1. Introduction

In industrial practice, numerous conditions the dissimilar combination of Ni-Cr based austenitic stainless steel (AISI 316L) and Cr based ferrite stainless steel (AISI 430) joining is found to be needed. Hence, they are having excellent strength and corrosion resistance which can be used in various industries including marine, petrochemical, aerospace industries, containers, industrial piping and vessels, architectural facades, constructional structures and so on. Suresh Kumar L et al. (2011) reported that austenitic Stainless steel grades are widely used in stainless applications due to their chemical compositions, high thermal elongation and corrosion resistant due to its high chromium and nickel substances, which are providing fine mechanical properties. Debidutta Mishra et al. (2014) observed the dissimilar combinations of Monel 400 and AISI 316 welds obtained by Gas Tungsten Arc Welding has been addressed. Ni-Cr based ERNiCr-3 and Ni-Cu based Nb-free ERNiCu-7 filler rods were employed to join these types of dissimilar combinations. The weldments were systematically characterized using optical microscopy (OM) and scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS). It is recommended from the studies that the welds obtained from ERNiCu-7 fillers were free from deleterious Laves phase formation. Irrespective of fillers, the tensile failures were experienced at the base metal side of AISI 430. In ambient temperature condition Charpy V-notch impact trials highlighted that the weld joints employing ERNiCu-7 observed better tensile and impact toughness than current continuous GTA weldments. This study is highly demanded in paper and pulp industries and effectively addressed the choice of fillers in conquering the Laves phase.

Keywords: AISI 316L and AISI 430 Steels, ERNiCu-7 and ERNiCr-3 filler metals, Continuous Gas Tungsten Arc Welding, Pulsing Current Gas Tungsten Arc Welding
Cleiton Carvalho Silva et al. (2009) experimented on the effect of weldments with rigorous heating cycle on AISI316L corrosion resistance stainless steel which is used in a Brazilian heavy petroleum refinery. The mass of the test objects was measured before and after the treatments and evaluated the loss of mass due to corrosion. Mehmet Burak Bilgin et al. (2015) examined about AISI 430 Ferritic stainless steel sheets were successfully joined for automotive applications and aerospace industries by considering weld bead and the strength of welded joint by selecting proper weld parameters and tool material. They have also reported that the best combinations of weld parameters, ultra-fine grain structures in the welding zone with high-quality welded joint. Mallaiah et al. (2014) investigated the influence of grain refining elements such as Cu, Ti and Al addition on AISI 430 FSS weldments to obtain the most favorable combinations of these grain refining elements for growing the mechanical properties and austenite content using Taguchi method for the applications of making vessels for food and chemical industries, heat exchangers, architectural and automotives. Mallaiah et al. (2012) studied the influence of Ti addition on AISI 430 ferritic stainless steel welds for improving mechanical properties, residual stresses and corrosion behaviors.

Alizadeh-Sh et al. (2014) investigated about metallurgical and mechanical properties of resistance spot welded of AISI 430 FSS on Automobile structural assembly applications. It was found that the microstructure of the fusion and heat affected zones are influenced by different phenomena including grain growth, martensite formation and carbide precipitation, also discussed about mechanical properties of the spot welding in terms of peak load, energy absorption and failure. Brando et al. (1992) explained about several welding techniques followed and it was considerably improved weld ability of AISI 430 ferritic stainless steel. This technique reported about reducing problems of grain growth, martensite formation, loss ductility, toughness and sensitivity to hot cracking in weld joints obtained by adding nitrogen to shield gas. Madhusudan Reddy et al. (2009) investigated the dissimilar welds of austenitic stainless steel (AISI 304), ferritic stainless steel (AISI 430), and duplex stainless steel (AISI 2205), they observe metal working industries are making use of this ferrite with austenite Stainless steels with different chemical composition and different conditions as in the case of thermal cycling and corrosive environments were required special awareness would be directed towards dissimilar metals. Satyanarayana et al. (2003a,2005b) reported that micro structural changes, residual stress, hardness, tensile strength, and impact strength have studied to find mechanical behavior using electron beam welding and friction welding. These studies showed that dissimilar welds exhibit lower resistance to pitting corrosion compared to the ferritic and austenitic stainless steel welds. Austenitic stainless steel was exhibited high residual stress due to its upper flow stress and superior coefficient of thermal expansion. It was observed that coarse grain size in the weld zone led to low hardness and high toughness whereas welds having fine grain size which exhibits high hardness and superior tensile strength. Madduru Phanindra Reddy et al. (2014) investigated the bimetallic joints of low alloy steel and stainless steel which are widely used in high-temperature-corrosive environments for example fossil fuel boilers and fossil–fuel fired power generating equipment’s including steam generators, furnace, economizer assemblies, front and rear portions of super heater and re-heaters. The authors have also conducted the welding studies about AISI 4140 and AISI 316 by Gas Tungsten Arc Welding (GTAW) process with and without employing filler metals. A corrosion behavior study of AISI 316L stainless steel coupons have taken from different parts of the ship pipeline and investigated in chloride solutions by Kozu et al. (2013) the results proved that the low corrosion damage occurred on the base metal while the coupon interface of the weld metal/heat affected zone (WM/HAZ) had severe pitting damages. It was witnessed that Inclusions were observed at the interface of the WM/HAZ and this can be the main cause for pitting initiation. Devendranath Ramkumar et al. (2014) differentiated the mechanical properties of the dissimilar weldments Inconel 625 and AISI 304 attained from CCGTAW and PCGTAW methods using ERNiCrMo-3 fillers. The studies illustrated that the PCGTAW welding resulted in the lower segregation effects at the weld zone and the minimization of precipitation of chromium carbides at the HAZ. However, the selection of process parameters and an appropriate filler wire for joining these dissimilar metals is cumbersome, as it has a great impact in altering the structure as well as property in the weld zones. Improper selection of filler metals may contribute for the problems, which include hot cracking, solidification cracking and ductility dip cracking etc. which could affect the quality of welds. It was reported by several researchers that problems such as micro-segregation, secondary phase formation and dilution cracks could be attributed to the improper selection of the welding process and filler material. Jeng et al. (2007) explored the microstructure of the alloy 690 and SUS 304L stainless steel dissimilar weld joints attained by Gas Tungsten Arc Welding (GTAW) method utilizing different filler wires. The authors viewed the precipitation of Cr-carbides at the inter-dendritic areas because of multi-pass welding. It was established that the Cr content near the grain boundary decreased as an effect of Cr-carbide precipitates.
Additionally, the Cr reduction caused by the Cr-carbide precipitation along with grain boundary results in the depletion of corrosion resistance. Naffakh et al. (2009) examined the bimetallic combinations of Inconel 657 and austenitic stainless steel 310 by employing Inconel 82, Inconel A, Inconel 617 and 310 SS filler metals. It was viewed from the studies that weld joints showed low tensile strength and exhibited brittle fracture which was caused due to the separation of Mo, likewise Lee and Fontana, (1998) reported the typical problem of hot cracking associated with the dissimilar weldments and it was witnessed 3–20% delta ferrite in the weld zone could improve the resistance to hot cracking propensity. Özdemira et al. (2007) reported that the similar and dissimilar joints involving austenitic steels are susceptible to unexpected phase propagation. Due to this, unexpected or a series of negative metallurgical changes, such as sigma formation phase, occurs which in turn leads to grain boundary corrosion at the weld interface. So, higher welding speeds are necessary to avoid such effects. Sundaresan et al. (1999) reported the typical benefits of current pulsing techniques which include the enhancement of fusion zone grain size and substructure, reduced width of HAZ, controlled separation, low residual stresses due to controlled heat input which would improve the weld mechanical properties. (Mohandas et al., 1996) compared the effect of Continuous Current (CC) and Pulsed Current Gas Tungsten Arc (PCGTA) welding techniques on the metallurgical and mechanical properties of ultra-high strength steel. The authors reported that the strength and ductility of the PCGTA welds was found to be greater than CCGTA welds. It was also concluded that PCGTA welding resulted in finer grain size, and smaller martensitic platelets coupled with less tendency of segregation.

As witnessed from the past works, even though there is a unique demand for these bimetallic combinations in the different fields of engineering, very insufficient information has been evidenced in the open literatures previously. Hence, this work assumes potential significance in the areas where these dis similar combinations are employed.

It is clearly reported an enormous demand for joining bimetals to adds value towards the metallurgical and mechanical properties. Since this time, the effect of filler metals and current pulsing on the metallurgical, mechanical properties of dissimilar welds in-spite of its frequent applications on AISI 316L and AISI 430 have not been addressed so far. Chemical composition of both parent metal was witnessed that Ni-Cr rich alloy in AISI 316L and Cr rich alloy in AISI 430. So, Ni-based fillers and containing high Cr and lower Mo can be suitable for the parent metals to weld and most importantly they minimize the sigma phase and secondary phase formations. In this proposed method, these bimetal combinations were joined together using CCGTA and PCGTA welding process by employing ERNiCr-3 and ERNiCu-7 filler wires. It is being analyzed by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) techniques for metallurgical properties of dissimilar weldments. The weldments have been characterized to assess the mechanical properties by conducting destructive mode of testing as in the cases of hardness, tensile and impact studies. The results of this work should be very useful to the end users who are working under these dissimilar combinations.

2. Experimental processes

2.1 Welding procedures and Base metals

The chemical compositions of the received annealed stainless steel AISI 316L and AISI 430 base metals and the filler wires are shown in Table 1 [5]. Before welding, microstructures of both parent metals were examined and shown below in fig. 1a and the base metal plates were machined to have the dimensions of 150x55x4 mm using wire-cut Electrical Discharge Machining (EDM). Welding was carried out on these plates using a special welding jig (rigid fixture) with a copper back plate so as to hold the parts in alignment and to ensure for accurate grip without bending standard butt joint configuration (single V-groove having a 2 mm of root gap, land size of 1 mm and included angle range of 60⁰–70⁰) was chosen for the current study. The process parameters were established based on the bead on plate welding studies and also by trial runs and are represented in Table 2. In this study the filler wires employed were ERNiCu-7 and ERNiCr-3. Weldments obtained by GTA and PCGTA welding techniques employing different filler wires were assessed for their metallurgical and mechanical properties. All the welding trials were conducted using ESAB TIG 160 welding machine in continuous and pulsed current mode. The samples were tested using (NDT-Radiography Testing) gamma ray Non-Destructive Testing technique to investigate for any macro/micro level surface and sub-surface defects. Ensuing to the NDT results, the weldments were sliced to various coupons for carrying out the metallurgical and mechanical tests in order to arrive at the construction–property correlations and outlined in the sub-sequent sections.
2.2 SEM/EDS analysis and Optical microscopy

Macro and micro-structure examination on the weldments has been carried out using OM and SEM technique on the coupons termed as “composite region” [which covers all the zones of the weldment such as parent metals, Heat Affected Zone (HAZ) and weld zone]. The dimensions of the composite regions were 30mmx10mmx5mm. Standard metallographic procedures have been adopted to determine the microstructure of these dissimilar coupons. The microstructures of the parent metal and HAZ of AISI 316L and AISI 430 by employing ERNiCu-7 and ERNiCr3 fillers have been determined using electrolytic etching (10% oxalic acid – 6 V DC supply; current density of 1 A/cm2); whereas the ERNiCu-7 weld was revealed using Marble’s reagent. On the other hand, a solution mixture containing 15 ml HCl, 10 ml HNO3 and 10 ml CH3COOH was used to establish the microstructure of the HAZ and parent metal of AISI 316L for all the cases.

The EDS line mapping analysis on the etched coupons was carried out to infer the elemental migration across the weldments. In addition, SEM and Electron Dispersive X-ray Analysis (EDAX) point analysis was also carried out on these coupons to analyze the quantitative elemental profiles on the weldment.

### Table 1 Chemical composition of base and filler metals.

| Material     | C  | Si  | Mn  | Cr   | Ni  | Mo  | Ti  | Al  | S   | Ph  | Nb  | Cu  | Fe          |
|--------------|----|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|----|-------------|
| AISI 316L    | 0.028 | 0.31 | 1.26 | 16.79 | 10.22 | 2.11 | 0.01 | 0.01 | 0.007 | 0.038 | 0.08 | 0.227 | remains     |
| AISI 430     | 0.048 | 0.38 | 0.37 | 16.27 | 0.15 | 0.01 | 0.02 | 0.03 | 0.006 | 0.020 | 0.11 | 0.078 | remains     |
| ERNiCu-7     | 0.03 | 0.95 | 3.3 | - | 67.5 | - | 0.75 | 1.25 | 0.015 | 0.02 | - | 28.4 | 0.95       |
| ERNiCr-3     | 0.02 | 0.1  | 3.1 | 20.5 | 58  | - | 0.4  | 0.4  | -    | -    | - | 2.6  | 0.5        |

### Table 2 Weld parameters employed in CCGTAW and PGTAW on AISI 316L and AISI 430.

| Welding | Filler wire | Filler diameter (mm) | No. of passes | Root | Cap | Peak current | background current | Voltage (v) | Weld Speed (mm/sec) | Shield gas flow rate (lpm) |
|---------|-------------|----------------------|---------------|------|-----|--------------|---------------------|-------------|---------------------|-----------------------------|
| GTAW    | ER NiCu-7   | 1.6                  |               | 85   | -   | -            | -                   | 10          | 3.17                |                             |
|         | ER NiCr-3   | 1.6                  |               | 85   | -   | -            | -                   | 11          | 2.48                |                             |
|         | ER NiCu-7   | 1.6                  |               | 90   | -   | -            | -                   | 12          | 2.14                |                             |
|         | ER NiCr-3   | 1.6                  |               | 90   | -   | -            | -                   | 12          | 2.14                |                             |
| PGTAW   | ER NiCu-7   | 1.6                  |               | 160  | 75  | 10           | 1.59                | 11          | 2.42                |                             |
|         | ER NiCr-3   | 1.6                  |               | 165  | 70  | 11           | 2.21                | 12          | 2.34                |                             |
2.3 Mechanical characterization

The welded coupons were characterized to establish the mechanical properties by conducting various tests such as hardness, tensile and impact are studied in the prevailing atmospheric conditions. Micro-hardness studies were performed on the composite zone of the dissimilar weldments at different passes were cap, filler and root pass using Vicker’s hardness equipment. The readings were recorded at regular intervals of 0.25 mm across the of the composite zone by applying a test load of 500 gf and dwell time of 10 s duration. ASTM: E8/E8M – 13a standard coupons are undergone tensile test was carried out using universal testing machine with the extensometer attached. Two test trials strain rate of 2 mm/min were carried out. Impact toughness was determined on the sub-sized samples prepared as per ASTM: E23-12c standard by conducting Charpy V-notch impact test. The data obtained from the microstructure and mechanical properties studies were utilized to correlate the structure–property relationships. The results obtained from the various metallurgical and mechanical tests are outlined in detail in the following chapters.

3. Comparison of results

3.1 Macrostructure examinations on weldments

The photographs of the dissimilar weldments of AISI 430 and AISI 316L in the welded conditions are shown in Fig. 1. The cross-section macrographs of the dissimilar weldments of AISI 430 and AISI 316L employing different welding methods and filler wires are represented in Fig. 2. Macro-structure examination ensured that both the welding techniques and filler metals employed in this study exhibited proper fusion with the base metals. Further fig.1 showed NDT-RT gamma ray analysis has shown clearly that the weldments are free from under-cuts, porosities and inclusions.

Fig.1 Macrograph images of the bi metal weldments of AISI 316L and AISI 430 using ER NiCu-7 and ER NiCr-3 filler wires.
3.2 Microstructure examinations on weldments

3.2.1 Microstructural observations of CCGTA weldments

Microstructure studies revealed the presence of secondary phases as unmixed zone at the HAZ of AISI 430 for both the fillers (Fig. 3). However, the width of the segregated zone was found to be minimal for the weldments employing ERNiCu-7 filler.
3.2.2 Microstructural observations of PCGTA weldments

It is inferred from the microstructure of the PCGTA weldments shown in Fig. 4 that the secondary phases on the grains as well as grain boundaries at the HAZ of AISI 430 were formed for both the filler wires. As reported in section 3.2.1, the unmixed or precipitation zone was found to be nil at the HAZ of AISI 316L side for both the filler wires. Migrated grain boundaries and a well-defined fusion boundary were observed at the weld zone employing ERNiCu-7 filler. In all the cases, multi-directional grain growth was observed at the weld zone for these fillers (Fig. 5). SEM point analysis has been carried out at the weld zone of CCGTA and PCGTAW weldments employing ERNICR-3 and ERNiCu-7 and is shown in Figs. 6(a) and (b) and 7(a) and (b). Several researchers reported the main reason for migrated grain boundaries (MGBs) at CCGTA and PCGTA weld zones (fig.3 & fig.5) and the solidification mode was found to be ferritic - austenitic due to high Cr/Ni ratio. MGBs are most predominant in the fully austenitic (A), Austenitic Ferritic (AF) and in Ferritic Austenitic (FA) modes of solidification. Also, MGBs are also formed due to multi-pass welding employed by Ni based fillers.

![Microstructural photos of the bimetal joints at interface of both AISI 430 and AISI 316L obtained by PCGTA welding by employing (i) ERNiCr-3 and (ii) ERNiCu-7 Fillers.](image)

3.3 Observations of line charting on weldments

3.3.1 Analysis of CCGTA line charting

As per Fick's law of diffusion, Line charting analysis on the ERNiCr-3 weldments has shown the movement of Nb (2.6% in filler) whereas (Nb- 0.11% in AISI 430) and Ni (58% in filler) whereas (Ni-0.15% in AISI 430) from the weld zone to AISI 430 side. The presence of Nb and Ni in the secondary phase is greater as compared to the matrix. It was also observed that the element Fe has moved from the AISI 430 to weld zone side whereas Cr movement was found to be minimal. However, the constituent’s Fe and Cr are found to be lesser in amount in the secondary phases than the matrix. The elemental migration on the AISI 316L to weld or vice versa was almost little and is evident from Fig. 8(a) and (b). The line charting analysis on the magnified portion of the GTA weldments employing ERNiCu-7 is shown in Fig. 8(c) and (d). It was observed from the SE micrographs the presence of pits appearing as dark spots at the weld zone where the elements such as Ni, Cr, and Fe have decreased. The constituent Ni was found to be slightly higher in the weld zone compared to AISI 430 side.
A minimal amount of Fe, Cr and Nb has migrated from AISI 430 to weld zone. The element Ti was found to be greater at the weld interface. Similarly, the movement of Ni from the weld zone to AISI 316L side and Fe from AISI 316L to weld zone was also witnessed.

![Fig. 5 Weld microstructural photos of ERNiCr-3 weldments showing (a) and (b) migrated grain boundaries observed in CCGTA and PCGTA welding techniques respectively; (c) and (d) stratified etch pits and MGB observed at the cap portion of CCGTA and PCGTA weld techniques respectively.](image)

3.3.2 Analysis of PCGTA line charting

It is evident from the line charting analysis (Fig. 9(a) and (b)) that Ni has migrated from ERNiCr-3 weld zone side to AISI 430 for weldments. As the Cr constituent is almost same in the base and filler metal, its movement is not varying much; whereas Fe has moved from AISI 430 side to weld zone. It was also observed that the secondary phases were enriched with Nb and Mo. For the PCGTA weldments employing ERNiCu-7 (Fig. 9(c) and (d)), the movement of Ni from the weld zone to AISI 430 side was observed to be non-uniform; whereas Cu has moved from the weld zone to AISI 430 side. The constituent Nb rich secondary phase was observed in the HAZ of AISI 430 side. On the other hand, Fe and Cr have migrated from AISI 316L side to weld zone.
Fig. 8 Line charting investigation on the CCGTA weldments by employing ERNiCr-3 filler (a and b); ERNiCu-7 filler (c and d) respectively.
Fig. 9 Line charting investigation on the PCGTA weldments by employing ERNiCr-3 filler (a and b); ERNiCu-7 filler (c and d) respectively.
Fig. 6a SEM/EDS investigation on the CCGTA weld zone of AISI 430 and AISI 316L by employing ERNiCr-3 Filler rod.

Fig. 6b SEM/EDS investigation on the CCGTA weld zone of AISI 430 and AISI 316L by employing ERNiCu-7 Filler rod.
Fig. 7a SEM/EDS investigation on the PCGTA weld zone of AISI430 and AISI 316L with ERNiCr-3 Filler.

Fig. 7b SEM/EDS investigation on the PCGTA weld zone of AISI430 and AISI 316L with ERNiCu-7 Filler.
3.4 Hardness analysis

3.4.1 CCGTA hardness analysis

Hardness studies were carried out across the entire width of the weldments vis-a-vis cap, middle and root passes of the CCGTA weldments shown in Fig. 10(a)&(b). In table 5 average hardness of the weldments employing ERNiCr-3 filler was almost same in the cap, middle and root passes. The average weld zone hardness was found to be greater in the root pass than the cap and middle pass. Peak hardness values were observed at the weld zone both in middle and root pass. On the other hand, the hardness values were lower at the weld zone employing ERNiCu-7 in all the passes. Amongst the various passes, the root pass exhibited maximum hardness. A peak hardness value of was observed at the weld zone.

3.4.2 PCGTA hardness analysis

The hardness profile of the PCGTA weldments employing ERNiCr-3 and ERNiCu-7 is depicted in Fig. 11(a) and (b). It was exemplified that the weld zone of ERNiCr-3 weldments exhibited greater hardness compared to ERNiCu-7 weldments whose average hardness as in table 5. The peak hardness value was observed in both root passes of ERNiCr-3 weldments and ERNiCu-7 weldments.

3.5. Trials on Tensile samples

3.5.1 Trials on CCGTA weldments

Tensile test was carried out on the dissimilar weldments obtained from the CCGTA welding techniques employing ERNiCr-3 and ERNiCu-7 fillers and are shown in Fig. 12a. The tensile strength of the parent metals was observed to be around 500 MPa for AISI 316L and 470 MPa for AISI 430. It was evident from the studies that in all the cases, the tensile failures occurred at the parent metal of AISI 430. In table 3 shows the average ultimate tensile strength values of ERNiCu-7 weldment is 479.58 MPa whereas the value is 474.29 MPa for ERNiCr-3 weldments respectively. It was also observed that the weldments undergo severe plastic deformation during rupture. The average elongation exhibited by ERNiCr-3 and ERNiCu-7 weldments was found to be 47.39% and 58.78% respectively. SEM fractography results showed that the fractured surface consists of macro/micro-voids and river pattern voids observed in ERNiCr-3 weld zone and more macro voids and more shallow dimples observed in ERNiCu-7 as shown in (Fig. 13a (i) and (ii)).

![Fractured tensile samples of CCGTA dissimilar weldments of AISI 430 and AISI 316L respectively.](image)
3.5.2 Trials on PCGTA weldments

PCGTA weldments have shown in Fig.12b similar trend as discussed in Section 3.5.1 that the tensile fractures occurred at the parent metal of AISI 316L. There was not much difference observed in the ultimate tensile strength while employing these fillers (468.79 MPa for ERNiCr-3 and 484.36 MPa for ERNiCu-7) during PCGTA welding process. However, the elongation values were greater for ERNiCu-7 weldments compared to ERNiCr-3 (Table 3). Further SEM fractographs showed the macro and presence of river pattern voids observed at ERNiCr-3 weld zone and more shallow dimples, less macro voids observed at ERNiCu-7 weld zone as shown in (Fig. 13b (i) and (ii)).
Fig. 13b SEM tensile fractographs of PCGTA weldments of AISI430 and AISI316L employing (i) ERNiCr-3 and (ii) ERNiCu-7 fillers.

Table 3 Tensile properties of AISI430 and AISI 316L weldments.

| Weld Method | Fillers  | Trials | Ultimate tensile load (KN) | Ultimate tensile Strength (MPa) | Elongation (%)25 mm gauge length | Fracture zone         |
|-------------|----------|--------|----------------------------|---------------------------------|----------------------------------|-----------------------|
| CCGTAW      | ERNiCu-7 | 1      | 11.25                      | 480.83                          | 22                               | Base metal AISI 430 side |
|             |          | 2      | 11.2                       | 478.33                          | 20                               |                       |
|             |          | Avg    | 11.22                      | 479.58                          | 21                               |                       |
| CCGTAW      | ERNiCr-3 | 1      | 11.31                      | 472.82                          | 21.04                            | Base metal AISI 430 side |
|             |          | 2      | 9.69                       | 475.29                          | 18.54                            |                       |
|             |          | Avg    | 10.5                       | 474.05                          | 19.7                             |                       |
| PCGTAW      | ERNiCu-7 | 1      | 11.16                      | 485.75                          | 22                               | Base metal AISI 430 side |
|             |          | 2      | 11.15                      | 482.97                          | 22                               |                       |
|             |          | Avg    | 11.15                      | 484.36                          | 22                               |                       |
| PCGTAW      | ERNiCr-3 | 1      | 10.7                       | 460.79                          | 21.5                             | Base metal AISI 430 side |
|             |          | 2      | 10.99                      | 476.79                          | 21                               |                       |
|             |          | Avg    | 10.84                      | 468.79                          | 21.25                            |                       |
Fig. 10 Hardness profile of CCGTA weldments of AISI 430 and AISI 316L employing (a) ERNiCr-3 (b) ERNiCu-7 fillers.

Fig. 11 Hardness profile of PCGTA weldments of AISI 430 and AISI 316L employing (a) ERNiCr-3 (b) ERNiCu-7 fillers.
### Table 5 Average hardness of the CCGTA and PCGTA weldments of AISI 316L and AISI 430.

| Description          | Hardness (HV)       | Cap | Middle | Root  |
|----------------------|--------------------|-----|--------|-------|
| CCGTA-ERNiCu-7       | Average hardness of the weldment | 175.6 | 178    | 181.5 |
|                      | Average hardness at the weld zone | 171.3 | 179    | 183.5 |
|                      | Peak hardness at the weld zone    | 195.5 | 198    | 202.4 |
| CCGTA-ERNiCr-3       | Average hardness of the weldment  | 223.5 | 216    | 209.6 |
|                      | Average hardness at the weld zone | 218.4 | 224    | 231.2 |
|                      | Peak hardness at the weld zone    | 240.6 | 250    | 260.5 |
| PCGTAW-ERNiCu-7      | Average hardness of the weldment  | 180.6 | 178    | 181.5 |
|                      | Average hardness at the weld zone | 176.5 | 178    | 180.5 |
|                      | Peak hardness at the weld zone    | 188.6 | 190    | 192.8 |
| PCGTAW-ERNiCr-3      | Average hardness of the weldment  | 190.6 | 192    | 195.8 |
|                      | Average hardness at the weld zone | 187.3 | 188    | 190.8 |
|                      | Peak hardness at the weld zone    | 195.6 | 197    | 197.6 |

#### 3.6 Trials of Impact toughness samples

It is important to predict the behavior of the weldments when they are subjected to sudden impact loads. This could give information on the response of the weldments during sudden mechanical and thermal impacts under service conditions. The following sub-chapters address the results of the impact studies at room temperature.

#### 3.6.1 Trials on CCGTA weldments

Impact studies on these dissimilar weldments clearly conveyed that the average value of impact toughness of ERNiCu-7 weldments (20.5 J) was found to be better compared to ERNiCr-3 weldments (14 J). It is evident from both weldments employed from ER NiCr-3 and ER NiCu-7 (fig.14(a) & (b)) witnessed that the fractures are ductile mode which are having the characteristic of larger plastic deformation before fracture. SEM fractographs showed the presence of micro-macro voids which coalesced and intended to form the crack causing the fracture for the weldments employing ERNiCu-7 whereas river pattern markings which spread as feathery ridges with the presence of unbroken carbides were observed for ERNiCr-3 weldments (Fig. 15(a) and (b)).

![Fig. 15 SEM fractographs of the Charpy V-notch impact tested CCGTA weldments employing (a) ERNiCr-3 (b) ERNiCu-7 respectively.](image-url)
3.6.2. Trials on PCGTA weldments

It was ascertained from the impact studies that the PCGTA weldments employing ERNiCu-7 showed better resistance to impact loading than the ERNiCr-3 weldments. The average impact energies were 17 J for ERNiCr-3 and 22.5 J for ERNiCu-7 weldments. As discussed in Section 3.6.1, it is also evident from both weldments employed from ERNiCr-3 and ERNiCu-7 (fig.14(c) & (d)) witnessed that the fractures are ductile mode which are having the characteristic of cleavage ductile fracture. Further SEM fractographs (Fig. 15(c) and (d)) depicted the mixed mode of fracture showing the micro dimpled pattern for the ERNiCr-3; whereas the ERNiCu-7 weldment has shown the presence of macro-dimpled pattern tearing ridges on the fractured surface. Table 5 indicates the impact toughness values of these dissimilar weldments.

Fig. 15 SEM fractographs of the Charpy V-notch impact tested PCGTA weldments employing (c) ERNiCr-3 (d) ERNiCu-7 respectively.
Table 5 Impact toughness properties of AISI 430 and AISI 316L weldments.

| Type of Weld | Property   | ER NiCu-7 |     |     |     | ER NiCr-3 |     |     |     |
|--------------|------------|-----------|-----|-----|-----|-----------|-----|-----|-----|
|              |            | Trial 1   | Trial 2 | Avg. |     | Trial 1   | Trial 2 | Avg. |
| CCGTA        | Toughness  | J         | 20    | 21  | 20.5| J         | 16    | 15  | 14  |
| PCGTA        | Toughness  | J         | 22    | 23  | 22.5| J         | 16    | 18  | 17  |

4. Results and Discussions

Macro-photographs and NDT-Radiography testing have clearly corroborated that both the welding techniques as well as the filler wires resulted in sound welds which were free from any macro/micro level surface defects. This clearly confirms the use of these techniques and filler wires for joining AISI 430 and AISI 316L are good. The interferential and weld microstructures of the dissimilar weldments are shown in Figs. 3–5. In all the cases, the HAZ of AISI 430 consists of secondary phases. These secondary phases were enriched with the elemental constituents such as Nb, Mo and Cr which was evident from the line mapping analysis. However, the segregation effects were almost reduced on employing PCGTA welding which could be witnessed from the EDS results (Fig. 7). As reported by other researchers, the grain refinement and controlled grain growth could be achieved on employing PCGTA welding. Multi-directional grain growth was observed at the weld zones in all the cases owing to the multi-pass welding. Migrated grain boundaries have distinctly appeared in the ERNiCu-7 weld for both welding processes. Improper selection of filler metals may contribute the problems, which include hot cracking, solidification cracking and ductility dip cracking etc. which could affect the quality of welds. It was reported by several researchers that problems such as micro-segregation, secondary phase formation and dilution cracks could be attributed to the improper selection of the welding process and filler material.

However, there were no signs of solidification cracking in these weld zones irrespective of the presence of MGBs. The weld zones employing ERNiCu-7 was fully austenitic and this was also confirmed by the EDS analysis where the Ni constituent in the matrix was found to be higher. Etch pits were observed at the weld zones of CCGTA and PCGTA weldments employing ERNiCu-7 filler. In this case also, interfacial microstructures have been studied using electrolytic etching followed by controlled swabbing of Marble’s reagent.

Line charting analysis depicted the elemental migration across the HAZ and the weld zone of both the sides. As reported in section 3.3.1, the secondary phase that appears as white in color at the HAZ of AISI 316L was enriched with Nb and Ni. As reported by other researchers, this could be the formation of probable inter metallic such as Ni,Nb, and NbC. However, there was no evidence of laves phase formation at the HAZ of AISI 430. EDS/SEM analysis on the GTA weld zone employing ERNiCr-3 filler showed the phases appearing as white in color consist of richer amounts of Nb, Mo, Ni and Fe. As reported by other researchers, the enrichment of these elements resulted in the deleterious laves phase (Fig. 8 (a)). Laves phase has been prominent in the weld zone adjacent to AISI 430 whereas it was not remarkably visible in the middle of the welds. The absence of laves phase was witnessed on the CCGTA welds employing ERNiCu-7 filler. This could be reasoned to the use of filler wires without having much Nb and Fe additions. The weld zone displayed the presence of etch-pits as evident from the SEM micrographs. The reasons of obtaining etch pits have been dealt already. It was evident from the line mapping analysis and EDS/SEM analysis that PCGTA welding using ERNiCr-3 controlled laves phase formation in the weld zone and precipitation at HAZ of AISI 430 to the extent possible compared to CCGTA welding process. Similarly, in the case of ERNiCu-7 the formation of secondary phases and laves formation were totally controlled (Fig. 9 (c) and (d)). Hardness measurements indicated that the weld zone of CCGTA weldments employing ERNiCr-3 filler possessed maximum hardness compared to ERNiCu-7 weldments. The reason should be owing to the rich presences of Nb, Mo and Ni constituents present in the matrix as well as in dendritic sites. Also, the formation of strong inter-metallic carbides and nitrogen in the filler wire results in the complete dissolution which constitutes for higher weld hardness. Whereas the filler wire ERNiCu-7 had lower hardness and was almost equivalent to the parent metal of AISI 316L. Similar trend has been observed in the PCGTA weldments. Even though, the weld hardness was found to be greater for GTA welds as compared to PCGTA welds. The lower weld hardness in the ERNiCu-7 could be attributed to the etch pits observed due to decrease in the elemental constituents such as Ni, Cr and Fe as depicted in...
section 3.3.1. Additionally, the tensile studies reported the fracture occurred at the parent metal of AISI 430 and not in the weld zone for all the cases of weldments in all the trials. This clearly proposed that the weld strength is quite higher compared to the parent metals employed in this work. Hardness data also supported and agreed with tensile plots. It was observed that both CCGTA and PCGTA weldments employing ERNiCu-7 demonstrated better tensile strength, impact toughness and ductility compared to ERNiCr-3 filler. The SEM fractographs of the tensile tested samples had confirmed the ductile mode of fracture by showing the presence of micro-voids and/or dimples which coalesce together to undergo plastic deformation. Charpy V-notch test results have given a clear indication that the CCGTA and PCGTA weldments employing ERNiCu-7 demonstrated better impact toughness average values of 20.5 J and 22.5 J respectively. PCGTA weldments employing ERNiCu-7 has shown improved toughness values in all the trials compared to CCGTA weldments. This could also be supported with the hardness plots such that lower values of hardness (weld zone) of ERNiCu-7 pitched for the toughness values comparatively greater than ERNiCr-3 weldments.

It was proposed that the post weld heat treatments resulted in completely control dissolution of laves phase formation, but its persistence could not be eliminated completely. Though, the major attempts of post weld heat treatment were carried out on the AISI 430 only. There are no concurrent updates existing in the literatures on the control of laves phase in the dissimilar joints of AISI 430 and AISI 316L stainless steel grades. Also, it is difficult to perform post weld heat treatments for the dissimilar joints due to the differences in their chemical composition. This paper addressed the ambient temperature mechanical properties of the weldments. As these dissimilar combinations are operated in high temperature environments, additional studies are required to assess the same. As a nutshell, this proposed research work was aimed to control laves phase formation which was identified and reported as a major problem by the researchers. As evident from the current studies, the use of appropriate filler wire ERNiCu-7 and the current pulsing resulted in healthier metallurgical and mechanical properties. It was observed from the studies that the deleterious phases were totally absent on employing PCGTA welding technique using ERNiCu-7. From the outcomes of the study, it is suggested to use PCGTA welding for joining the bimetallic combinations of AISI 430 and AISI 316L as this technique showed better combination of mechanical properties such as weld strength and toughness. These results are the major contributions to the present literature and also open for a wide range of research opportunities in the dissimilar joints by employing AISI 430 and AISI 316L.

5. Conclusion

The present work addresses on the weld ability, microstructure and mechanical properties of the dissimilar joints of precipitation hardened Cr based alloy ferritic AISI 430 and Ni-Cr based alloy Austenitic AISI 316L using CC and PCGTA welding process employing two different fillers. The summaries which are drawn out from the present investigation are described here.

1. Sound joints of AISI 430 and AISI 316L could be obtained on employing the CCGTA as well as PCGTA welding techniques using ERNiCr-3 and ERNiCu-7 fillers.

2. The formation of higher amounts of Nb and Mo rich secondary phases was witnessed at the weld zone of AISI 316L for the GTA weldments employing ERNiCr-3 filler. PCGTA welding demonstrated that the weld grain boundary retains the elements like Mo and Cr which controlled laves phase formation. Both GTA and PCGTA weldments employing ERNiCu-7 were totally free from any deleterious phases.

3. Migrated grain boundaries were formed without any solidification cracking due to multi pass welding while employing ERNiCu-7 and ERNiCr-3 fillers for both welding techniques. The formation of Nb rich secondary phases was observed both in the weld and HAZ of GTA weldments employing ERNiCr-3 filler which contributed for lower tensile strength.

4. Laves phase was totally controlled in the PCGTA weld zone employing ERNiCu-7 which contributed for improving the mechanical properties.

5. Tensile fractures occurred at the parent metal of AISI 430 for all the weldments. Both GTA and PCGTA weldments employing ERNiCu-7 corroborated for better tensile properties. The study concluded that the weld strength was greater than that of the parent metals employed.

6. Both GTA and PCGTA weld zones of ERNiCu-7 filler have shown the plummeted hardness values which contributed for better toughness values compared to ERNiCr-3 weldments.

7. Both CCGTA and PCGTA weldments employing ERNiCu-7 demonstrated better impact toughness but PCGTA weldments employing ERNiCu-7 has shown superior toughness values in all the trials compared to CCGTA weldments.
This could also be supported with the hardness plots such that lower values of hardness (weld zone) of ERNiCu-7 pitched for the toughness values comparatively greater than ERNiCr-3 weldments.

8. Based on these current studies, it is highly witnessed to employ PCGTA welding using ERNiCu-7 filler owing the numerous advantages resulted and can be possibly adopted in the paper and pulp industries demanding these bimetallic joints.

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