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Enhancing Strength and Toughness of HSLA Steel Welds through Microalloying with Titanium and Vanadium Addition

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الملخص

تهدف هذه الدراسة إلى تحسين قوة ومتانة منطقة اللحام للصلب عالي القوة ومنخفض السبائك (HSLA) عن طريق إضافة عناصر السبائك الدقيقة والمتمثلة في التيتانيوم والفاناديوم عبر تقنية لحام شعلة غاز التنجستن الخامل. تم إجراء إذابة العناصر المضافة للحام باستخدام المسحوق المسبق مع متغيرات اللحام للتيار 80−100 أمبير والجهد 30−40 فولت. أظهرت نتائج الأختبارات المعملية أن عناصر Ti وV تلعب دورا هاما في خصائص المنطقة المتأثرة بالحرارة (HAZ)، وصلابة الصدمات، وقوة الشد للفولاذ HSLA. علاوة على ذلك، تم تحقيق أقصى قوة شد (UTS) بلغت 693 ميجا باسكال و730 ميجا باسكال مع إضافة كل من Ti وV على التوالي. كما لوحظ الانخفاض في قيم صلادة HAZ مع إضافة Ti و V 15% و 19% على التوالي، مقارنة بلحام السبيكة بدون إضافات، مما يقلل من خطر الكسور المفاجئة والهشة التي تحدث في المنشاءات الصناعية وتسبب خسائر بشرية وإقتصادية.

Abstract

The study aims to improve the strength, and the toughness of the welding zone of high strength low alloy steel (HSLA) by adding microalloying elements, titanium, and vanadium via tungsten inert gas torch technique. The melting was carried out using powder preplacement procedure with the welding variables of current, 80-100A and voltage, 30-40V. Experimental results showed that Ti and V elements play an

important role on the heat affected zone hardness, impact toughness and tensile strength of HSLA steel. Furthermore, a maximum ultimate tensile strength of 693 MPa and 730 MPa were achieved with Ti and V addition respectively. The reduction in HAZ hardness values with Ti and V addition was 15% and 19% respectively, compared to base material, thereby reducing the risk of brittle fracture.

Keywords
High strength low alloy steel, Ti and V microalloying elements, heat affected zone, microstructure and mechanical properties.

1. Introduction

The design of high strength low alloy (HSLA) steels play an important role in structural performance which can easily be done with their performance properties such as, lower structural thickness, weight, and load-bearing capacity. This in turn can provide an excellent balance between strength, toughness, ductility, formability, and weldability in contrast to conventional carbon steels [1-3]. In recent decades, much steel research and development efforts have focused on HSLA. The application of this kind of steel has expanded to various industries including shipbuilding, oil and gas pipelines, building, storage tanks, pressure vessels, high strength fasteners and suspension springs after its initial application in the automobile industry.

This is due to its high strength-to-weight ratio, excellent weldability, formability, and cost reduction [4, 5]. In most of the cases, welding is indispensable to use HSLA steel for any application. There are major challenges associated with the welding zones for this type of steel, and the welding processes which have a significant effect on the integrity of the welded structures and their performance in service. The main problem associated with this HSLA steel is to obtain a good combination of strength, toughness, and weldability properties specifically in a welded zone which includes grain coarsening in and around the region of the weld [6]. Furthermore, due to a longer thermal cycle and slower cooling rate, formation of martensitic in weld section and precipitation of carbides at the grain boundaries cause poor mechanical properties in HAZ and hence, lead to several fracture problems [7, 8].

The desired welding variables are selected based on the data available in handbook or experience of the users. However, it might not be accurate for achieving optimum characteristics feature of HAZ or welded zone for wide range of applications. Moreover, it is very difficult to optimize the welding variables because of the complex interaction of the melt pool during welding process. This probably explains why the issue persists and not much has been achieved [9]. Another problem associated with the HSLA steel is the brittleness related to the formation of high carbon martensite-austenite (M-A) and prior austenite grains (PAG) constituents along the grain boundaries which located in the HAZ and the fracture behavior of HAZ developed due to low ductility and low notch impact toughness of HAZ material [10].

These fractures are initiated mostly from second phase particles and inclusions and lead to catastrophic failure related to injury or fatality of humans and the loss of national assets [11, 12]. These losses of toughness properties in HAZs constrain the wide application of high strength steel. It is thus required to understand how to minimize the risks resulting from welding zones and the behavior of the HAZ which determines the efficiency of the entire welded joint. During the past decades, investigations on the morphology and mechanical properties of the HAZ in welding of HSLA steels have focused on finding several practical solutions to prevent sudden fractures in welding zones during their service conditions [13, 14].

It is necessary to find an alternative method to reduce and overcome these risks in the metallurgical and weldability issues related to the HAZ associated with the welding processes of these types of steels to improve the structure and properties of the HAZ. The addition of microalloying elements through small quantities of Ti and V play a vital role for performance property and structural integrity of HSLA steels [15]. These alloying elements have the high affinity to carbon and nitrogen which can greatly influence the new microstructure formation such as by carbide or nitride precipitates. However, these precipitates are in generally complex and the Ti, and V as well as C and N are all interchangeable depending on the formation temperature. Furthermore, stable Ti-rich carbonitrides can work negatively by constricting austenite grain coarsening during austenitization and V-rich carbides promote precipitation hardening during cooling [16-18].

Maduraimuthu et al. [19] have performed parametric optimization of TIG welding using Taguchi design method for P92 (9Cr-0.5Mo-1.8W-VNb) Steel by using response surface methodology and emphasized on the optimization of process parameters in welding process. However, addition of these microalloying elements would be better choice to avoid the problems associated with brittle fractures and environmental degradation occurring in welding zones. Based on the literature, it is evident that weld parameters influence the strength, toughness, and microstructure of HSLA steel, but the results are still insufficient in finding ideal solutions due to the continued deterioration of weld properties, and catastrophic failure occurring particularly in the HAZ area. Furthermore, little research has been done on the microalloying elements addition and its effects on mechanical properties and microstructures performance of HAZ for HSLA steel.

Therefore, the main aim of this study is to explore the addition of Ti and V microalloying elements on the improvement of metallurgical and mechanical performance of HSLA steel. Implementing this optimized TIG welding parameters can be benchmark for welding companies as TIG welding is an international welding concept. This can attract end-users to exploit this approach of HSLA steel with improved metallurgical and mechanical performance avoiding catastrophic failure.

2. Experimental Method

2.1 Material

HSLA steel with L450 specifications was used in this investigation in the form of 10 mm thickness plate was cut and machined to accomplish thin plate specimens of dimensions 150 mm x 50 mm x 5 mm. The chemical composition and mechanical properties of HSLA steel are presented in Table 1 and 2, respectively and details of the measurement procedure can be found elsewhere [21]. The surface of the specimens was cleaned in a Branson 2510 ultrasonic cleaner for duration of 10 min. For experiments with microalloying element preplacement, the substrate surfaces were ground by 180 grit emery paper to have better retention of the preplaced powder.

Table 1: Chemical composition of L450 steel (wt. %) [21]

C	Si	Mn	S	P	Al	V	Nb	Ti	Fe	*C_{eq}
0.08	0.17	1.41	0.014	0.0017	0.032	0.022	0.019	0.015	Bal.	0.38

*C_{eq}: CE = (%C) + (%Mn/6)+ (%Cr+%Mo+%V)/5 + (%Cu+%Ni)/15

Table 2: Mechanical properties of raw L450 HSLA steel [21]

Steel Grade	Yield strength Y.S, MPa	Tensile strength UTS, MPa	Elongation, %	Impact toughness, J	Hardness, Hv0.5
L450	450-500	550-600	35	105	175

Microalloying elements

Ti microalloying element in the form of powder with average particle size, 45 µm, 99.70 wt. % purity, and V microalloying element in the form of powder with average particle size of 45 µm, 99.45 wt. % purity was selected as reinforcing microalloying elements to act as grain refining elements in HSLA steel welds [22, 23]. These elements were added as alloying elements during the welding process. A different approach was adopted to add these microalloying elements only in the weld pool, and not in the bulk material using a powder preplacement technique. The range of individual microalloying element powders used in this study was determined through a preliminary investigation and through previous studies [24, 25].

Polyvinyl Alcohol Binder

The polyvinyl alcohol (PVA) is an organic binder mixed with distilled water in the ratio of 40 grams of PVA to 960 ml of water to prepare one liter of 4% PVA. The mixture was then heated stirring occasionally until a clear solution was obtained, which was stored and used for the preplacement of the microalloying element. It is effective in film forming and has a strong adhesive quality. It is characterized by properties such as chemical resistance; water solubility and it can chemically bind with a nanoparticle surface [26].

2.2 Test equipment

Several equipment and machines were used to produce and investigate the welding heat affected zone of welded HSLA. The machining of HSLA steel substrate was carried out using Milling and EDM- W11FX2K wire cut machines. Miller-Telwin 165-TIG welding machine was used to produce welding tracks. JEOL, JSM-IT100 scanning electron microscope (SEM) integrated with energy dispersive X-ray (EDX) was used to characterize the microstructures and the morphology of heat affect zone (HAZ) of welding region, and to detect the elemental compositions. Phase identification was conducted using Shimadzu 6000 XRD diffractometer.

Instron SI-1C3 300FT-LBS Impact testing machine and Mitutoyo MVK-H2 digital microhardness testing machine were used for impact toughness and hardness measurements, respectively. Instron 5582-100KN universal testing machine was used for tensile testing. The arc generated by the TIG torch welding process using non-consumable tungsten electrode under different welding variables was adapted for the realization of powder melting by reinforcing microalloying elements in the form of powder on the melt pool of HSLA steel. The TIG arc process allows localized heat source that established between a pointed non-consumable tungsten electrode and the substrate materials.

A 3.2 mm diameter tungsten electrode with 2% thorium was selected for the TIG torch used in this study. The electrode has good current carrying capacity, and resistance to contamination the arc generated was more stable. Argon gas with a flow rate of 20 l/min was used to create an inert environment during the TIG melting process due to its advantageous characteristics. These advantages offered a clean, small, and robust joint weld, suitable for most applications. It gives more energy imparted to the surface of the metal and gives deeper penetration than other shielding gases.

2.3 Methodology

The experiments were conducted by preparing Ti and V microalloying elements powder reinforced on the surface of L450 HSLA steel substrates. The surface melting experiment was achieved using powder preplacement procedures and TIG torch melting techniques under a non-oxidizing atmosphere. For a comparison with the modified welded specimens with the addition of microalloying element, the sample of the base material was welded using the same input parameters without microalloying addition.

Preparation of preplaced microalloying element on HSLA steel substrate

The first step of the welding modification process was to prepare the microalloying element powder material on the surface of L450 HSLA steel as a substrate material using the powder preplacement approach. Before applying the microalloying element powder, the surface of the substrate sample was abrasively ground to a smooth surface roughness using silicon carbide (SiC) emery paper. The grounded substrates were subsequently rinsed with acetone followed by ethanol in an ultrasonic bath for 20 minutes.

This treatment removed impurities such as grease, dust, and oxide layer from the substrate surface. Two types of microalloying element powders namely Ti and V were selected for welding modification in this study via melting in the weld pool through the welding of HSLA steel substrate. The amount of microalloying element was a primary variable, while the powder types were used as the categorical variables as presented in Table 3.

All results are average from three measurements. Before preplacement process, each microalloying element powder was weighed using 1.0 mg/mm2 of the substrate surface which was made in a pasty form after mixing of PVA, distilled water and alcohol. The pastes of the microalloying element were evenly preplaced on the HSLA steel surface with the aid of a plastic sheet. PVA was used to prevent the powders from blowing away due to the shielded Ar gas flow during melting process. The minimum quantity of PVA was used with a thumb rule of 0.5 ml for 2.0 mg of powder to avoid porosity development on the re-solidified layer of the steel [26, 27]. Finally, the preplacement surfaces with thickness layer of about 0.5-1.5 mm were dried in an electric oven at 70 °C for 1 hr to remove any moisture.

TIG melting of preplaced microalloying element on HSLA steel substrate

The melting of the dry preplaced surfaces was carried out beneath a direct current electrode negative (DCEN) arc of TIG welding machine to produce a series of autogenous weld tracks on the previously prepared substrates. The experimental setup, powder preplacement and welding track development using TIG torch melting process of HSLA steel is shown in Fig. 1.

Table 3 Design matrix and responses for TIG torch processing of HSLA steel without and with microalloying element (Ti, V) addition.

Exp. Run	Parameters			Responses								
	A	B	C									
	Welding current (A)	Welding voltage (V)	Ti or V microalloy element (mg/mm2)	Hardness (Hv0.5)			Impact toughness (J)			Tensile strength (MPa)		
				No alloy	Ti	V	alloy No	Ti	V	alloy No	Ti	V
1	80	30	1	293	246	233	41	58	68	605.05	675.4	669.4
2	90	35	1	264	*234*	202	48	69	72	704.30	611.7	693.2
3	100	40	1	242	226	217	50	77	75	653.00	644.9	688.0
4	80	35	1.5	273	225	225	43	68	72	611.36	685.8	729.8
5	90	40	1.5	250	223	208	47	81	69	641.80	692.9	635.4
6	100	30	1.5	265	202	206	44	78	76	644.06	635.4	714.3
7	80	40	2	259	211	218	40	53	74	611.81	676.8	596.0
8	90	30	2	287	239	213	42	66	68	665.43	686.8	700.3
9	100	35	2	255	250	223	49	63	72	670.79	601.0	699.2

*Fixed parameters (Argon flow rate= 20 l/min and welding travel speed= 1.0 mm/s).

The melt pool for the process was created by striking a metal arc between the tip of a throated tungsten electrode (3.2 mm diameter) and the steel substrate. The arc produced was controlled using an arc gap length maintained at 2 mm while the welding speed was controlled through externally loaded software interface attached to the welding machine. The TIG process was conducted under the streamed argon gas at 20 l/min, which was channeled through electrode gun to prevent oxidation of the molten surface layer during the melting process. The detailed specifications for the TIG melting conditions are provided in Table 4.

Table 4 Details of TIG melting process parameters

Current (A)	80-100 with increment of 10 A
Current frequency (Hz)	20 Hz
Speed (mm/s)	1.0 mm/s
Voltage (V)	30-40 with increment of 5V
Electrode configuration	3.2 mm, W-2%. Th., 60° cone included angle
Arc gap (mm)	2.0 mm
Argon flow rate (ml/min)	20 l/min
Specimen position	Flat
Torch orientation	Vertical
Process	DCEN

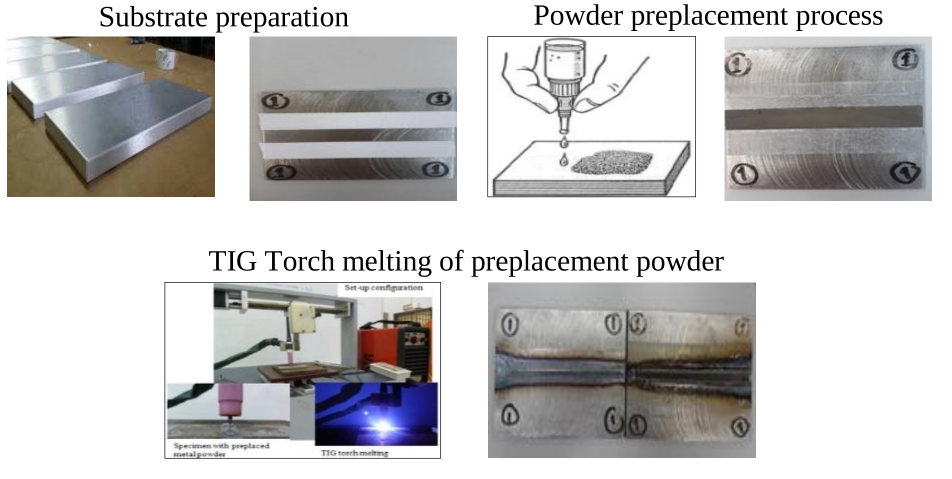

Figure 1: Powder preplacement and welding track Development

The TIG torch welding was carried out using a range of heat input from 1152 to 1920 J/mm and shielded by argon delivered at a rate of 20 l/min.

Heat input, $E= \eta IV/S$ (1)

Eq. 1 was used to calculate the heat input (E), where V and I are the voltage and current, respectively, and s is the scanning speed of the torch in melting a track across the prepositioned powder sample. The symbol η is the efficiency for energy absorbed in the sample and was designated elsewhere [28] as 48%. The process parameters including control factors are provided in Table 4.

The WOLPERT WILSON Vickers microhardness testing machine was used for the material 200 hardness measurement with an indentation load range 500 gf for dwell time of 10 seconds. Hardness profiles were measured both from the beginning and along the depth of the transverse sections of the HAZ. Microhardness measurements taken from the center were performed at a depth of about 300 µm away from the surface region and these were conducted for all the samples under parametric study using L9 Taguchi array.

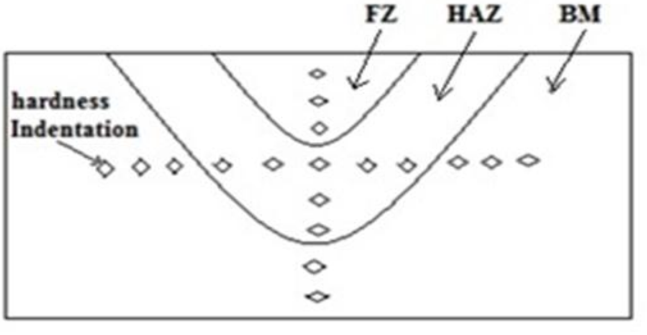

Fig.2: Schematic diagram showing the path of hardness measurements of the weld; FZ: Fusion zone, HAZ: Heat affected zone, BM: Base metal.

The hardness measured for the performance analysis of modified welded HSLA steel after optimization process was conducted across the HAZ at an interval of 200 µm. The microhardness values were the average of five readings taken from the respective interval depth. Fig. 2 shows the hardness indentation track of the welded zones. Samples for impact toughness were cut and prepared from the welding area specifically in HAZ by means of wire cutting machine. Charpy V-notch impact test was performed at room temperature using an INSTRON-SI-1C3 universal pendulum impact tester on the sub-size specimens, shown in Figs. 3 (a), (b), and (c) following ASTM E23-02a guidelines.

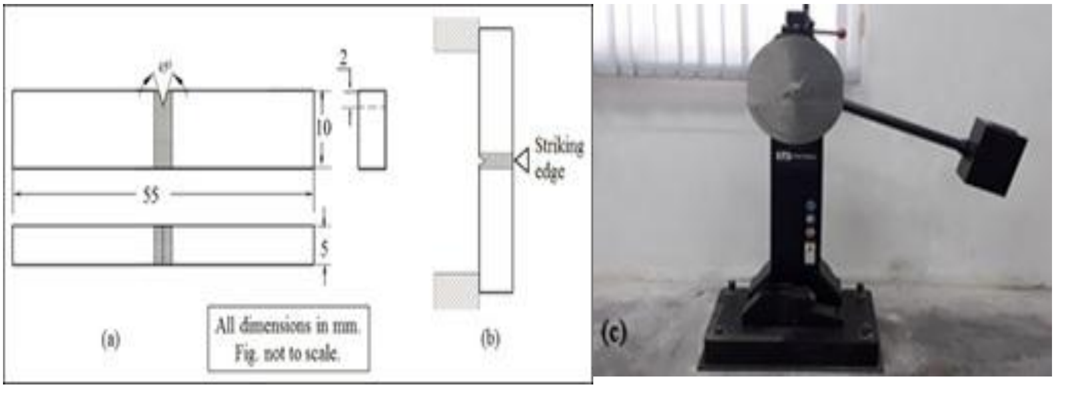

Fig. 3: (a) ASTM E23 proportions of Charpy V-notch specimen, (b) Position of specimen during the test, and (c) Impact testing machine.

The tensile test was conducted on the specimens by pulling transversely to the weld line in accordance with ASTM E8/E8M–11 to determine the tensile strength of the material.

3. Results and discussion

3.1 X-ray diffraction (XRD) analysis on HAZ of HSLA steel

The phase identification of substrate HSLA steel was performed using X-ray diffraction (XRD) technique. Fig. 4(a) shows a typical X-ray diffraction pattern for the un-welded HSLA steel. The diffraction peaks at 45°, 65° and 82.3° corresponded to the alpha(110), alpha(200) and alpha(211) phase respectively, whilst the peaks at 37.5°, 43° and 54.5° indicated the presence of pearlite Fe_3C(112), Fe_3C(121) and Fe_3C(211) phase respectively in the HSLA steel raw material 225 with low intensity. The XRD spectrums of TIG torch welded HSLA steel with Ti and V microalloying addition are shown in Figs. 4(b) and 4(c) respectively. The precipitates of intermetallic compounds formed in the HAZ of welded HSLA steel are identified in the figures, corresponding to TiN, TiC and TiS for Ti microalloying element addition (Fig. 4b) and VN, VC and VS for V addition (Fig. 4c).

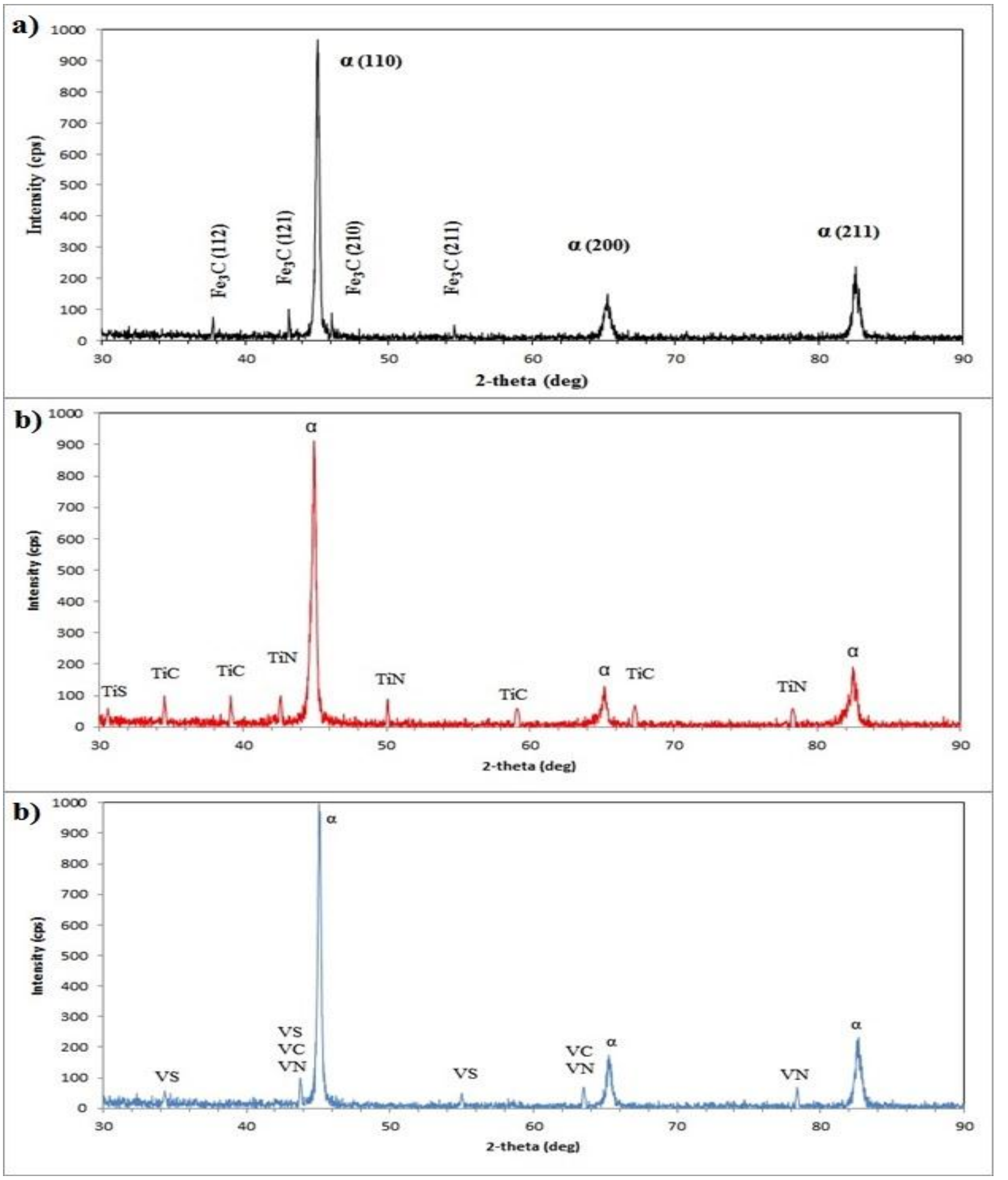

Fig. 4: XRD spectrum of (a) L450 substrate material, (b) TIG torch welded HSLA steel with Ti addition, (c) TIG torch welded HSLA steel with V addition.

3.2 Effect of microalloying elements addition on microstructure

The significant reduction in the HAZ hardness, and enhancement in the tensile strength and the impact toughness of welded HSLA steel is associated with the presence of carbonitride forming microalloying elements Ti and V in the newly formed microstructure which can considerably mitigate the negative influence of welded zones on the mechanical properties and microstructure for HSLA steel. The microstructure of the as-received HSLA steel showed the nature and morphology of the grain structure and distribution of other intrinsic features in the microstructure. Fig. 5 shows the ferrite and pearlite phases that distributed along the diffraction angle within the range of 30° - 90°, see Fig. 4(a)

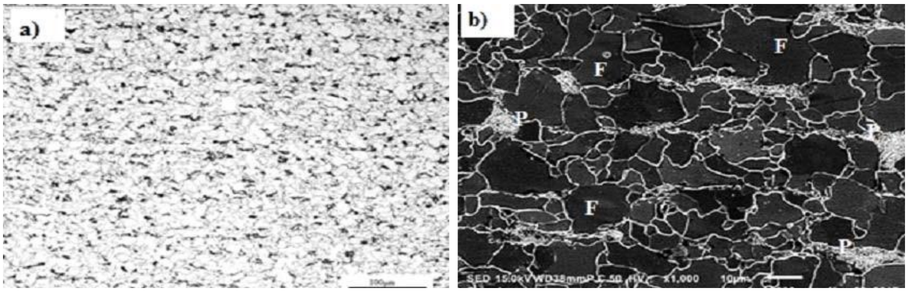

Fig. 5: (a) Optical microstructure and (b) SEM microstructure of HSLA steel L450 substrate material.

The microalloying element, particularly Ti is mainly used to reduce the grain size and to ensure grain refinement because austenite grain growth is retarded by titanium nitride. It is worthy to mention that the best Ti amount for obtaining precipitates should be small enough to accelerate the pinning effect on the austenite grain boundaries as the higher amount of Ti has adverse effect on the formation of coarse precipitates. The developed precipitates are known for higher hardness but make the welded material brittle as reported by [29, 30]. The addition of Ti accelerates the transformation of austenite to ferrite and modifies the morphology of ferrite from Widmanstätten ferrite (WF) to acicular ferrite (A-F). The microstructural evolutions of the HAZ of HSLA steel with 1.0 mg/mm^2 Ti microalloying element addition were characterized via scanning electron microscopy (SEM). Fig. 6 shows the HAZ microstructure of melted HSLA steel with 1152 J/mm heat input. At lower heat input range, the influence of heat input and microalloying element addition on the mechanical properties are both significant, see Figs. 7-9.

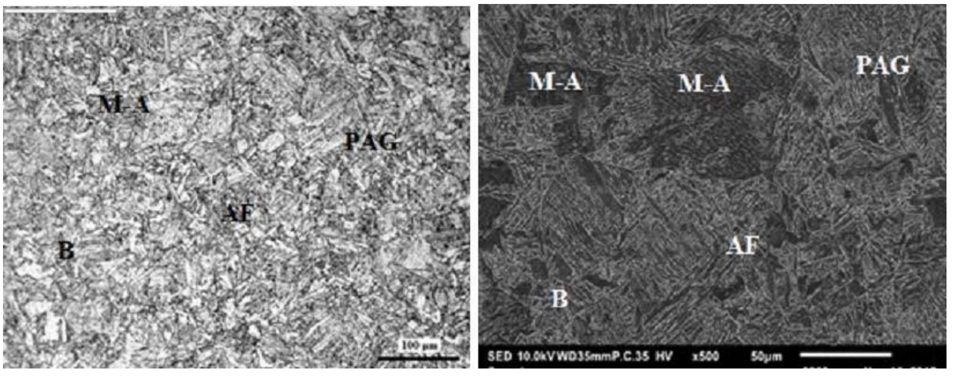

Fig. 6: OM and SEM micrographs of HAZ of welded HSLA steel with 1.0 mg/mm^2 Ti-microalloying element addition.

Different microstructures of HAZ are derived from the different welding thermal cycles and cooling efficiency. The microstructure of original base metal (BM) on HSLA steels shown in Fig. 5 has demonstrated fine grains of ferrite (F) with some pearlite (P). The application of different mode of welding by TIG torch changes the microstructure of HAZ in welded HSLA steel. The microstructure of HAZ of welded HSLA steel with addition of Ti-microalloying element in Fig. 6 mainly consists of bainite with small fractions of A-F and M-A microconstituents phases. However, the austenite grains are resembled as smaller without any typical columnar shape.

Similar microstructures are reported by [15, 31, and 32]. In this study, the addition of Ti reduced the prior austenite grain size in the HAZ due to the existence of high-volume fraction of TiC and TiN inclusions or intermetallic compound which retarded the austenite grain growth during the welding process. Ti microalloying element acts as nucleation sites for the solidification of the melt pool and the subsequent growth is pinned at the grain boundary. The welded HSLA steel by TIG torch welding technique with the addition of different amounts of titanium to the melt altered the microstructural constituents of HAZ, and different ferrite phases formed including acicular ferrite and Widmanstätten ferrite phases aligned along with the bainitic microstructure and finally enhanced the grain refinement of the morphology. This morphological characteristic contributes to the improvement of mechanical properties of TIG welded HSLA steel.

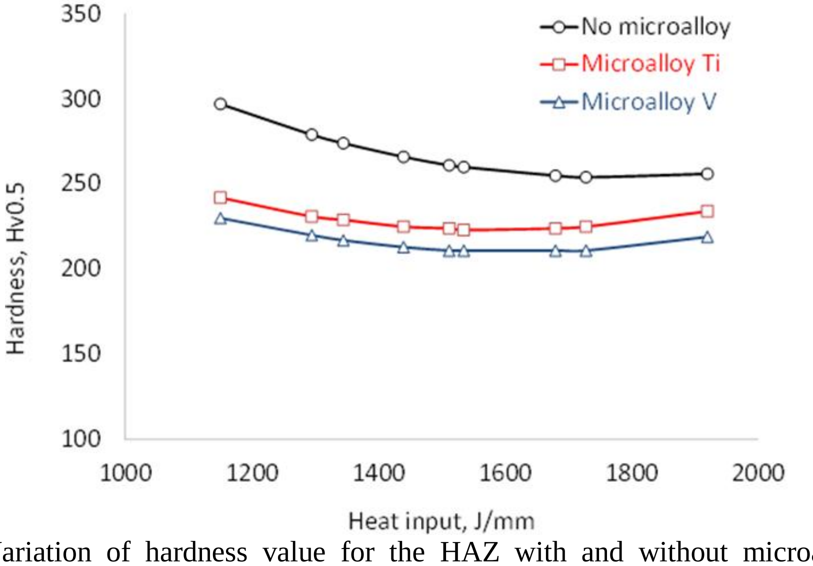

Fig.7: Variation of hardness value for the HAZ with and without microalloying element addition.

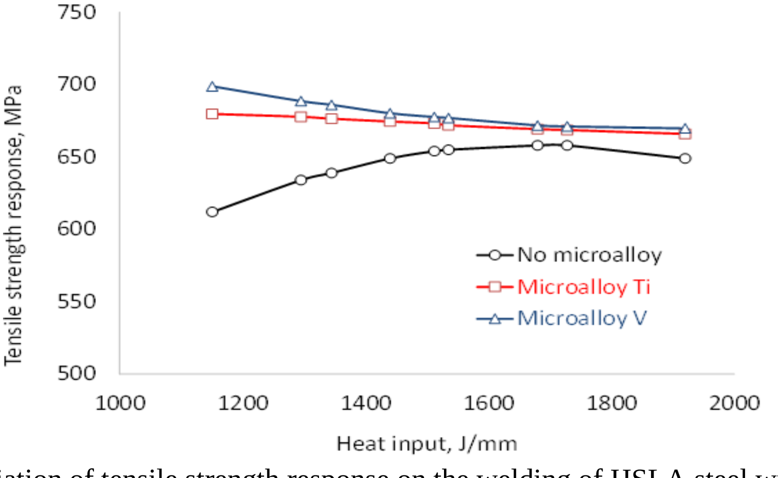

Fig. 8: Variation of tensile strength response on the welding of HSLA steel with and without microalloying element addition.

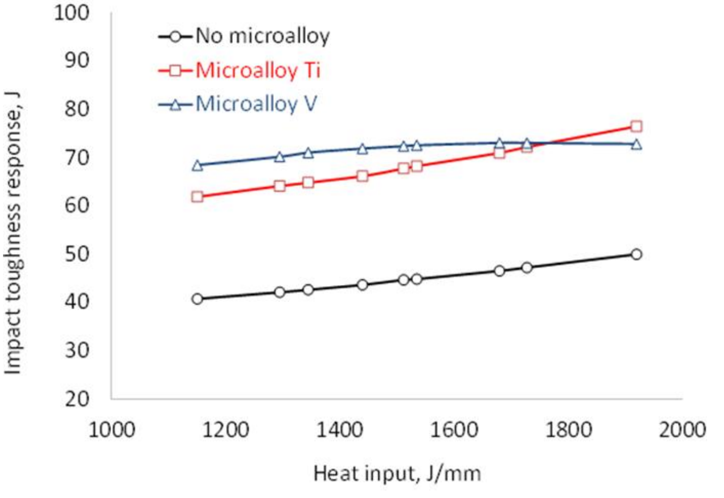

Fig. 9: Variation of impact toughness value on the HAZ with and without microalloying element addition.

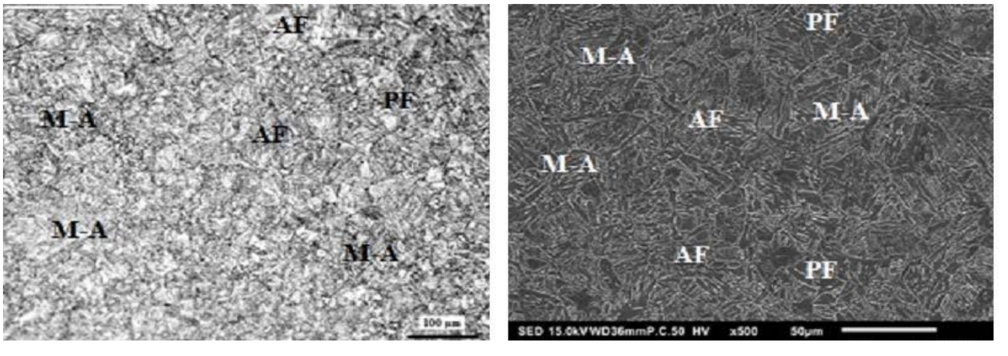

Fig. 10: OM and SEM micrographs of HAZ of welded HSLA steel with 1.0 mg/mm2 V-microalloying element addition.

According to literature, the solubility of vanadium in austenite is higher than the other microalloy to form carbide and nitride phase after resolidification of the molten metal. Vanadium carbide, nitride, and carbonitride precipitates have the strong pinning effect on the austenite grain boundaries and on the transformation a fine ferrite grain structure development as well. In the same note, it is believed that small amount of vanadium in structural steels produce a significant refinement in the final ferrite microstructure, through both enhancements of the nucleation of grain boundary ferrite and by intragranular nucleation of ferrite [25, 26]. Fig. 10 shows the HAZ microstructure of melted HSLA steel with 1152 J/mm heat input. It presents the HAZ microstructure of welded HSLA steel with addition of V-microalloying element, mainly consisting of grain boundary polygonal ferrite, with small fractions of A-F and M-A constituents located along the austenite grain boundaries and polygonal ferrite (PF) grain boundaries. However, M-A constituent was also observed along the bainitic-ferrite lath boundaries, which were a common feature in the high strength low alloy steel. This might have a negative effect on the property of the weld since M-A constituents are still present in microstructure and generally reduce HAZ property particularly the toughness and ductility. This finding is similar to the findings reported elsewhere [27, 28].

3.3 Effect of microalloying element addition on mechanical properties

In this section, results are presented on the hardness, tensile strength, and the impact toughness of HAZ of welded HSLA steel without and with the addition of different microalloying elements under different heat inputs as shown in Figs. 7-9. Fig. 7 shows the hardness variation for the HAZ with and without micro-alloying element addition to the welded HSLA steel for different energy input during welding. The HAZ hardness characterization results of welded HSLA steel without microalloying elements revealed that the hardness gradually decreased on increasing the energy input. The addition of alloying elements also affected the hardness. The reduction of hardness values in the HAZ was approximately 15% for the welded samples with titanium microalloying element addition compared to the welding samples without any additive, while the decrease of HAZ hardness when the vanadium microalloying element was added was approximately 19% compared to the welding samples without microalloying element addition. For all three cases the hardness generally decreased with increasing energy input and was essentially insensitive beyond the energy input of approximately 1680 J/mm. Fig. 8 shows the variation of tensile strength response of the welded HSLA steel with and without micro-alloying element addition for different welding energy inputs.

The tensile strength results of the welded HSLA steel without microalloying elements showed that the ultimate tensile strength increased gradually on increasing the heat input followed by a slight decrease at a higher energy input while there is a remarkable increase in the tensile strength values for all welded HSLA steel samples with the additions of both titanium and vanadium micro-alloying elements compared with welded HSLA steel without microalloying elements. However, there is slight decrease in tensile strength with increasing heat input for both Ti and V additions samples. The reduction in the tensile strength with increasing energy input is assumed to be due to the increased dilution associated with higher energy input which induces dissolution of the grain pinning precipitates resulting in grain coarsening. This trend agrees with the welding metallurgy principle which states that higher heat input results in lowering of mechanical property of weld section [28]. The improvement of ultimate tensile strength values was ≈4% for welded samples with Ti additive, while the increase in ultimate tensile strength was ≈5% for welded samples with V additive, compared with the welding samples without any addition of microalloying element. Fig. 9 shows the variation of impact toughness value in the HAZ with and without microalloying element addition of welded HSLA steel for different welding heat inputs.

The impact toughness trend of HAZ of welded HSLA steel without microalloying elements and welded HSLA steel samples with the additions of titanium increased gradually on increasing the energy input while there is a marginal increase in the impact toughness values for HAZ of welded HSLA steel with vanadium addition, particularly for heat input above 1510 J/mm. A noticeable improvement in the impact toughness after the additions of titanium and vanadium microalloying elements was obtained compared to the impact toughness of HAZ for welded HSLA steel without microalloying elements during welding processes. The average increment of impact toughness values in the HAZ was ≈30% for welded samples with titanium microalloying element addition while the average improvement of HAZ impact toughness with the vanadium microalloying element addition was approximately 37% compared with the welding samples without the addition of microalloying elements. However, the variation in the impact toughness values with increasing energy input between vanadium and titanium additions was slightly up to approximately 5%.

3.4 Comparison of Ti and V microalloying elements on structure and mechanical performance

Table 5 summarizes a comparison of mechanical performance parameter for Ti-added and V-added HSLA steels after TIG torch melting process whereas, Fig. 11 shows the percentage improvement in hardness, tensile strength, and impact toughness for the same microalloying element additions. The formation of small TiC and TiN particles in the microstructure of high-strength low alloy steel weld metal has been reported by [29] which can be of great strengthening effect and contributes to the improvement of mechanical properties of the current HSLA steel in this investigation. TiS phases significantly influence both the texture and the mechanical properties of HSLA steel. It has been suggested that this compound has an adverse effect on the fracture of welded steels [30]. The formation of these phases (TiN and TiC) plays an important role in the new microstructure development (acicular ferrite) in the nucleation sites for the improvement of mechanical properties. Moreover, titanium carbide and titanium nitride inclusions retard austenite grain growth. The polygonal ferrite also formed during subsequent transformation of austenite to ferrite along the austenite grain boundaries. Consequently, the precipitation of carbides or carbonitrides during cooling cycle of weld pool can prevent the grain growth of austenite. This can be beneficial for refining grains in HAZ and leads to better mechanical properties of welded micro-alloyed high strength steels [30-32]. In one study, it is mentioned that the addition of small amount of Ti revealed an improvement in the high-temperature strength of tantalum alloy [33].

Table 5: Comparison of improved performance properties due to microalloying additions

Performance properties	Hardness, %			Strength, %			Impact toughness, %		
Heat input, J/mm	Ti	V	V - Ti	Ti	V	V - Ti	Ti	V	V - Ti
1152	19	23	4	11	14	3	52	68	16
1295	17	21	4	7	9	2	52	67	14
1345	16	21	4	6	7	1	52	67	15
1440	15	20	5	4	5	1	52	65	13
1512	14	19	5	3	4	1	52	62	10
1535	14	19	5	3	3	1	52	62	10
1680	12	17	5	2	2	0	52	57	4
1728	11	17	6	2	2	0	53	55	2
1920	9	14	6	3	3	1	53	46	-7

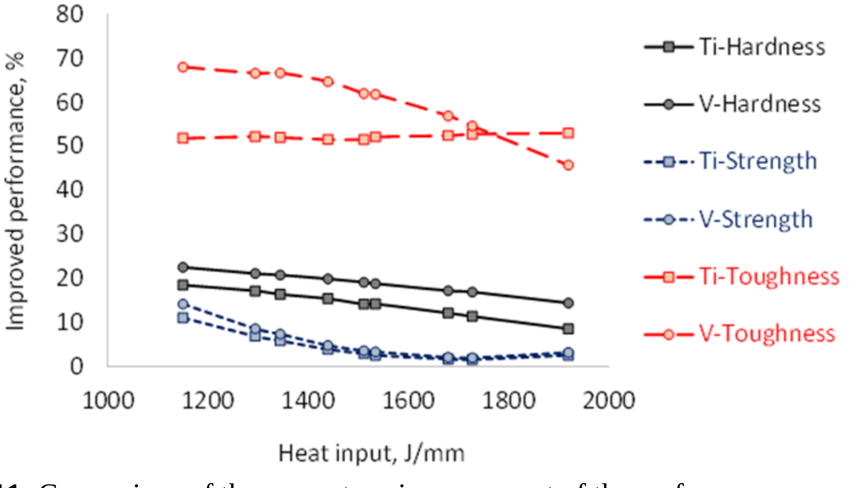

Fig. 11: Comparison of the percentage improvement of the performance properties due to addition of Ti and V microalloying elements.

Vanadium carbide, nitride, and carbonitride particles are known to pin austenite grain boundaries, and on transformation, form a fine ferrite grain structure. There is strong evidence to show that small quantities of vanadium in HSLA steels produce a significant refinement in the final ferrite microstructure (as shown in Fig. 10) through both enhancements of the nucleation of grain boundary ferrite and by intragranular nucleation of ferrite. The presence of vanadium carbide and vanadium nitride enhanced the mechanical properties of welded HSLA steels [33, 34-38]. The XRD results, Fig. 4 demonstrated the characterization of the TIG torch melted microalloying elements (Ti and V) and revealed the existence of new phases in HAZ of HSLA steel containing the intermetallic compound of TiC, TiN, TiS, VC, and VN. The peaks have different concentrations at different angles of the XRD profile which depends on the microalloying element quantities and heat inputs of welding processes [39]. These intermetallic compounds play important roles in the morphology of microstructures and the mechanical properties of HAZ of welded HSLA steel.

In Table 5, mechanical properties performance for Ti-added and V-added HSLA steels after TIG torch melting process are notable which was produced from different heat input of the welding. The addition of both the titanium and the vanadium microalloying elements improved the overall performance properties with a subsequent reduction in hardness and increase in strength and impact toughness. In particular, the microalloying element vanadium demonstrated a greater influence on improving the performance properties. This is illustrated by the difference between V and Ti additions, i.e., “V-Ti” column in Table 5. Compared to titanium the addition of vanadium improved the hardness, the strength, and the toughness by 4%, 3% and 16% respectively corresponding to low heat input of 1152 J/mm. From Fig. 11, the percentage improvement in hardness, tensile strength and impact toughness for Ti and V microalloying element addition is significant. However, the improvement is more prominent at lower heat input and gradually decreases with the increasing heat input. The addition of Ti and V resulted in the improvement of the mechanical performance illustrated by positive values. Overall, the addition of V resulted in a higher performance compared to Ti. The difference in performance between V and Ti is plotted in Fig. 12 which clearly shows the higher performance due to V over Ti. Apart for the toughness at high heat input corresponding to 1920 J/mm all the points in the graphs are in the positive range.

It was demonstrated that different microstructures were formed with these two microalloying elements, which finally enhanced the grain refinement of the morphology. The morphological characteristic contributes to the improvement of mechanical properties of TIG welded HSLA steel.

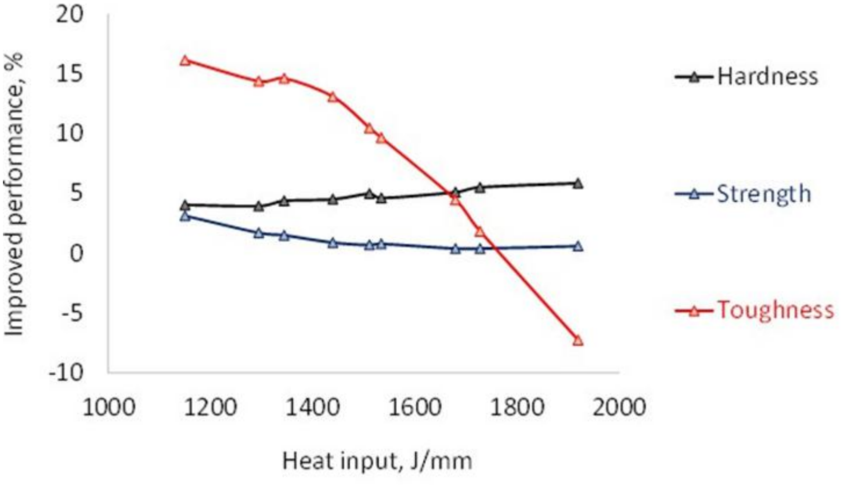

Fig. 12: Percentage difference between the improved performances due to the V microalloying element addition over Ti microalloying element.

4. Conclusions

The present study characterized the microstructure and mechanical properties of HAZ for welded HSLA steel aiming to optimize the microstructure-mechanical property relationship with the addition of Ti and V microalloying elements using TIG torch melting technique. The characteristics of the heat-affected zone (HAZ) were enhanced with a combination of lower hardness, higher strength, and improved impact toughness through the additions of microalloying elements compared to conventional welding without elements. Analysis of results showed that Ti and V microalloying elements significantly influence the HAZ hardness, impact toughness and the tensile strength of TIG torch melted HSLA steel. A maximum ultimate tensile strength of 692.85 MPa and 729.80 MPa was achieved with Ti and V addition respectively. The reduction in HAZ hardness values of welding samples with the addition of Ti and V addition was approximately 15% and 19% respectively, relative to the welding samples without any microalloying additions. The decrease in HAZ hardness after welding region can reduce the risk of brittle fracture of the welded component.

The average increase in the impact toughness values of the HAZ was approximately 30% for the welded samples with Ti and 37% for welding samples with V compared to the welding samples without the addition of microalloying elements. However, the variation in the impact toughness values with increasing heat input between vanadium and titanium additions was slightly higher, approximately 5%. The overall positive outcome on the mechanical properties of HAZ supports the use of the present technique and encourages further development of a new advanced and sustainable HSLA steel material for a variety of engineering applications.

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