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MICROSTRUCTURE VARIATION EFFECTS INFLUENCE ON CHARACTERISTICS AND MECHANICAL PROPERTIES OF MONEL 400 AND LOW ALLOY STEEL (ASTM 387-Gr.11) GTAW DISSIMILAR JOINT

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Monel 400 with low alloy steel dissimilar joints are widely used in oil industry, petrochemical and nuclear engineering, this kind of applications needs welding joints with good mechanical properties, stable magnetic permeability and good weldability. Difference in mechanical, chemical and physical properties between these unique alloys makes such joint difficult and joints mechanical properties and microstructure will be different from parent metals. In this study, GTAW process has been employed with ERNiCrFe-3 electrode to produce dissimilar welding joints with specifies welding procedure parameters, SEM/EDS microstructure analysis, microstructure optical test, Vickers microhardness and tensile test used to study microstructure details and its impacts on welding joint mechanical properties. Research results according to welding zone microstructure analyses shown formation of Widmanstatten ferrite structures and second phase particles with fine graine structure in low alloy steel side the formation of transion zone (TZ). Moreover, clearly fusion line (FL) clearly marked in Monel 400 side while weld metal solidification microstructure with (MGBs) and (SGBs) respectively and interdendritic microstructure observed in weld zone center. Weldment mechanical and microstructure examination indicated the ability to produce like this dissimilar joint with requirement of design criteria and indicated that the failure in like this joint excepted to be in low alloy steel side. The result and microstructure analyses of this research is very important to understanding the variation in welding zone and HAZ microstructure and its impact in weldment mechanical properties and establish the base to produced best welding procedure according to welding zone microstructure properties

Keywords: dissimilar weldments, carbon depleted zone, Transition zone, Monel 400, migrated grain boundary

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1. Introduction

Dissimilar weldments joints are very important in many applications, like oil industry, aerospace industry, petrochemical, military and high critical nuclear industries, many previous research deals with Monel 400 dissimilar welding joints with stainless steel or low carbon and low alloy steel but almost no previous research work studied the dissimilar joint between Monel 400 and ASTM 387-Gr.11 low alloy steel grid, this joint is very important in oil industry but unfortunately there is very little research paper in this field, abilities of Monel 400 to low alloy steel dissimilar welding joints in provided and satisfactory critical design requirements such as corrosion resistance, high temperature resistance and magnetic characteristic. Also, the high reduction in production and materials cost could be gained from these weldments' joints, same time design requirements go in dissimilar weldment joints direction to satisfy these requirements, one of the most important aims of this research work is studying characteristics of these joints and variation in microstructure from HAZ to welding zone. These complex variations will control and deeply affected welding zone mechanical properties and microstructures, and this variation could be very large in mechanical, physical and microstructure. Deeply analyses to welding zone and HAZ microstructures done to understand the filler metal chemical composition effects on final welding zone microstructure and study its impact in weldments mechanical properties and weldments fitting to design criteria. The difficulty in Monel 400 to low alloy steel dissimilar weldments joints is needed to predicate the produced microstructure and its effects on mechanical and physical properties of welding joint as well as it's fit with design criteria and requirements, which make that more difficult is the contribution of filler metal in joint composition and this is the situation in this work. In this study, the dissimilar fusion welding joint between (AISI Monel 400) nickel alloy and (ASTM 387-Gr.11 steel) low alloy steel plate type prepared to simulate joint design in oil industry equipment and applications such as oil gasification plants. Oil industry plants produced high levels of hydrogen and sulfur oxides, which forced the equipment to service under high corrosive environment, and the welding joints in like this equipment must satisfy the design corrosion resistance criteria. Therefore, the research in this field in very important to welding procedure specialist, welding engineering and manufacturing companies which deals with like these dissimilar joints in different industry sectors such oil industries to understand resultant welding microstructure and prediction weldment serviceability in structures.

2. Literature review and problem statement

The most important issue in Monel 400 and ASTM 387-Gr.11 steel dissimilar fusion welding is welding zone microstructure dilution with molten filler metal and the final microstructure resulted from this dilution, to estimate this issue and found out how solve it, research paper [1], shown large evolutions in welding zones and HAZ microstructural must be done, but the paper results did not discuss the SEM and EDS results of welding zone deeply or explain the texture. This paper results deeply analyzed these effects and marked its impacts on final welding zone properties. Results in research paper [2] reveals the realestillun resolved questions in this research related to migration of carbon to welding zone from parent metal and fusion line creation phenomena and all microstructural solidification phenomena's, which caused huge variation in structural, chemical composition, mechanical and physical characteristics of (Monel 400) nickel base alloys in comparison with low alloy steels in welding joints zone but it's not explain what cause or the source of this phenomena and its relation to welding results. Transition zone (TZ) formation shown in paper [3], is one of most important phenomena which marked in HAZ, but the results in paper [3] did not illustrated the effects of this zone formation on failure location and mechanism when weldments undergo over stress. This point deeply discussed in this research duo to its important. Results revels with paper [4] shown migrated grain boundaries (MGB) formation in welding zone microstructure which had major effect on welding zone properties without highlight its effects on dislocations movement hindering. Both these important structures observed and marked in welding zone and HAZ microstructure in presents study and deeply studding and analyzing to understanding its impact on final weldments fit with design criteria. Papers [5, 6] studying unmixed zone (UZ) formation due to welding zone elements segregation between it and HAZ with lacking in explain its effect on failure mechanism. EDS Analyzing in this zone in presents paper employed to understanding unmixed zone impacts in weldments failure mechanism. Corresponding researches in paper [7] analyzing hydrogen induced cracking (HIC) and evidence about its formation and how starting but didn't explain how welding filler can eliminated it, this is the approach used in this study to investigated HIC formation in welding zone microstructure and study the effects of resulted microstructure on its formation and its progresses. All these phenomena reflected the high possibility of metallurgical structure problems and the important to understanding the welding zone and HAZ microstructure formation criteria. Last years, cladding and joining processes of unmatched structures metals had large focusing and interesting in these phenomena. Most of previous works [8] achieved weldments with sound appearance by using filler metals with nickel base, and results with superior mechanical properties can be obtained with proper fillers with Mo addition, the uniqueness of this study was in welding with low Mo filler like ERNiCrFe-3 filler and produced soundness joint. Paper [9] shows that dissimilar metals welding usually resultant in many of microstructural assessments and effected metallurgical issues appearing in particular at welding zone interface, but in a lot of cases, these difficulties in joining processes are preferred because of operating condition criteria, technical requirements, or economic considerations like the distinguish joint in the present study between these important alloys. The approach used in [10] reveals the reducing size, extent of design, manufacturing technical and economic problems to a minimum was main objective driving to employ dissimilar metals welding DMWs. GTAW process was used in the present research for this goal. Filler metal effects on mechanical properties and microstructures of DMWs of Monel 400 alloy and A387-Gr.11 low alloy steel have been studied

Related literature revealed that a very limited number of studies has been reported on Monel 400 alloy and A387-Gr.11 steel dissimilar welding joint. Therefore, investigation of mechanical properties and microstructural features is the main objective of this research study.

3. The aim and objectives of the study

The aim of the study is illustrated the alteration in welding zone and base metals microstructures and highlight its impacts on dissimilar joints of Monel 400 and low alloy steel (ASTM 387-Gr.11) characteristics and mechanical properties using GTAW process.

To achieve the aim, the following objectives are accomplished:

– to analyze Monel 400 HAZ and A387-Gr.11 low alloy steel HAZ microstructural features;

– to investigate A387-Gr.11 and Monel 400 HAZ carbon migration phenomena;

– to examine the Transition zone of A387-Gr.11 and Monel 400 dissimilar welding;

– to explain the Microstructures of weld metal and unmixed zone;

– to show weldment mechanical properties.

4. Material and methods

Samples of rolled Monel 400 alloy with solution annealed conditions and tempered A387-Gr.11 ferritic low alloy steel with same conditions and 10 mm thickness were prepared. Filler metals ERFeNiCr-3 with 2.4 mm diameter were used. Chemical compositions of filler and base metals are listed in Table 1.

Parent metal samples were cut and finished to 100×50×4 mm dimensions. The samples were placed in butt joint configuration with 2 mm opining between them. The welding procedure includes two passes by the GTAW implying direct current type with negative electrode (DCEN) polarity and commercially pure argon as protection gas. Process parameters were established from the earlier studies and try and error experiments. Final parameters are listed in Table 2. After the welding done, wire cut process EDM (Electrical Discharge Machining) was used to cut the samples to the required dimensions for metallurgical and mechanical investigations tests. Parent metal, (HAZ) heat affected zone, and weld metals transverse cross section samples were prepared for metallography examinations. Normal technique to metallographic sample preparation was applied to all specimens, including SiC papers grinding with different grits, followed by diamond paste polishing with 1 µm size. Etching process was used to the all specimens for microstructures testing. Marbel and then Nital (etchant) were employed for low carbon steel specimens and then for nickel base specimens. (OM) optical microscope was used to examine the samples. (SEM) scanning electron microscopy with x-ray energy-dispersive spectroscopy (EDS) analyzer was employed to microstructural evaluation. Vickers micro-hardness techniques was used to measure the micro-hardness across the weld metals with a test load of 100 g tester.

Table 1

Base and GTAW filler metal chemical analyses

Composition (Wt%)	Base metal		Filler metal
	Monel 400	A387 Gr.11	ERNiCrFe-3
C	0.13	0.13	0.053
Si	0.38	0.61	0.8
Mn	1.11	0.54	5.8
Cu	Bal.	–	0.53
Cr	–	1.20	20
Co	–	–	0.12
Ni	64.86	–	61.8
Fe	2.24	Bal.	11.2
Mo	–	0.5	0.68
S	–	–	0.018
P	–	–	0.03
Al	–	–	0.78
Nb	–	–	1.5

Table 2

GTAW process parameters

Welding techniques	Voltage, volt	Current, Amp	Shielding gas flow rate, lpm	No. of passes	Filler wire Dia, mm
GTAW (filler)	10	130	15	2	2.4

Nominal strain rate of 2 mm/min to all the tensile testing specimens was performed by using tensile testing machine. Schematic drawing showing tensile test samples location depicted in Fig. 1.

From the length perpendicular to welding direction three transverse tensile specimens were prepared and then tested according to ASTM E370 standard at the room temperature.

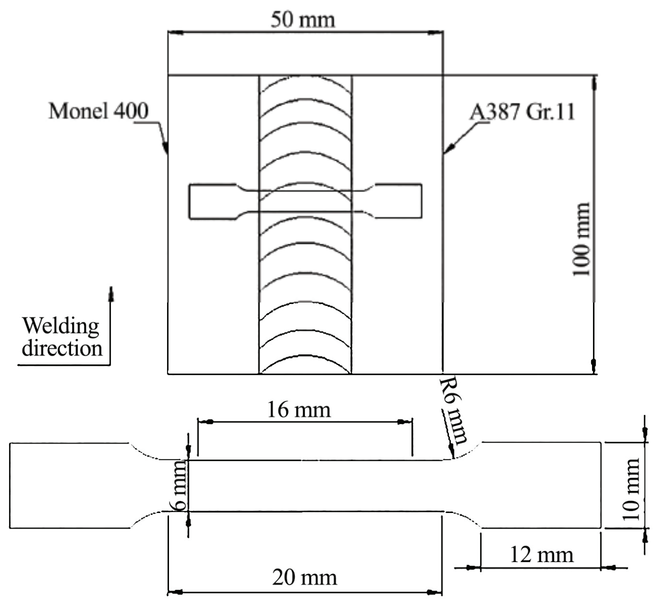


Fig. 1. Illustrated geometry of tensile test specimens

5. Results of the comparison of characteristics and mechanical properties of dissimilar joints for Monel 400

5. 1. Monel 400 and A387-Gr.11 low alloy steel Heat Affected Zone HAZ microstructural features

Optical micrographs tests obtained from Monel 400 nickel alloy are shown in Fig. 2, *a*, *b*. Single phase solid solution nickel-copper enriched structures with annealed grain boundaries were identified in the microstructure, also fully austenitic matrix of base metal microstructure with a normal grain size far from HAZ can be observed. HAZ microstructure show enlarging grain size due to welding heat effects.

Table 3 displays the EDs analysis of two carbide points. The source of Mo, Cr, and carbon was the element migration process from its high constraint zone in ERNiCrFe-3 weld metal to HAZ direction.

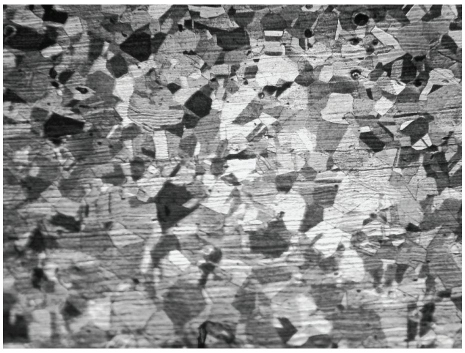
Table 3

EDS Chemical composition of the base metals (Wt.%)

Element Wt. % / Point No.	Cr	C	Ni	Mo	Cu
1	31.71	7.19	34.35	3.44	23.31
2	44.34	6.86	31.89	2.87	14.04

Which will receive the required carbon to form the carbides from the carbon depleting phenomena from the HAZ to the welding zone. The microstructure of A387-Gr.11 low alloy steel Heat Affected Zone (HAZ) in as received condition is shown in Fig. 3. This micrograph manifests three different distinct sizes of grain size, fine grains, big or coarse size grains, and partially refined grains zone [10, 11]. Location for each previous zones marked A, B, and C for fine, coarse size, and partially refined grains, respectively (Fig. 4, *a*).

The coarse grains of austenite were transformed to low carbon bainite/martensite or Widmanstatten ferrite structures when cooling from welding temperature with a relatively high cooling rate (Fig. 4, *b*). When temperature is much lower just above Ac3, fine grain size zone formed (Fig. 4, *a*) just next to the coarse grain size zone. The austenite grain growth at this temperature was noticed to be limited at these conditions. When cooling process continues from welding temperature, extremely fine size pearlite and ferrite grains will produce (Fig. 4, *c*). This temperature range, are not high enough to transfer all initial pearlite and ferrite to austenite. For this reason, this zone exhibited partially austenite formation. When cooling process continues in structure, the austenite transformed into fine size pearlite and ferrite at low temperature (Fig. 4, *d*).



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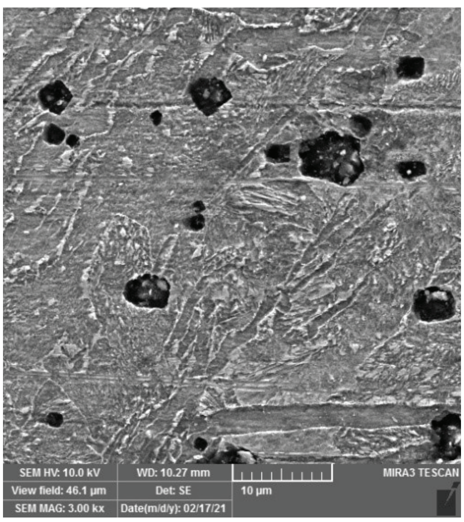

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Fig. 2. Optical micrographs tests: *a* — As-received Monel 400 alloy microstructure; *b* — Scanning electron microscopy and Energy Dispersive Spectroscopy of inter-granular precipitates near the fusion line

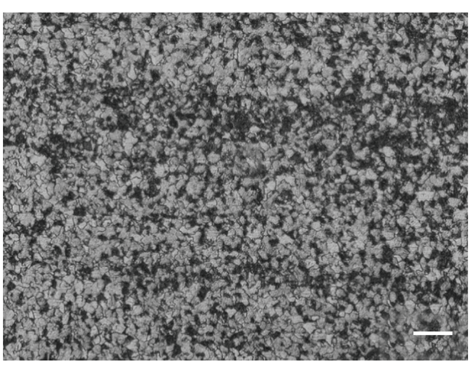
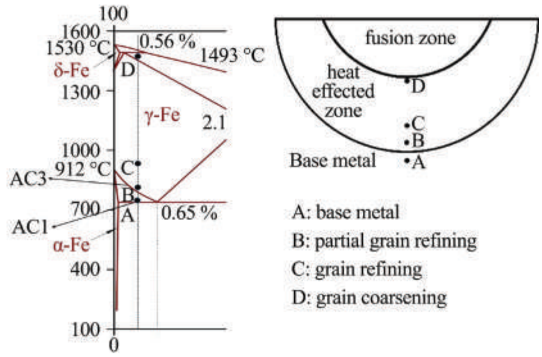


Fig. 3. A387-Gr.11 low alloy steel parent metal microstructure in as received condition



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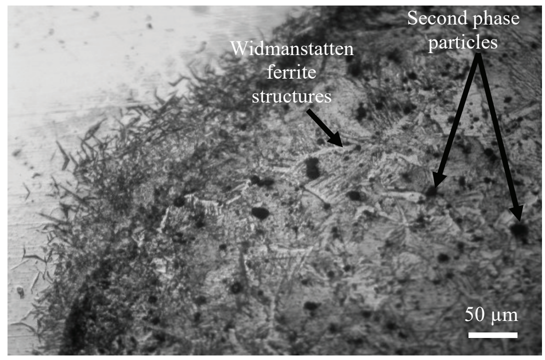

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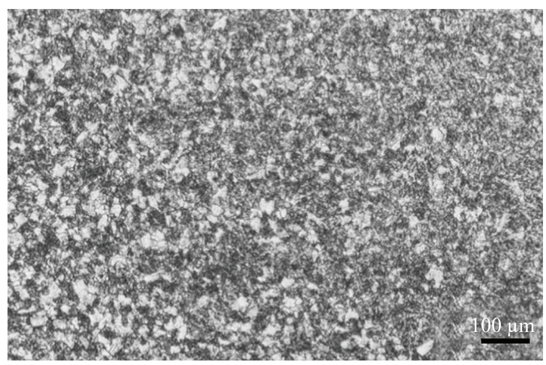

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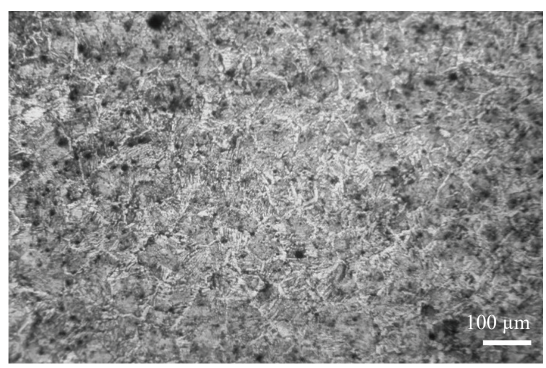

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Fig. 4. (A387-Gr.11) Heat Affected Zone HAZ microstructure (welded by ERNiCrFe-3 filler): *a* – HAZ regions schematic drawing view its locations [12]; *b* – HAZ with coarse grains size and Widmanstatten ferrite structures just near the fusion line (location D in Fig. 4, *a*); *c* – HAZ fine grains size microstructure (location C in Fig. 4, *a*); *d* – partially refined grains size (HAZ) (location B in Fig. 4, *a*)

Finally, the formation of grains just next to parent metal will be a microstructure with partially refined size grains structure, this microstructure will expose to heating range between (Ac1 and Ac3) which represent the lower critical temperature and upper critical temperature range.

5. 2. A387-Gr.11 and Monel 400 HAZ carbon migration phenomena

A387-Gr.11 parent metal chemical analysis in Table 1 display a high carbon percentage and low chromium percentage comparing with weld metals and Monel 400 nickel base alloy parent metal. This high percentage will cause carbon diffusion or migration phenomena to take place from the high percentage A387-Gr.11 HAZ towards the low carbon weld metal zone. And at the same time, diffusion or migration phenomena will happen from high percentage chromium zone in weld metals to low chromium percentage in A387-Gr.11 HAZ [13, 14]. Microstructure in low alloy steel side in Fig. 5, *a* illustrated clearly carbon diffusion zone (CDZ) and same zone can indicated in Fig. 5, *b* in Monel 400 side.

The amount of carbon migration across the HAZ will be affected be Ni content. As a result, it can be observed that the HAZ microstructure with coarse grain is a direct result of carbon migration phenomenon and by sequence, the CDZ carbon constraint, which effects the resultant phases also.

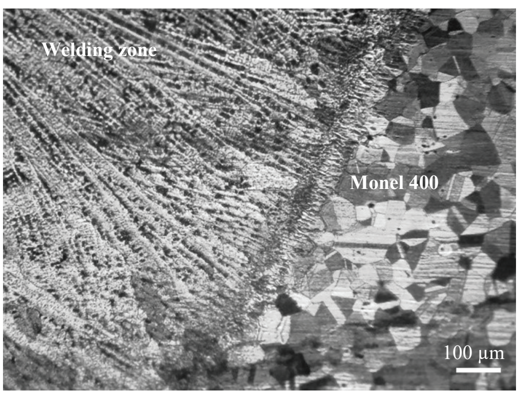

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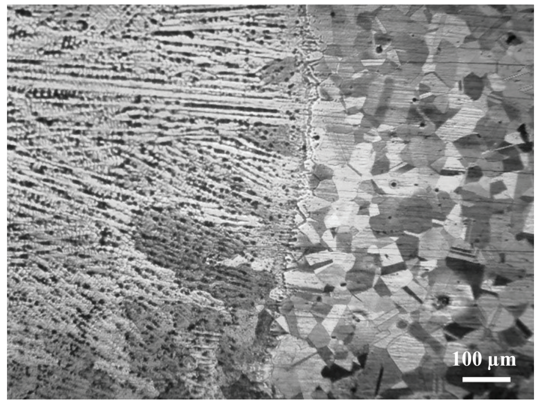
Fig. 5. Carbon diffusion zone (CDZ) in parent metal Heat Affected Zone (HAZ): *a* – CDZ in A387-Gr.11 low alloy steel HAZ; *b* – CDZ in Monel 400 alloy HAZ

5. 3. Transition zone of A387-Gr.11 and Monel 400 dissimilar welding

Transition zone (TZ) in dissimilar metals welding appears like narrow zone observed sometimes close to fusion line in weld metal, and can be defined as the zone bounded by undiluted weld metal and the fusion line. Fig. 6, *a, b* reveal transition zone formation in both low alloy steel and Monel 400 side but with great differences in composition between low alloy steel base metal TZ and weld metals compositions. Variety in transition zone (TZ) width depends on a group of variables [2] including chemical composition and Ni, Fe, Cr, C, elements contents.

According to the results that obtained from (Fig. 5, 6), it can be determined that the soft and hard zones will produce due to the carbon migration which takes place towards the weld metals from the steel base metal.



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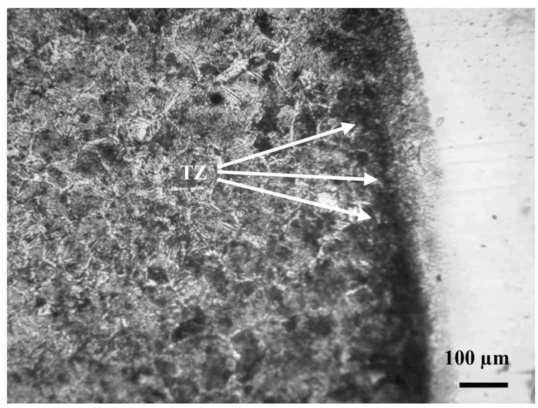

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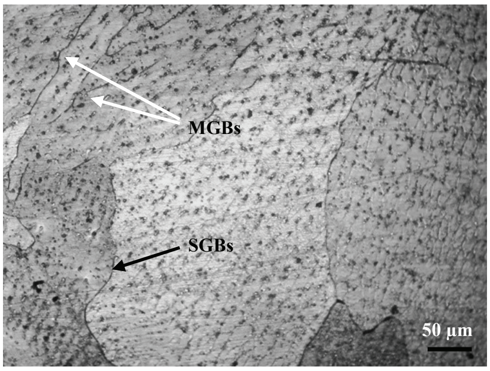
Fig. 6. interface microstructure between:
a – A387-Gr.11 parent metal and weld metals;
b – Monel 400 base metal and weld metals

5. 4. Microstructures of weld metal and unmixed zone

Weld metal microstructure produced with ERNiCrFe-3 filler is shown in Fig. 7, *a–d*, respective chemical analysis of welding zone is given in Table 4, ERNiCrFe-3 weld metal microstructure shown in Fig. 7, *a* near the fusion line contains about 2 wt.% niobium (Nb) and about 57 wt.% Ni, with fully austenitic microstructure.

The Nb presence in this microstructure would stabilize the austenite phase at high temperature and influence in changing the solidification microstructure to starting segregation process ended with inter-dendritic zones and carbides forming. The formation of the unmixed zone (UZ) is a distinguish phenomenon that can be observed in the dissimilar welding process (DWMs) at the fusion boundary. The UZ phenomenon exists when the fusion line between base metal and molten filler metal weld melts and then re-solidifies without a proper or required mixing or dilution. In this experimental study, (Fig. 8, *a*) elucidates the UZ formation between Monel

400 base metal alloy and filler metals. UZ formation was not observed in A387-Gr.11 low alloy steel side as in (Fig. 8, *b*).



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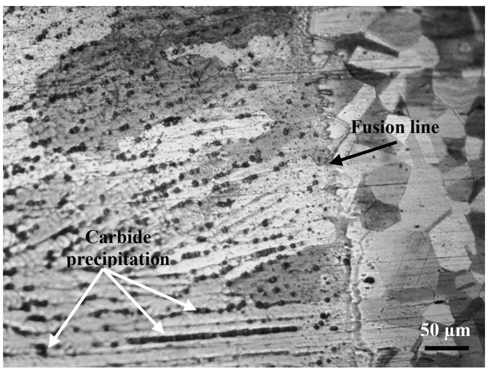

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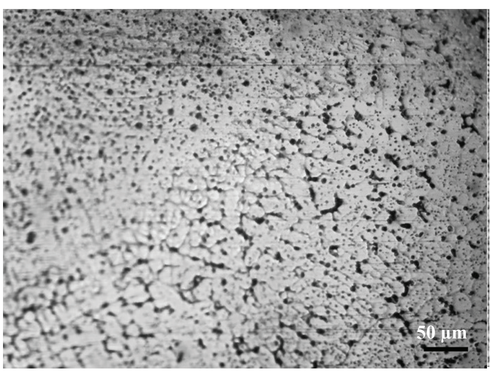

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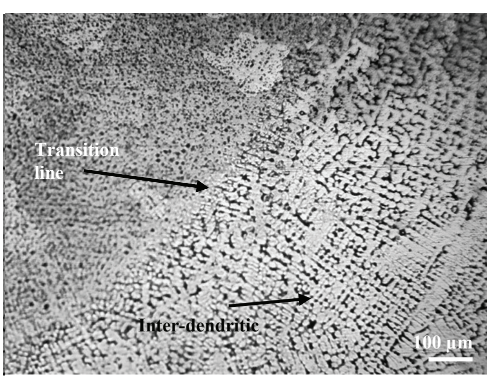

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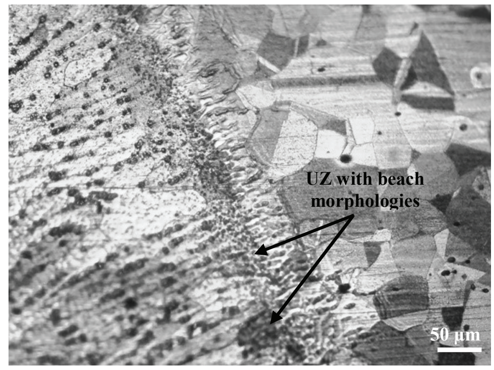
Fig. 7. Weld metal microstructure of: *a* – ERNiCrFe-3 weld metal near the fusion line; *b* – Weld metal solidification with (MGBs) and (SGBs) respectively; *c* – Weld metal center (transition line); *d* – Inter-dendritic microstructure in weld zone center

Table 4

Weld metals with ERNiCrFe-3 filler chemical analysis (Element (Wt. %))

C	Si	Mn	Cu	Cr	Co	Ni	Fe	Mo	Al	Ti	Nb
0.09	0.34	1.76	0.14	17.52	1.57	56.9	17.84	1.43	0.11	0.28	2.11



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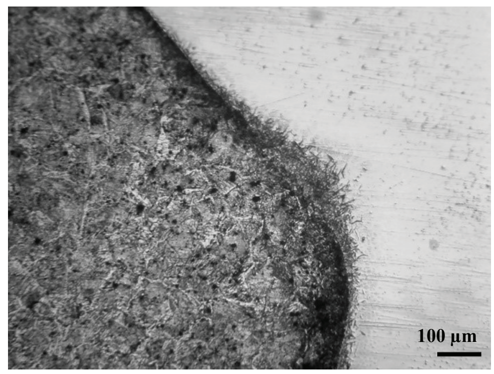

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Fig. 8. UZ and interface between weld metals: *a* – Monel 400 alloy; *b* – A387-Gr.11 low alloy steel with no UZ formation

This may be due to the following reasons:

1) higher fluidity of this alloy;
2) narrow range of solidification temperature;
3) at the elevated temperature the ferrite exhibits rapid diffusion that reduces or eliminates the UZ formation.

5. 5. Weldment mechanical properties

More than 38 points were taken to record the micro-hardness test results from the center of welding zone for ERNiCrFe-3 filler metal as starting point and then from the both sides of the welding zone to the both base metals direction as shown in (Fig. 9). A gradual increasing in hardness was recorded starting from A387-Gr.11 ferritic steel parent metal side toward Monel 400 base metal. In this side, increasing the hardness values was resulted from the microstructural changes which occurred during cooling from welding temperature. Hardness profile in fusion line and its approaching illustrated a decline diagram, which is considered to be the results of carbon immigration phenomena and the formation of soft zone (CDZ). The next change with hardness profile was a narrow band where hardness demonstrated increasing recorded values, possibly because of the martensitic layer (hard zone) presence in this zone which resulted from the carbon migration phenomenon. Tensile test results obtained in DMWs for three samples shown in (Fig. 10) were 591 MPa for the second sample, which represented the maximum tensile strength recoded, 579 MPa for the third sample which was the minimum tensile strength recorded, and 586 MPa for the first sample.

All samples were manufactured according to ASTEM E370 code, from (Fig. 10) it is possible to see that all three tensile specimens fractured in A387-Gr.11 HAZ, and these results reflected the effect of CDZ presence and coarse grain in the HAZ of A387-Gr.11 side, also they are responsible for the lower tensile strength values.

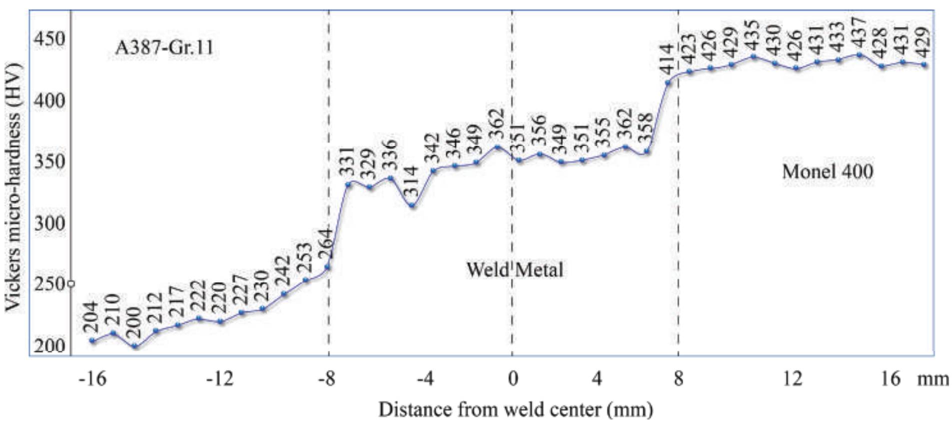

Fig. 9. Vickers micro-hardness values across the welded samples

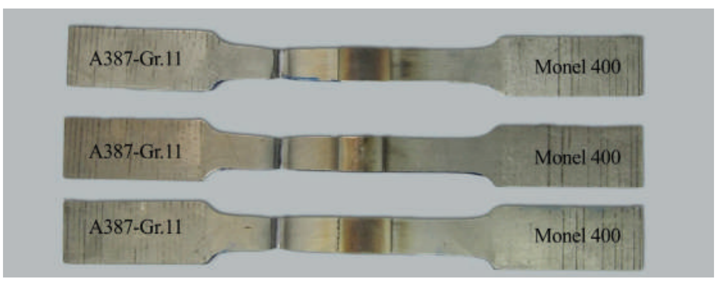

Fig. 10. ASTM E370 Tensile test samples after failure

6. Discussion variations in welding zone and base metals microstructures of Monel 400 and low alloy steel (ASTM 387-Gr.11) characteristics and mechanical properties using GTAW process

Carbon migration phenomena which, observed in A387-Gr.11 and Monel 400 HAZ as in Fig. 5, *a*, *b*. Usually, will result in formation of narrow zone in HAZ and welding fusion line vicinity known as carbon depleted zone (CDZ). In addition, by observing HAZ and fusion line microstructure of A387-Gr.11, a clear carbon-depleting zone in welding zone just near fusion line can be dedicated and sometime replaced some zones of the fusion line. Carbon depleted zone CDZ usually has soft mechanical properties because of the carbon depleting and called soft zone. According to this, carbon enriched zone with hard mechanical properties called hard zone formed just adjacent to welding fusion line in welding zone [13, 14]. Optical micrographic of A387-Gr.11 portrays distinctive CDZ because of Widmanstatten ferrite structures and ferrite grains with white appearance presence. CDZ in A387-Gr.11 parent metal HAZ is illustrated in Fig. 5, *a*. Monel 400 HAZ in Fig. 5, *b* shows almost the absence of CDZ, higher Ni percentage in Monel 400 and HAZ filler is the reason of this absence, Ni will behave as a diffusion process barrier in like this situation [13, 15]. Weld metal microstructure optical test shown fully austenitic solidification microstructure clarify solidification grain boundaries (SGBs) type and migrated grain boundaries (MGBs) as evident in Fig. 7, *b*. This solidification microstructure and grain boundaries reported in earlier studies but not with low alloy steel [16–18]. Nb presence in this microstructure would stabilize austenite phase at high temperature and influence in changing solidification microstructure to starting segregation process ended with inter dendritic zones and carbides forming [19, 20]. In this experimental study, Fig. 8, *a* elucidates UZ formation between Monel 400 base metal alloy and filler metals but UZ formation was not observed in A387-Gr.11 low alloy steel side as in Fig. 8, *b*. This may be due to the following reasons: (1) higher fluidity of this alloy, (2) narrow range of solidification temperature and (3) at elevated temperature ferrite exhibits rapid diffusion that reduces or eliminates UZ formation [6, 21]. Because of the difference in melting points and chemical compositions between base and filler metals, the appearance will be different from one case to anther of this zone. When the filler metals melting point is higher than or similar to the base metal melting point, a small fraction of the parent metal will melt and in result dilution process will not happen in re-solidification stage. Solid solution strengthening with precipitates formation provided higher hardness in the weld metal zone. Monel 400 base metal displayed higher hardness than A387-Gr.11 parent metal for the same reasons. From all the previous results, welding these dissimilar metals with GTAW technology give us the advantages of lower heat input to welding zone and give us same control on welding zone and HAZ microstructures. In addition, ERNiCrFe-3 using in weldments and the results of this study deeply explain welding filler effects on microstructures and afford excellent scientific facts about the resulted phenomena in welding zone microstructure to welding procedure specialist and welding engineers who consider about employing this filler in weldment structure. One of the most important limitations of this method is the need to professional welder to produce like this joint and by result the quality and soundness of welding joint will depend on this welder. This limitation can be disregard by automation welding processes in future. For future development of this research; authors can study the welding zone microstructure nucleation and formation sequence to obtain and achieved the best mechanical properties.

7. Conclusions

1. Weld metals demonstrated a dendritic and cellular microstructure with austenitic microstructure and intradendritic precipitates. Dendrite's structure observed with relatively fine and cellular, as a result of precipitates distribution along the SGBs and sub grain boundaries. This microstructure very effected in dislocation movements hindering and stopping plans slipping action which increasing weldments toughness and strength.

2. Unmixed zone (UZ) formation was observed in Monel 400 metal side with ERNiCrFe-3 filler metal, while A387-Gr.11 metal side illustrated transition zone (TZ) and carbon depleted zone (CDZ) formation. Formation of TZ and CDZ of carbon depleted zone formation in low alloy steel side produced soft zone in HAZ and failure under stress expected to occurred in this zone.

3. The highest microhardness was recorded in Monel 400 HAZ due to carbide formation and precipitate presence and lowest microhardness recorded in A387-Gr.11 HAZ duo to (CDZ) formation and carbon migration phenomenon and soft zone formation which ended with weak region.

4. Weld metal with ERNiCrFe-3 manifested a relatively good Charpy test results due to the finer dendritic microstructure and precipitates presence at grain and sub-grain boundaries which as mention above restricted dislocation movements in welding microstructure.

5. Weld metal with ERNiCrFe-3 evinced a relatively high tensile strength with a good yield strength, and elongation compared with the other weld metals by employing different fillers with different metals like stainless steel and low carbon steel.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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