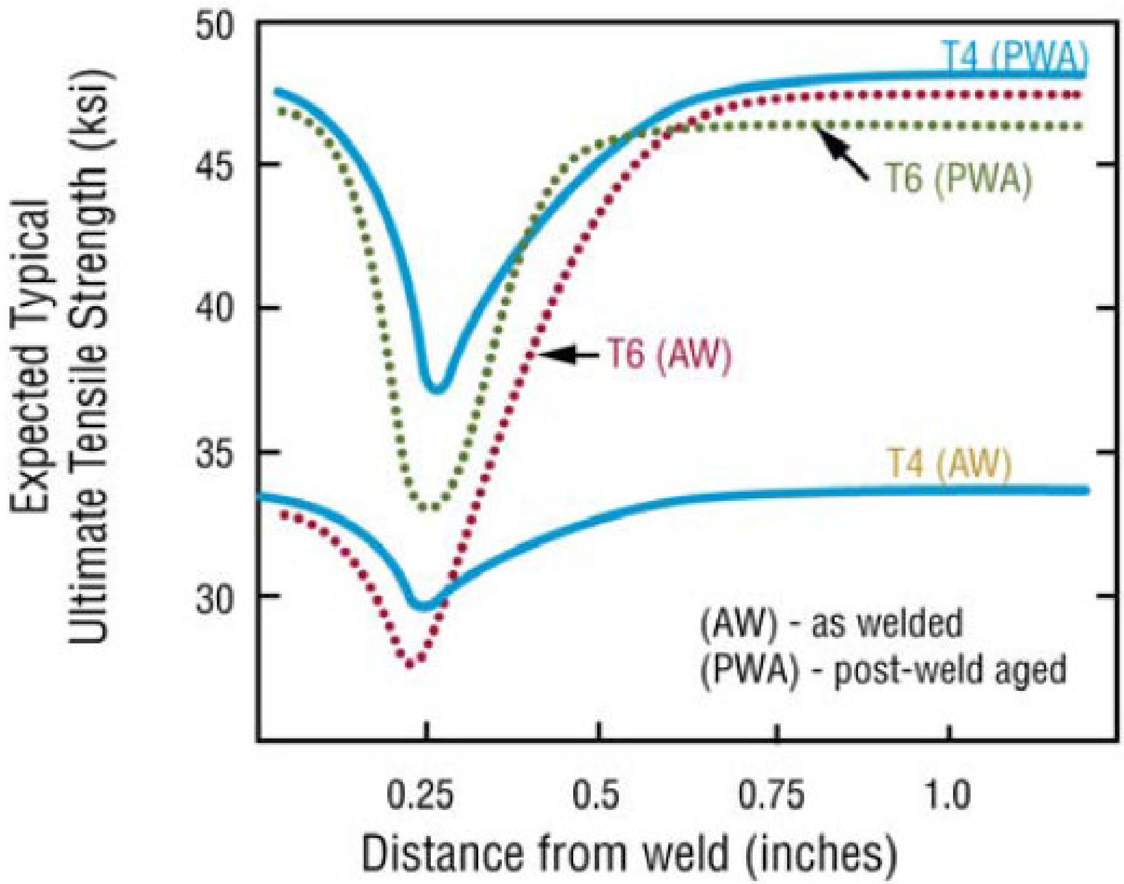
**How To Weld 4140 Steel**

**https://weldinganswers.com/how-to-weld-4140-steel/**

The danger of having a brittle HAZ in steel is the susceptibility for hydrogen induced cracking (HIC). This brittle microstructure fails under the pressure exerted by the hydrogen that diffuses out of a weld and HAZ. This is dangerous because unlike hot cracking which happens right after welding, most cold cracks (as in the case of hydrogen assisted cracking) do not occur until several hours after the part has cooled. This is why proper welding procedures call for inspection of welds susceptible to HIC 48 hours after welding is complete.
So with the HAZ being susceptible to all these problems it makes sense that minimizing it will only help. This is why post weld heat treatment (PWHT) is necessary on some steel weldments. And adequate PWHT will reheat a part that has been welded to a specific temperature to get rid of martensite and then cool at a very slow and controlled rate to avoid it from reforming, thus eventually cooling the part down to room temperature with no martensite to be found in the weld or HAZ.

Other alternatives are having welding procedures that minimize the HAZ. You can also use other processes that minimize it, such as laser welding. Welding with laser produces an extremely small HAZ thus reducing the problems associated with the HAZ.

Other types of base metals, such as aluminum, have their own set of challenges. In aluminum welds the heat affected zone is always the weakest area of the weld. The image below shows the tensile strength of the base aluminum away from the weld. As you can see the strength drops as we get into the HAZ and then comes back up when we are back in the pure, unaffected base material.



This is the opposite than in steel, where the HAZ can become extremely hard and has very high tensile strength.  Opposite conditions, but neither is necessarily desirable.  Having a clear understanding of the base material you are welding and how the heat input, cooling rate and other important factors affect the HAZ is crucial in avoiding failure.

References:


https://weldinganswers.com/the-importance-of-the-heat-affected-zone-haz/

Welding Procedure Development for Non-Welding Engineers (2021)

Metals and How to Weld Them – Theodore Jefferson, Gorham Woods

Welding Metallurgy and Weldability by John C. Lippold

AWS D1.1/D1.1M:2020 Structural Welding Code – Steel

Heat Affected Zone and Weld Metal Properties in Welding of Steels

https://www.ispatguru.com/heat-affected-zone-and-weld-metal-properties-in-welding-of-steels/

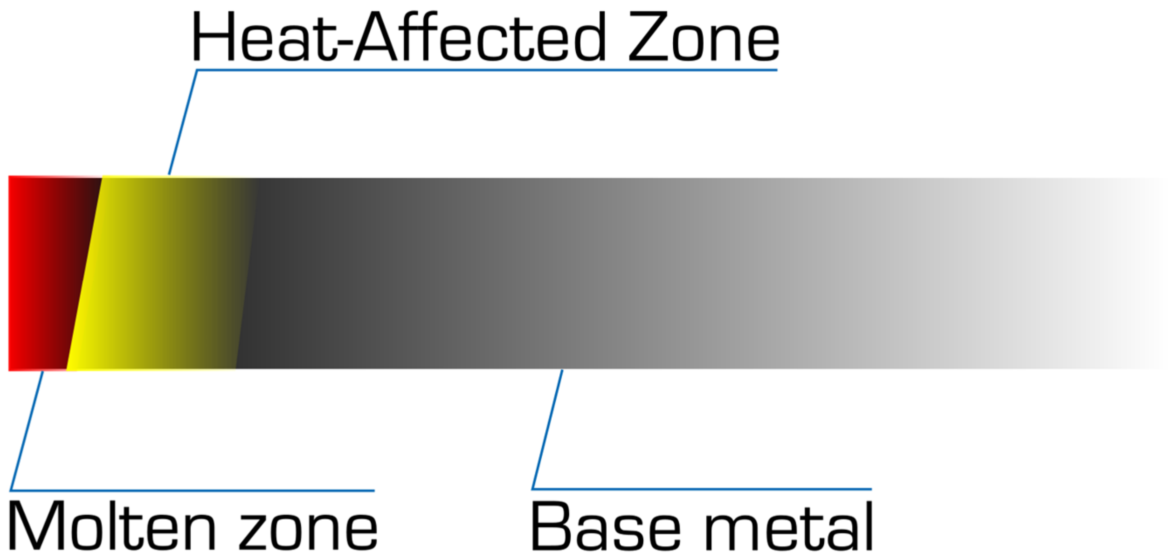
Advances In Martensitic Stainless Processing

https://www.kvastainless.com/martensitic-advances.html

## What is the Heat-Affected Zone?

Most sheet metal cutting techniques are based on localized melting of the material.

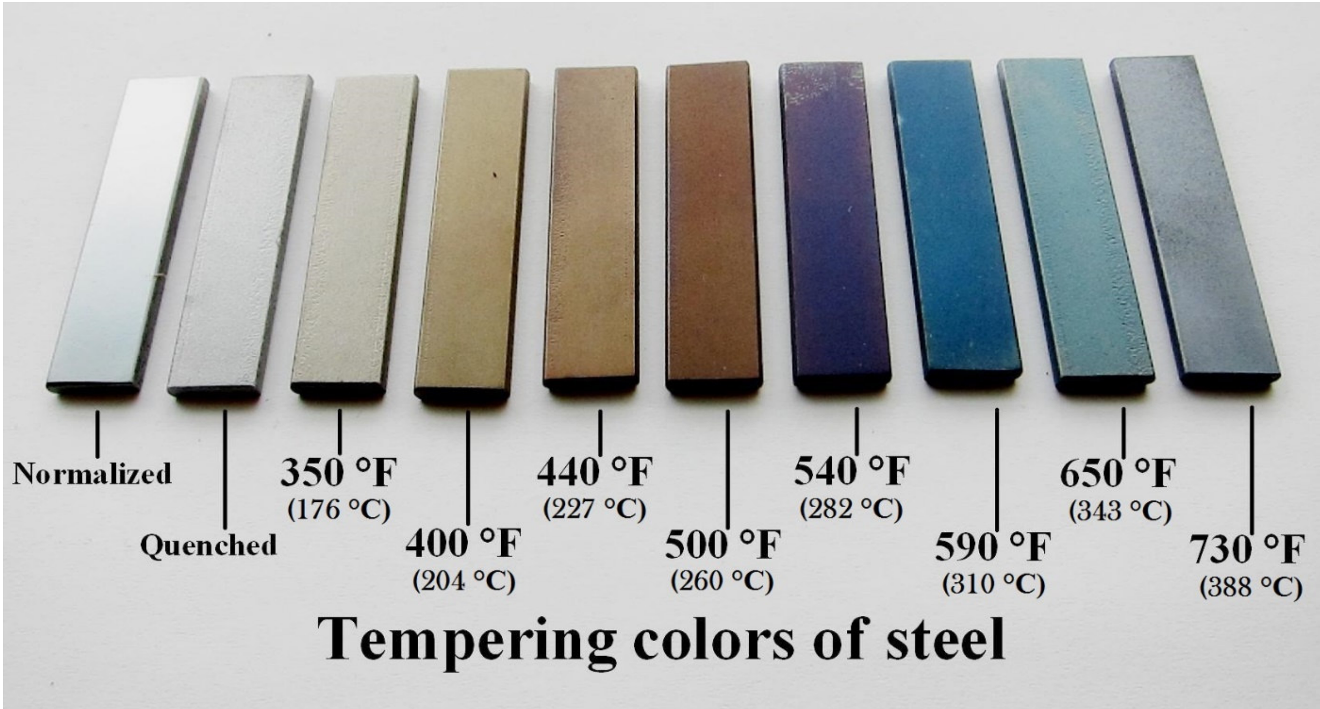
The area between the melt part and the unaffected base metal undergoes chemical and structural modifications, and is called Heat-Affected Zone (HAZ).



It can often be recognized by a series of brightly colored bands, also visible near welds. Colors are caused by surface oxidation, and are an approximate indicator of the temperature reached by the metal:

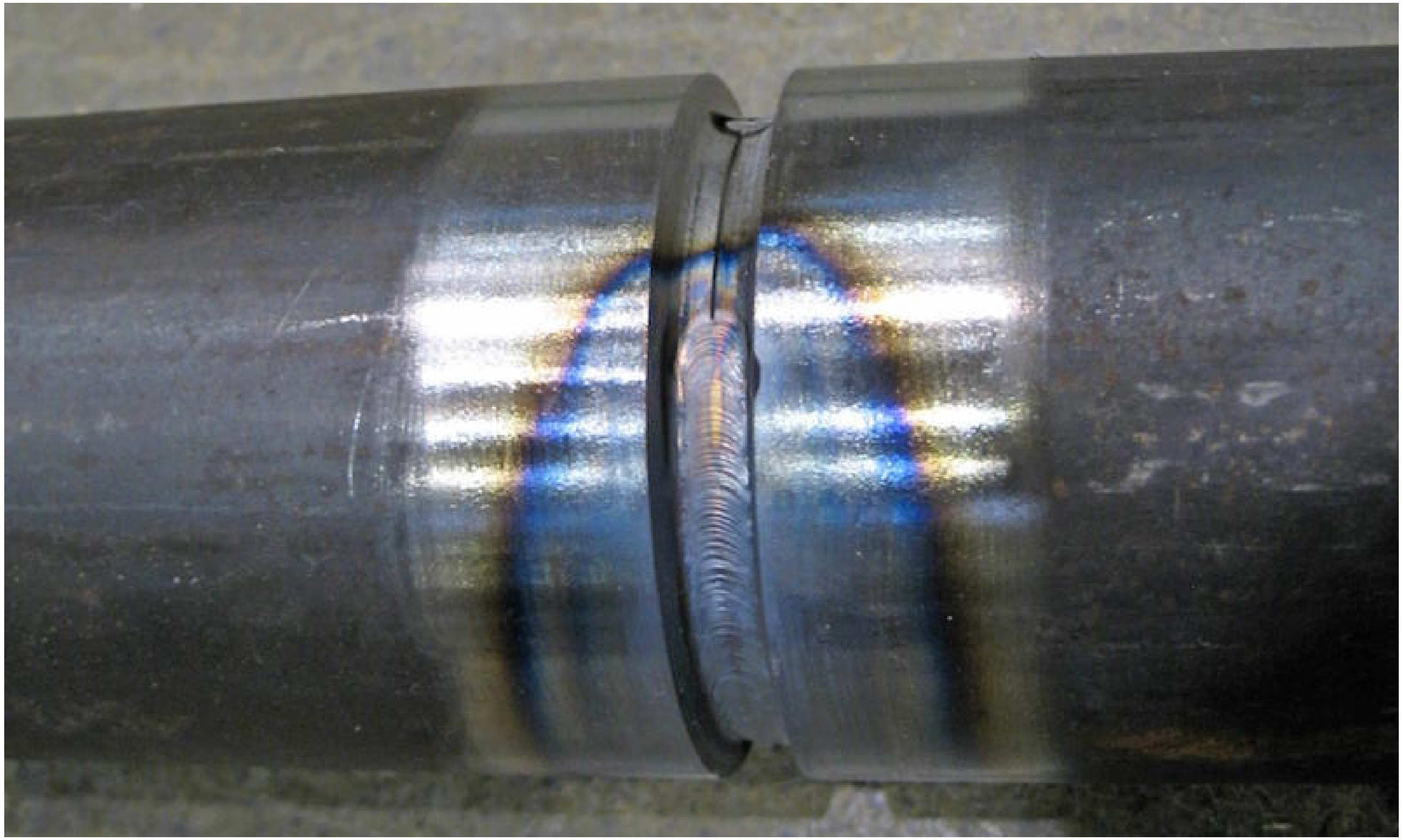
This table represents the oxidation colors that form on stainless steel type 1.4301 (AISI 304) when heated in open air.

| Color | Temperature |
| --- | --- |
| light yellow | 290 °C / 550 °F |
| straw yellow | 340 °C / 640 °F |
| yellow | 370 °C / 700 °F |
| brown | 390 °C / 735 °F |
| purple brown | 420 °C / 790 °F |
| dark purple | 450 °C / 840 °F |
| blue | 540 °C / 1000 °F |
| dark blue | 600 °C / 1110 °F |



These colors, also called “Heat tint”, depend on four factors:

- Steel chromium content: this metal increases the material resistance to oxidation, therefore colors will be less intense or their formation will be delayed;
- Oxygen level: during welding, usage of protective gas and electrode coating can reduce the coloration because they partly shield metal from oxidation;
- The rougher the surface, the faster it oxidizes, causing darker colors;
- Substances like paint, oil, rust, and even fingerprints can alter heat tint, but do not affect the extension of the heat-affected zone.



**What are the causes?**

The most important factor is thermal diffusivity. Technically speaking, this coefficient depends on thermal conductivity, density, and specific heat of a substance. Materials that show a high thermal diffusivity, are able to quickly transfer variations in heat, rather than heat itself.

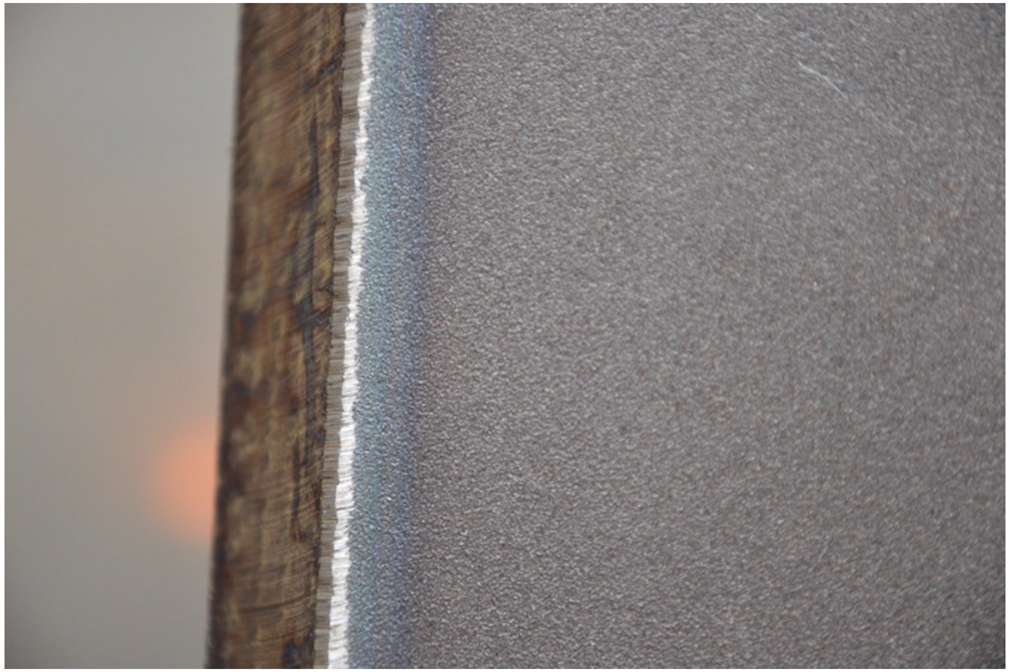
In other words, the higher the thermal diffusivity of a material, the faster it cools, and HAZ is reduced. Conversely, lower coefficients mean that the energy cannot be drained quickly and the heat-affected zone will be wider. 304A-grade stainless steel, for instance, has a thermal diffusivity of 4.2 $mm^2/s$, much lower than structural steel (11.72 $mm^2/s$).

From the point of view of the production process, the extension of the HAZ depends on three factors: quantity of heat applied, duration of exposure, and affected area. If you provide large amounts of energy, for a long time, and with wider beams, you will get a larger heat-affected zone.

This explains why, regardless of the material being cut, any cutting technique causes a different effect:

Plasma cutting generates an intermediate HAZ, because it uses a larger beam. Higher currents allow for a higher cutting speed, reducing the duration of exposure and therefore the width of the heat-affected zone;

•Oxyfuel cutting, because of the intense heat, slow speed, and wide flames, generates the wider HAZ of all thermal cutting systems.



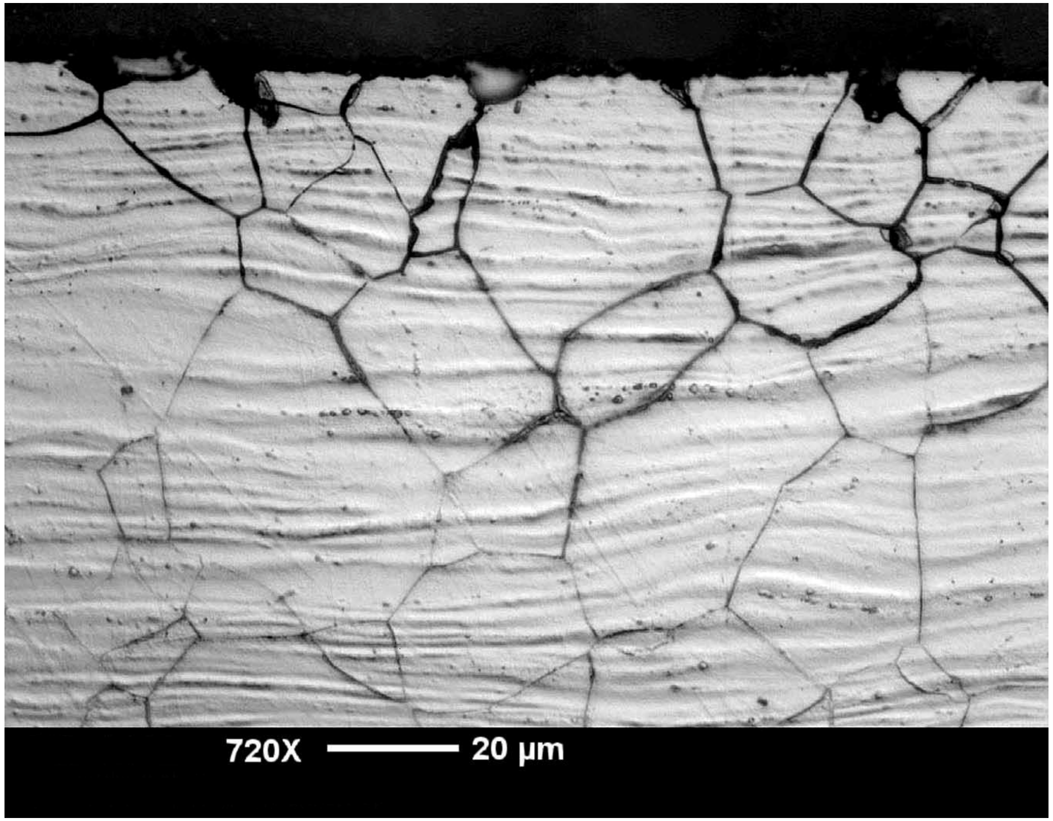
## What are the effects?

Heat provided by the welding or cutting process, and consequent fast cooling, result in both chemical and metallurgical alterations.

- Oxidation is the most noticeable and immediate change, and as we have seen, is also responsible for the brightly colored bands.
- A light surface nitriding can occur, resulting in an increased hardness and decreased weldability of the metal.
- Another common issue is corrosion, derived from stainless steel sensitization. Intense heat causes the precipitation of chromium carbides around the grain boundaries. In these areas, chromium content drops below 10,5% and steel will lose its ability to form a passive film and will no longer be stainless. The result is the so-called intergranular corrosion. In extreme cases, metal will turn black.

•High temperature can also provoke hydrogen embrittlement. Gas diffuses through the metal and create a strong pressure within the lattice, reducing its tensile strength and toughness. Should hydrogen gas not be removed, it can cause spontaneous cracking even 24 hours after heating.

•From a metallurgical point of view, heat generates localized hardening. In some circumstances, austenitic stainless steel can turn into martensitic, increasing its hardness as well as its brittleness. In other cases, heated metal can become less strong.



**How to deal with the HAZ?**

The heat-affected zone can alter the sheet metal figures as declared by the rolling mill to a great extent. When forming, the HAZ can make it difficult to manage the bending angle because it becomes impossible to foresee how metal will behave after a heat-intensive cutting process.

One of the affected behaviors is springback. To get consistent angles with varying elastic recovery, it’s useful to rely on an angle control system, either laser- or contact-based. The former are quite common but somehow cumbersome, and they do not operate with small flanges, and with rough or polished surfaces. GPS4 contact systems are more precise and work well also with counterbends or small flanges, but have a slightly reduced angle span.

Imprecise crowning is the other culprit: every cut piece will be different from each other, and the machine frame will be stressed in an unpredictable way. For this reason, it’s important to use a press brake with an ACSG real-time crowning system, able to compensate for the machine deformation. This technology helps obtaining regular angles along the entire length of the profile.

Heat tint caused by oxidation can be removed with fine sandpaper or ground away. This exposes the underlying layer and activates chromium self-passivation, but you risk to weaken the part. On the other hand, the only way to remove the entire extension of the heat-affected zone is to machine it away, but at the price of a higher waste of material and time.

https://www.gasparini.com/en/blog/what-is-heat-affected-zone/

# Aeat - affected zone (HAZ)

The area between the melted part and the unaffected base metal undergoes chemical and structural modifications. It's called the heat-affected zone (HAZ).

It often can be recognized by a series of brightly colored bands, also visible near welds. Colors, caused by surface oxidation, are an approximate indicator of the temperature the metal reaches (see **Figure**). For example, this table explains the oxidation colors that form on stainless steel Type 1.4301 (AISI 304) when heated in open air:

These colors, also called heat tint, depend on four factors:

1. **Steel chromium content.** This metal increases the material resistance to oxidation, and therefore colors are less intense or their formation is delayed.
2. **Oxygen level.** During welding, usage of protective gas and an electrode coating can reduce the coloration because they partly shield metal from oxidation.
3. **Surface condition**. If the surface is rough, it oxidizes faster, causing darker colors.
4. **Surface contaminants**. Substances like paint, oil, rust, and even fingerprints can alter heat tint, but do not affect the extension of the HAZ.

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Surface condition. If the surface is rough, it oxidizes faster, causing darker colors.

Surface contaminants. Substances like paint, oil, rust, and even fingerprints can alter heat tint, but do not affect the extension of the HAZ.

In some cases, the HAZ does not cause these colors or even extend farther than the colored area.

| Color | Temperature |
|---|---|
| Light Yellow | 550 degrees F/290 degrees C |
| Straw Yellow | 640 degrees F/340 degrees C |
| Yellow | 700 degrees F/370 degrees C |
| Brown | 735 degrees F/390 degrees C |
| Purple Brown | 790 degrees F/420 degrees C |
| Dark Purple | 840 degrees F/450 degrees C |
| Blue | 1,000 degrees F/540 degrees C |
| Dark Blue | 1,110 degrees F/600 degrees C |

**What Are the Causes?**

The most important factor that influences the creation of the HAZ is thermal diffusivity. Technically speaking, this coefficient depends on thermal conductivity, density, and specific heat of a substance. Materials that show a high thermal diffusivity are able to quickly transfer variations in heat, rather than heat itself.

In other words, if a material demonstrates high thermal diffusivity, it cools faster, and HAZ is reduced. Conversely, lower coefficients mean that the energy cannot be drained quickly, and the HAZ will be wider. For instance, 304A-grade stainless steel has a thermal diffusivity of 4.2 $mm^2/s$, much lower than structural steel (11.72 $mm^2/s$).

From the production process standpoint, the extension of the HAZ depends on three factors: quantity of heat applied, duration of exposure, and area affected . If large amounts of energy are provided for a long time and with wider beams, the HAZ is larger.

This explains the reason that, regardless of the material being cut, any cutting technique causes a different effect:

- Shearing and waterjet cutting do not provoke a HAZ because they do not overheat the sheet metal.
- Laser cutting generates the smallest HAZ among all thermal cutting techniques because it applies heat on a very small area.
- Plasma cutting generates an intermediate HAZ because the plasma pulse is wider than a laser beam. Higher currents allow for a higher cutting speed, reducing the duration of exposure and the width of the HAZ.
- Oxyacetylene cutting generates the widest HAZ of all thermal cutting systems because of the intense heat, slow speed, and wide flames.

Common Weld Impurities on Stainless Steel and How to Remove Them

https://cougartron.com/blog/common-weld-impurities-on-stainless-steel-and-how-to-remove-them/

Heat tints & discoloration in Stainless steel welding!

https://shipbuildingknowledge.wordpress.com/2019/07/16/heat-tints-discoloration-in-stainless-steel-welding/

**What Are the Effects?**

Heating caused by the welding or cutting process and subsequent fast cooling result in both chemical and metallurgical alterations. Oxidation is the most noticeable and immediate change, and it is also responsible for the brightly colored bands. A light surface nitriding also can occur, resulting in an increased hardness and decreased weldability of the metal.

Another common effect is corrosion, derived from stainless steel's sensitive nature. Intense heat causes the precipitation of chromium carbides around the grain boundaries. In these areas, chromium content drops below 10.5 percent, and steel loses its ability to form a passive film and relinquishes its ability to be stainless. The result is the so-called intergranular corrosion. In extreme cases, metal will turn black.

High temperature also can provoke hydrogen embrittlement. Gas diffuses through the metal and creates a strong pressure within the lattice, reducing its tensile strength and toughness. If the hydrogen gas is not removed, it can cause spontaneous cracking even 24 hours after heating.

From a metallurgical point of view, heat generates localized hardening. In some circumstances, austenitic stainless steel can turn into martensitic, increasing its hardness as well as its brittleness. In other cases, heated metal can become weaker.

## Koji su učinci?

Zagrijavanje uzrokovano postupkom zavarivanja ili rezanja i kasnije brzo hlađenje rezultiraju i kemijskim i metalurškim promjenama. Oksidacija je najuočljivija i najneposrednija promjena, a odgovorna je i za jarko obojene trake. Također može doći do laganog površinskog nitriranja, što rezultira povećanom tvrdoćom i smanjenom zavarljivošću metala.

Drugi uobičajeni učinak je korozija, koja proizlazi iz osjetljive prirode nehrđajućeg čelika. Intenzivna toplina uzrokuje taloženje kromovih karbida oko granica zrna. U tim područjima sadržaj kroma pada ispod 10,5 posto, a čelik gubi sposobnost stvaranja pasivnog filma i odriče se svoje sposobnosti da bude nehrđajući. Rezultat je takozvana interkristalna korozija. U ekstremnim slučajevima, metal će pocrniti.

Visoka temperatura također može izazvati vodikovu krtost. Plin difundira kroz metal i stvara snažan pritisak unutar rešetke, smanjujući njegovu vlačnu čvrstoću i žilavost. Ako se vodikov plin ne ukloni, može uzrokovati spontano pucanje čak i 24 sata nakon zagrijavanja.

S metalurške točke gledišta, toplina stvara lokalizirano otvrdnjavanje. U nekim okolnostima, austenitni nehrđajući čelik može se pretvoriti u martenzitni, povećavajući njegovu tvrdoću, kao i njegovu krtost. U drugim slučajevima, zagrijani metal može postati slabiji.

**How to Deal With the HAZ?**

The HAZ can alter the sheet metal composition as declared by the rolling mill to a great extent. During forming, the HAZ can make it difficult to manage the bending angle because it becomes impossible to foresee how metal will behave after a heat-intensive cutting process.

One of the affected behaviors is springback. To get consistent angles with varying elastic recovery, it's useful to rely on a laser- or contact-based angle control system often found on modern press brakes. Laser-based systems are quite common but have problems working with small flanges and with rough or polished surfaces. Contact systems are more precise and work well with counterbends and small flanges. However, they have a slightly reduced angle span when compared to the laser-based systems.

Imprecise crowning is the other culprit. Every cut piece is different, and the machine frame is stressed in an unpredictable way. For this reason, it's important to use a press brake with a real-time crowning system, which makes it able to compensate for the machine deformation. This technology helps the press brake obtain regular angles along the entire length of the profile.

Heat tint caused by oxidation can be removed with fine sandpaper or ground away. This exposes the underlying layer and activates chromium self-passivation, but may lead to a weakening of the part.

The only way to remove the entire extension of the HAZ is to machine it away, but that comes with the price of reduced material yield and more labor and machine time required to address the problem area.

Which types of welding processes produce less HAZ?

The width of a heat-affected zone (HAZ) is influenced by the amount of heat going into the material which is related to the heat input of the welding process. The size of the HAZ is also influenced by the thermal diffusivity. Those materials with a high level of thermal diffusivity are able to transfer the heat faster, which means for a certain level of heat input, they cool quicker and, as a result, their HAZ width is reduced. The thermal diffusivity of copper is significantly greater than that of steel and so, for the same heat input, the HAZ of the copper would be narrower than that of a steel.

With regard to welding processes, assuming the same material, thickness and joint being welded, then those processes that give lower heat inputs will cool faster. This will lead to a smaller HAZ. Conversely, the higher heat input processes will have a slower rate of cooling, thus leading to a larger HAZ.

For the purposes of discussion, we can rank the heat input of the common welding processes as:

•Low:  Gas Tungsten Arc Welding (GTAW)

•Medium: Shielded Metal Arc (SMAW), Gas Metal Arc (GMAW, Flux Cored Arc (FCAW) and Metal Cored Arc (MCAW)

•High: Submerged Arc Welding (SAW)

•Very High: Electro Slag Welding (ESW). The Electroslag Welding Process cannot be regarded as a common welding process but, it is used for fabricating thick materials in one pass and is included here for comparison purposes.

By reference to Table 1 below, three processes with typical heat inputs (typical welding parameters) have been selected in the medium to very high range for the welding of steel. The difference in HAZ size is immediately evident. The SMAW process, with a heat input of 1.4 KJ/mm has a 2 mm wide HAZ while the very high heat input ESW, at a heat input of 88 KJ/mm, has a 17.80 mm wide HAZ

In terms of the metal properties, there are other things to consider when evaluating those of the HAZ itself. Due to the variations in temperature across the HAZ, the individual portions will have differing properties as they see different temperatures for different amounts of time. This fact, and its importance or otherwise, is beyond the scope of this article but may be covered in a sister article at a future date.

Other than welding, most cutting processes also produce a HAZ and precautions may have to be taken after cutting depending on the metal and the cutting process used. Conversely, the waterjet cutting process does not create a HAZ as it does not heat the material.

| **Process** | **Current** | **Voltage** | **Travel Speed** | **Heat Input** | **Width of HAZ** |
|---|---|---|---|---|---|
| | **Amps** | **Volts** | **mm/sec** | **KJ/mm** | **mm** |
| Electroslag (ESW) | 800 | 34 | 0.32 | 88 | **17.80** |
| Sub Arc (SAW) | 600 | 28 | 5.1 | 3.3 | **3.10** |
| Shielded Metal Arc (SMAW) | 200 | 23 | 3.4 | 1.4 | **2.00** |

**Table 1. Comparison of Welding Process and HAZ Width**

So, from this representative table, it can be seen that the lower heat input welding processes produce the smallest heat affected zones, all other things being equal. Figure 2 illustrates a macro-section from a portion of a 75mm, multipass SMAW weld at a magnification of less than x 5. The darker etching heat affected zone is seen located between the weld metal and base (parent) metal. The heat input was controlled at 1.5KJ/mm max and the material, due to thickness, was also preheated to 150 deg C. The resulting HAZ is 2.00 mm in width.

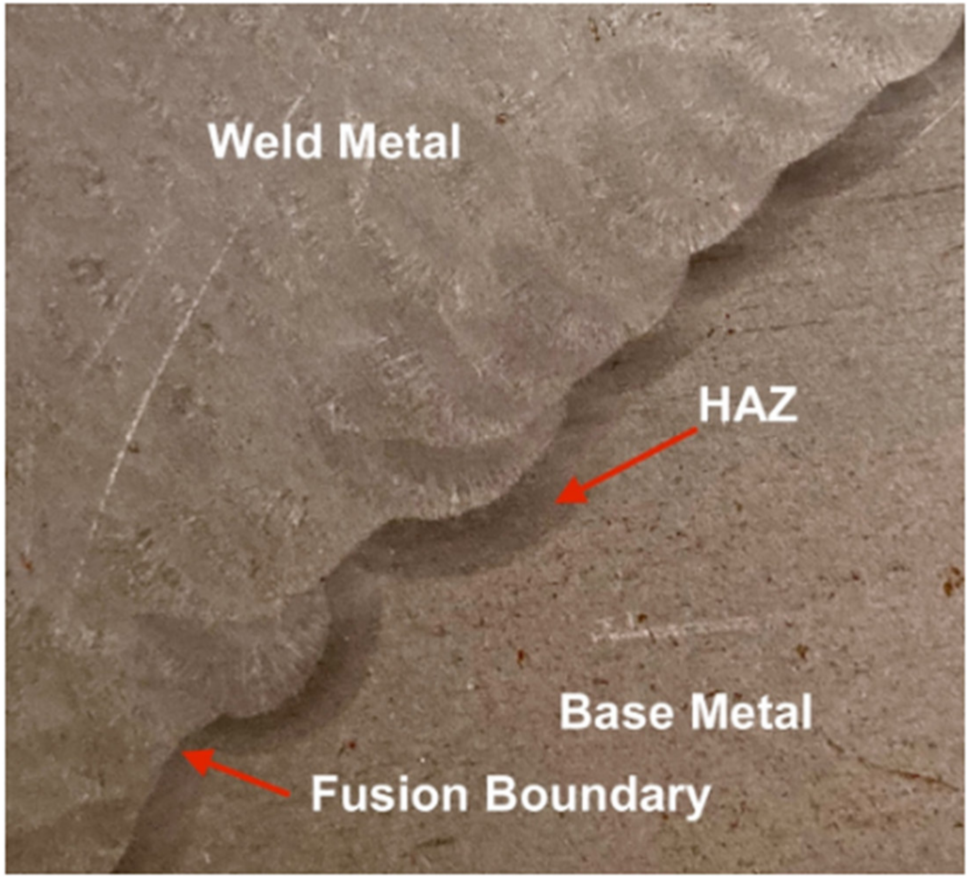



Figure 2 Macro of a SMAW Weld showing the three zones. Base Metal, Weld metal and the Heat Affected Zone (HAZ)

https://www.cwbgroup.org/association/how-it-works/what-heat-affected-zone-welding-and-which-types-welding-processes-produce

Mick J Pates IWE, President PPC and Associates

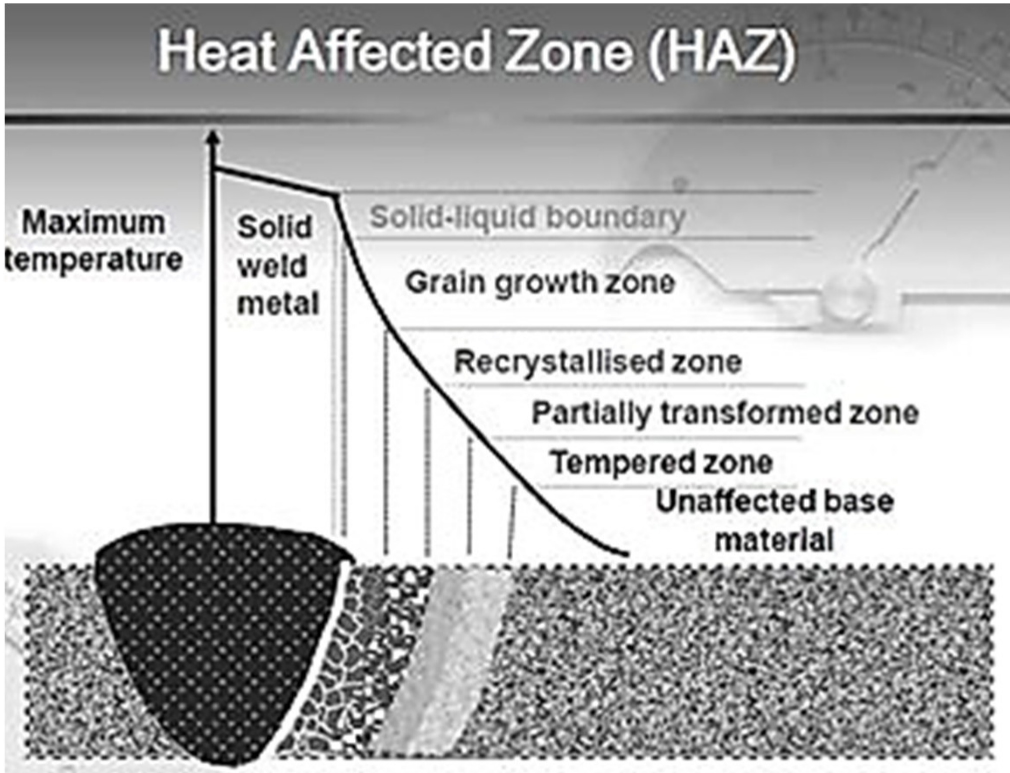
The blue color on this stainless steel tube used in a race car chassis indicates a gas tungsten arc weld that reached approximately 1,000 degrees F.

https://www.thefabricator.com/thefabricator/article/shopmanagement/all-you-need-to-know-about-the-heat-affected-zone

# THE HEAT AFFECTED ZONE (HAZ)

The heat affected zone (HAZ) is a non-melted area of metal that has undergone changes in material properties as a result of being exposed to high temperatures. These changes in material property are usually as a result of welding or high-heat cutting. The HAZ is the area between the weld or cut and the base (unaffected), parent metal.

The HAZ area can vary in severity and size depending on the properties of the materials, the concentration and intensity of the heat, and the welding or cutting process used.




Effect of microstructure on the mechanical properties and corrosion resistance of a welded joint of 620-grade marine steel

https://www.frontiersin.org/articles/10.3389/fmats.2023.1107125/full

## What are the Causes of Heat-Affected Zones?

The heating associated with welding and/or cutting generally uses temperatures up to and often exceeding the temperature of melting of the material in question, depending on the welding process used. However, the heating and cooling thermal cycle associated with these processes is different to whatever processing has occurred with the parent material previously. This leads to a change in microstructure associated with the heating and cooling process.

The size of a heat affected zone is influenced by the level of thermal diffusivity, which is dependent on the thermal conductivity, density and specific heat of a substance as well as the amount of heat going in to the material. Those materials with a high level of thermal diffusivity are able to transfer variations of heat faster, meaning they cool quicker and, as a result, the HAZ width is reduced. On the other hand, those materials with a lower coefficient retain the heat, meaning that that the HAZ is wider. Generally speaking, the extension of the HAZ is dependent on the amount of heat applied, the duration of exposure to heat and the properties of the material itself. When a material is exposed to greater amounts of energy for longer periods the HAZ is larger.

With regard to welding procedures, those processes with low heat input will cool faster, leading to a smaller HAZ, whereas high heat input will have a slower rate of cooling, leading to a larger HAZ in the same material. In addition, the size of the HAZ also grows as the speed of the welding process decreases. Weld geometry is another factor that plays a role in the HAZ size, as it affects the heat sink, and a larger heat sink generally leads to faster cooling.

High temperature cutting operations can also cause a HAZ and, similarly to welding procedures, those processes that operate at higher temperatures and slow speeds tend to create a larger HAZ, while lower temperature or higher speed cutting processes tend to reduce the HAZ size. The width of the HAZ from the cut edge is determined by the cutting process, cutting speed, and the material properties and thickness.

Different cutting processes have differing effects on the HAZ, regardless of the material being cut. For example, shearing and waterjet cutting do not create a HAZ, as they do not heat the material, whilst laser cutting creates a small HAZ due to the heat only being applied to a small area. Meanwhile, plasma cutting leads to an intermediate HAZ, with the higher currents allowing for an increased cutting speed and thereby a narrower HAZ, while oxyacetylene cutting creates the widest HAZ due to the high heat, slow speed and flame width. Arc welding falls between the two extremes, with individual processes varying in heat input.

**HAZ Areas**

While the HAZ occurs between the weld or cutting zone and the unaffected parent metal, the HAZ itself has different areas according to how close they are to where the cutting or welding heat was applied to the material.

The cutting or weld zone is the liquid region where the process itself takes place and is adjoined by the fusion boundary. The fusion boundary is the border of the fusion zone where the liquid and solid phases of the metal coexist. Further from the weld or cutting zone is the HAZ itself, which is where the non-melted parent metal has experienced changes to the microstructure. In conventional steels, the HAZ can be broken down into the grain coarsened zone (closest to the heated area), the grain refined zone, the partially transformed (intercritically heated) zone and the tempered zone. In other materials, which do not undergo a solid-state phase transformation during cooling, it is common to see a grain growth zone and a recrystallized zone, with some evidence of a tempered zone. Outside of these HAZ areas is the unaffected base material.

The various HAZ areas are formed by differing temperatures in the base metal further from the weld or cut itself. This should not be mistaken for the series of visible coloured bands, caused by surface oxidation, near a weld in stainless steel. The ‘temper colours’ represent much lower temperatures than those which form the heat affected zone, and extend for some distance beyond the actual heat affected zone.

These different colours, also known as heat tint, offer an approximate indication of the temperature reached by the metal. In the case of stainless steel type 1.4301 (AISI 304) heated in open air, the band colours and associated temperatures are as follows:

| Color | Temperature |
|---|---|
| Light yellow | 290 °C |
| Straw yellow | 340 °C |
| Intense yellow | 370 °C |
| Brown | 390 °C |
| Purple  brown | 420 °C |
| Dark purple | 450 °C |
| Blue | 540 °C |
| Dark blue | 600 °C |

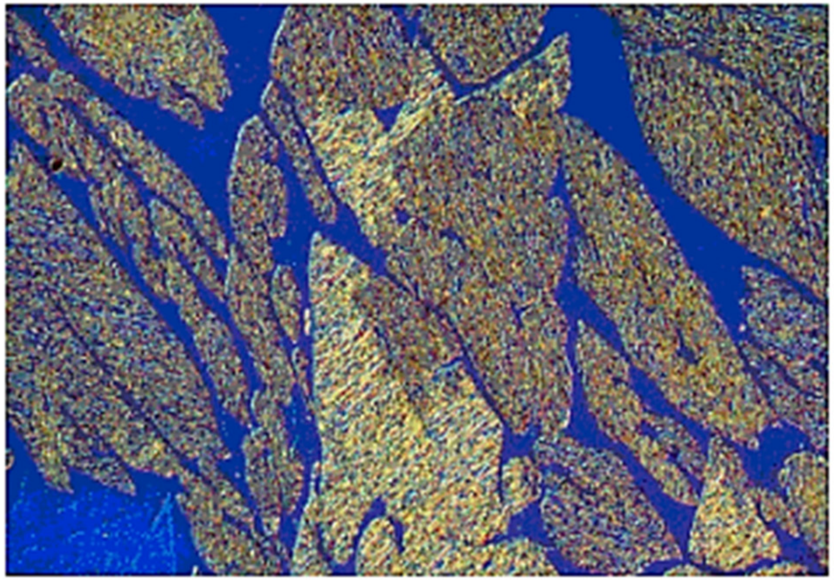
The heat tint colours depend on the material’s resistance to oxidation, with those metals with a higher steel chromium content showing less intense colouration as they are more resistant to oxidation.

The use of protective gas and electrode coatings can also reduce heat tint as they partially shield the metal from oxidation. Conversely, rougher surfaces oxidise faster, causing darker colours. In addition, paint, oil, rust and even fingerprints can alter the heat tint, although they do not impact the extent of the HAZ itself.

https://www.twi-global.com/technical-knowledge/faqs/what-is-the-heat-affected-zone

Metallographic Stainless Steel Etchants

Etching stainless steels can be somewhat difficult due to the anti-corrosive nature of stainless steel. Austenitic or 300 series stainless steels typically have higher chrome as well as a significant amount of nickel (e.g. 304 stainless steel - 18% chrome, 8% nickel) which makes them harder to etch. Martensitic or 400 series stainless steels are easier to machine, however, they are not as corrosion resistant so they are easier to etch.



431 Stainless Steel, etched with Modified Murakami's, Mag. 400X (DIC)

https://www.metallographic.com/Metallographic-Etchants/Metallography-Stainless-steel-etchants.htm

Microstructures and mechanical properties of stainless steel clad plate joint with diverse filler metals

https://www.sciencedirect.com/science/article/pii/S2238785419305903

## Recommended Etchants

| Etchant | Conc. | Conditions | Comments |
|---|---|---|---|
| **Adlers Etchant**<br><br>Ferric chloride<br>Copper ammonium chloride<br>Hydrochloric acid<br>Distilled water | <br>45 gm<br>9 gm<br>150 ml<br>75 ml | Immerse for several seconds. | A very effective etchant for 300 series, austenitic, duplex stainless steels |
| **Carpenter Etchant**<br><br>Ferric chloride<br>Cupric chloride<br>Alcohol<br>Hydrochloric acid<br>Nitric acid | <br>8.5 gm<br>2.4 gm<br>122 ml<br>122 ml<br>6 ml | Immerse for several seconds. | A nice etchant for 300 series, austenitic, duplex stainless steels |
| **Kalling' No. 2**<br><br>Cupric chloride<br>Hydrochloric acid<br>Alcohol | <br>12 gm<br>20 ml<br>225 ml | Immerse or swab - seconds to minutes | For 400 series or martensitic stainless steel |
| **Modified Murakami's**<br><br>K3Fe(CN)6<br>Potassium hydroxide<br>Distilled water | <br>30 gm<br>30 gm<br>150 ml | 1 second to several minutes by immersion or swabbing | Mix potassium hydroxide into water before adding K3Fe(CN)6 |
| Hydrochloric acid<br>Selenic acid<br>Ethyl alcohol | 20-30 ml<br>1-3 ml<br>100 ml | Immerse at room temperature for 1-4 minutes | Color etching. Colors carbides and gamma prime phase in heat resisting steels |
| Ammonium bifluoride<br>Potassium metabisulfite<br>Distilled water | 20 gm<br>0.5 gm<br>100 ml | Immersion at room temperature for 1-2 minutes | Color etching. Etching of austenitic stainless steel and welds. Reveals delta ferrite in welds |
| **V2A Etchant**<br><br>Hycrochloric acid<br>Nitric acid<br>Distilled water | <br>119 ml<br>12 ml<br>119 ml | Immersion or swabbing etch at 20 degrees Celsius | For etching austentic stainless steels |

# Heat Affected Zone in Welded Metallic Materials

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https://irispublishers.com/mcms/fulltext/heat-affected-zone-in-welded-metallic-materials.ID.000566.php

## Abstract

Welding is used extensively for pipe welding, aerospace, aviation, biomedical implants, fabrication of race cars, choppers, etc. Generally, the metallurgy of the welded joint performed by thermal fusion joining process can be categorized into two major regions, the fusion zone (FZ) and the heat-affected zone (HAZ). The heat-affected zone (HAZ) is a region that is thermally affected by the welding treatment. The main difficulty associated with welding is the prevention of unexpected deterioration of properties as a result of the microstructure evolutions which reduce the resistance to brittle fracture in the heat-affected zone (HAZ). Properties of the HAZ are different from those of the base material. According to the literature, the HAZ is the most problematic area in the high strength steels weld. For this reason, many research works investigated this critical zone in welded joint. The main research questions and results related to the HAZ will be presented.

**Keywords:** Welding; Heat affected zone; Microstructure; Mechanical properties; Thermal cycle simulation

**Abbreviations:** HAZ: Heat Affected Zone; Hv: Hardness Vickers; FZ: Fusion Zone; BM: Base Metal; T-HAZ: True Heat Affected Zone; PMZ: Partially Melted Zone

# Introduction

Welding is a process of joining materials into unique piece. Welding is an enabling technology applied across almost all industries, from micro-joining of medical devices, electronics and photonics, to larger scale applications such as bridges, buildings, ships, rail, road transport, pressure equipment and pipelines [1]. Welding processes are divided into thermal fusion joining processes and solid-state joining processes. The most common processes of welding are thermal fusion joining processes such electric arc welding. This welding method is performed under high temperature conditions.

Heat generated during welding induces an important temperature gradient in and around the welded area. Generally, the metallurgy of the welded joint can be divided into two main zones, the fusion zone (FZ) and the heat-affected zone (HAZ). The HAZ is a zone which is outside the FZ of the welded joint that is thermally affected by the welding treatment. The HAZ is considered as a transition zone, because it is composed with the microstructure of the BM and the FZ. The properties of the HAZ are very important after performing a weld, because it is considered as a weaker zone, i.e.; the area of failure when the welded metal is submitted to hard conditions. For this reason, it is important to understand this critical zone in welded joint.

## Microstructures of HAZ

The HAZ is the unavoidably heat treated area in the parent metal near the fusion zone during welding where structural transformations occur [2]. HAZ formed during welding is an area which some structural changes in the welded material take place as the result of experienced temperature [3]. Figure 1 shows how the HAZ in welded XC38 steel differs significantly from the base metal. There was a development of a recrystallization reaction in HAZ, with the partial dissolution of the colonies of pearlite (dark color).

Depending on the distance from the weld, the different parts of the HAZ can be affected differently during the welding process There are many descriptions of the HAZ, because it can be divided in different subzones and each subzone has its own microstructure. For example, It has been considered that the HAZ can be divided into four different zones [2], as shown in Figure 2, which are subjected to different heat treatments:

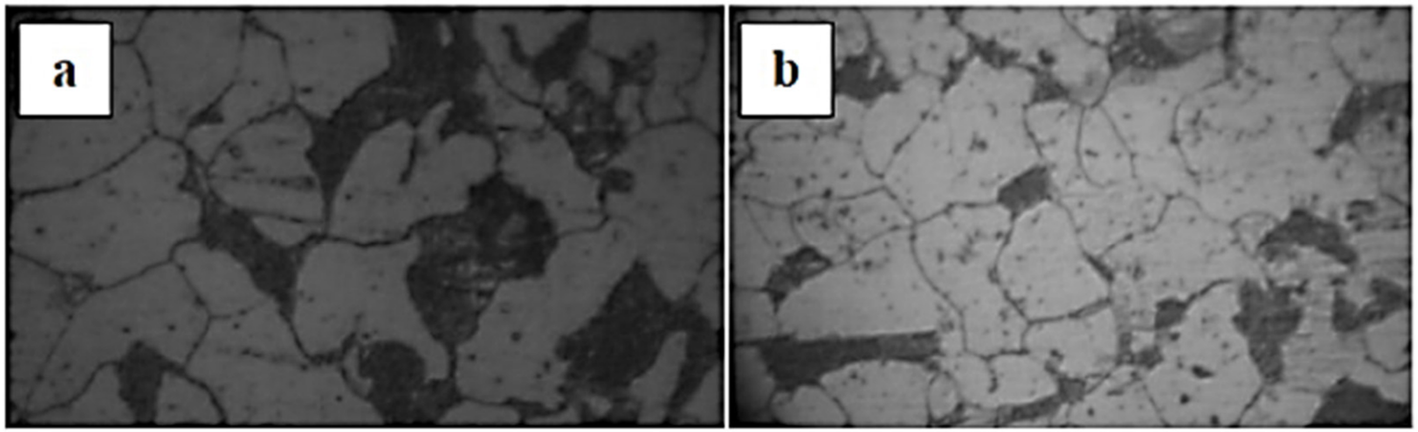


**Figure 1:** Microstructure of (a) base metal and (b) HAZ of welded XC38 steel.

However, according to Lippold [5], the HAZ was subdivided into two regions, the partially melted zone (PMZ) and the “true” heataffected zone (T-HAZ). The PMZ exists in all fusion welds made in alloys since a transition from 100% liquid to 100% solid must occur across the fusion boundary. According to Lippold [5], there are many possible metallurgical reactions in the HAZ: recrystallization, grain growth, phase transformations such as precipitation, and residual stress and stress relaxation.

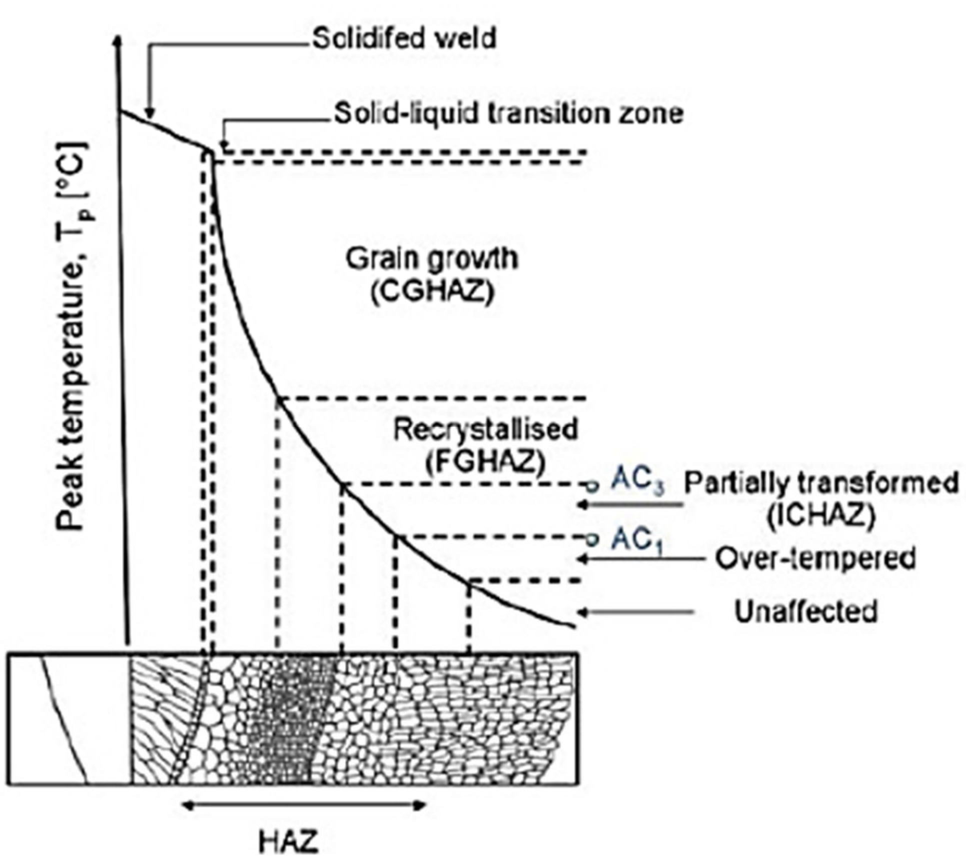


**Figure 2:** Schematic illustration of the heat-affected zone [4].

- Coarse grain zone
- The normalized zone
- The partially transformed zone,
- The annealed zone

Mechanical properties of HAZ

The mechanical properties and microstructures of the HAZ have its origin in the thermal heat treatment during welding and depend on the characteristics of the joint (position in the joint, thickness of the joint) and the heat input and the prior-heat treatment before welding (if it is applied) [6].

Controlling of HAZ

It has been concluded that by improving the microstructure of the HAZ, the properties of the welded joint can be improved [7]. The changes of microstructures in the HAZ depend on the level of thermal exposure and are varying with distance from the weld metal zone. High heat input increases the size of the HAZ which induces a low impact strength [8]. As reported by Gu et al. [9], the degradation in strength and toughness of welded joint, is generally happens in HAZ.

As many authors, Parmar and Dube [10] considered HAZ as the most complicated region. It is important to control its effects. HAZ is the most critical region in the welded joint as it affects the microstructure and grain size of weld bead. The main factors for improving welded joint quality are: welding process, material selection, and welding parameters. Concerning the welding parameters, they found that in order to study the heat-affected zone in welded carbon steel, following parameters were considered: welding current, welding speed, and arc voltage. These parameters can influence the Heat input and heat flow.

According to Lippold [5], heat input and heat flow conditions have an effect on the dimensions and nature of the HAZ. These dimensions are controlled by the temperature gradient from the fusion boundary into the surrounding base metal and the nature of the metallurgical reactions that occur over that temperature range. The size of HAZ has been studied by Śloderbach and Pająk [3]. They established an expression for determining the value of x of HAZ for a given time t and knowing diffusivity coefficient κ of given material: $[x/(2\sqrt{\kappa t})] \approx 0.61$

From this mathematic expression, the size of the HAZ x can be controlled by the time t during the welding. The x can be reduced by reducing the welding time

## Methods of Investigation of HAZ

It has been found that the study of the HAZ of real welded joints is not easy because of the narrowness of the HAZ [11]. Welding simulation is the appropriate technique to determine the different sub-zones in HAZ. This allows the prediction of the microstructure and the properties of these sub-zones [9]. Consequently, thermal cycle simulation in which the HAZ can be geometrically extended is the appropriate method in order to determine the different microstructures, which can be developed in real welded joints [12,13].

Hamza et al. [14] simulated HAZ of the welded stainless steel 304L by the thermal cycle simulation technique and compared it to the HAZ obtained from the real welded joint. They found that the simulated HAZ by the thermal cycle simulation technique has given more information. The HAZ is heterogeneous structure, because it is formed with different subzones. Raouache et al. [15], investigated the HAZ of welded 2014 aluminum alloy by the thermal cycle simulation of the base metal. They found that the HAZ is also a heterogeneous zone, because it is composed with different subzones and each subzone has a specific microstructure.

## Conclusion

From the above literature, followings points can be summarized: • The HAZ is the critical zone in welded joint, for this reason it is necessary to control its effects.

• The HAZ is a heterogeneous zone and it can be divided into different subzones

• There are many possible metallurgical reactions in the HAZ

• The mechanical properties and microstructures of the HAZ depend on the heat input during welding

• Main factors for improving weld joint quality such as the welding process, the material selection, and the welding parameters.

• Welding simulation is a suitable technique for the investigation of the HAZ and to determine the various HAZ subzones.

## References

1.Smallbone C (2019) IIWAP2019: The 8th Asia-Pacific IIW International Congress, March 20-22, QSNCC, Bangkok, Thailand.

2.Back M (2015) Welding of dissimilar metals in different welding positions, Examensarbette I Material Design 300 HP, Avancerad Niva Stockholm, Sverige.

3.Śloderbach Z, Pająk J (2015) Determination of ranges of components of heat affected zone including changes of structure. Archive of Metallurgy and Materials 60(4): 2607-2612.

4.Krishnasamy RK (2012) A computational approach to thermomechanical fatigue life predictions of dissimilarly welded Grin Verlag, Germany.

5.Lippold JC (2014 ) Welding Metallurgy and Weldability. John Wiley & Sons, Inc, Hoboken, New Jersey.

6.Stemne D, Narstrom T, Hrnjes B (2010) Welding Handbook: A guide to better welding of Hardox and Weldox. SSAB, pp. 132, Stockholm.

7.Digheche K, Boumerzoug Z , Diafi M, Saadi K (2017) Influence of heat treatments on the microstructure of welded of APX70 pipeline steel. Acta metallurgica Slovaca 23(1): 72-78.

8.Gunaraj V, Murugan N (2002) Prediction of Heat-Affected Zone Characteristics in Submerged Arc Welding of Steel Pipes. Welding res, 94-98 .

9.Guo YH, Lin L, Zhang D, Liu L, Lei MK (2018) Microstructure and Mechanical Properties of Heat-Affected Zone of Repeated Welding AISI 304N Austenitic Stainless Steel by Gleeble Simulator. Metals 8(10): 1-14.

10.Parmar A, Dubey A (2017) Study of heat affected zone for SMAW process for low carbon steel specimen with controlled parameters, IJMTER.

11.Dunder M, Vuherer T , Kladaric I (2010) Weldability Investigation of TStE 420 After Weld Thermal Cycle Simulation. Strojarstvo 52(2): 97-104.

12.Glover NE , Davis CL (1996) Thermal cycle simulation of a Ni-base superalloy. Scripta Materialia 34(5) 675-684.

13.Dunder M, Samardzic I, Klaric S (2007) Influence of cooling time δt8/5 on welded joint properties of the thermal cycle simulated TStE 420 specimens. Tehnicki Vjesnik 14(1-2): 47-57.

14.Hamza S, Boumerzoug Z, Raouache E, Delaunois F (2019) Simulated heat affected zone in 204L steel. Acta Metallurgica Slovaca 25(3): 142-149.

15.Raouache E, Boumerzoug Z, Delaunois F, Khalfallah F (2020) Investigation by Thermal Cycle Simulation of Heat Affected Zone in Welded AA2014 Aluminum Alloy. Res Dev Material Sci 13(3): 1407-1411.

# Useful links

https://www.harsle.com/What-is-the-Welding-Heat-Affected-Zone-id48017457.html

Heat Affected Zone and Weld Metal Properties in Welding of Steels

https://www.ispatguru.com/heat-affected-zone-and-weld-metal-properties-in-welding-of-steels/

Advances In Martensitic Stainless Processing

https://www.kvastainless.com/martensitic-advances.html

https://edurev.in/studytube/Chapter-2--Part-1--Welding--Manufacturing-Process-/cb94dd0f-df25-4858-8481-ebfed81d3a7e_t

Heat tints & discoloration in Stainless steel welding!

https://shipbuildingknowledge.wordpress.com/2019/07/16/heat-tints-discoloration-in-stainless-steel-welding/

Heat Affected Zone – Causes, Effects and How to Reduce It

https://fractory.com/heat-affected-zone-causes-effects-reduction/

https://fractory.com/types-of-welding-processes/

Nice welding

https://www.facebook.com/photo?fbid=218811613995009&set=pcb.218811670661670