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# Characterization of metallurgical and mechanical properties on the multi-pass welding of Inconel 625 and AISI 316L[†]

K. Gokul Kumar, K. Devendranath Ramkumar[*] and N. Arivazhagan

*School of Mechanical and Building Sciences, VIT University, Vellore 632 014, India*

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## Abstract

This article investigated the weldability, metallurgical and mechanical properties of Inconel 625 and AISI 316L stainless steel weldments obtained by continuous current (CC) and pulsed current (PC) gas tungsten arc welding (GTAW) processes employing ERNiCr-3 and ER2209 fillers. Microstructure studies showed the migrated grain boundaries at the weld zone of ERNiCr-3 weldments and multi-directional grain growth for ER2209 weldments. It was inferred from the tension tests that the fracture occurred at the parent metal of AISI 316L in all the cases. Charpy V-notch impact tests accentuated that the CCGTA weldments employing ERNiCr-3 filler offered better impact toughness of 77 J at room temperature. Further a detailed study has been carried out to analyze the structure - property relationships of these weldments using the combined techniques of scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis.

*Keywords*: Inconel 625; AISI 316L; Dissimilar metal welding; Microstructure; Mechanical characterization

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## 1. Introduction

Dissimilar metal welding not only satisfies the service conditions but also results in large savings by minimizing the volume of expensive materials used in these joints [1]. Welding of dissimilar metals is highly challenging and cumbersome task as compared to the similar metal welding owing to the differences in chemical composition and the coefficient of thermal expansions of the base metals employed [1-4].

Inconel 625 is a high-chromium, high-molybdenum, nickel-based superalloy, widely used in form of bulk, weld-overlay, and plasma-sprayed coatings for high temperature applications in many corrosive environments: gas turbines, waste-fired boilers as well as pulp and paper industries. Similarly austenitic stainless steels have wide range of applications in chemical, petrochemical industries and power engineering sectors due to the combined properties of strength and corrosion resistance. AISI 316L has typical advantages compared to the other grades of stainless steel such that they are not prone to sensitization at elevated temperatures.

Bimetallic combinations of Inconel 625 and austenitic stainless steels were employed by NASA [5] for the construction of sub-scale boilers. These boilers were tested to investigate the boiling stability after being operated with boiling NaK for 792 hr at temperatures from 700 to 750°C. Xiaowei Wu et al. [6] reported the typical advantages of brazed joints of Inconel and austenitic stainless steel, which were developed to withstand high temperatures and widely designed for aero-engine hot section components. Further various researchers [6, 7] reported that the joints of these combinations could be employed in oil-refinery converters where, the temperature can reach up to 1050°C and the atmosphere is highly carburizing and oxidizing. Austenitic stainless steel is most prevalent material used in high temperature applications which would be a good alternative for Inconel. Hence welding techniques were adopted to join Inconel series and cost effective stainless steel grade to accrue better mechanical properties [7-9].

Solidification/liquation cracking, ductility - dip cracking (DDC) and precipitation of Cr-carbides in the weld are the major problems usually encountered during welding of dissimilar alloys [10]. Patterson et al. [11] observed the solidification cracking at the weld zone during the autogeneous gas tungsten arc welding of Inconel 625 and 304L stainless steel. Studies made by Devendranath Ramkumar et al. [12] on the dissimilar joints of Inconel 625 and AISI 304 clearly showed the precipitation of chromium carbides at the HAZ of stainless steel. Due to the presence of higher amounts of Nb content in the filler metal, enriched segregation was observed at the HAZ of Inconel 625. Also the authors strongly believed that the effects of secondary phases were slightly lowered on employing PCGTA welding.

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[*] Corresponding author. Tel.: +91 416 2202184, Fax.: +91 416 2243092
E-mail address: deva@vit.ac.in

[†] Recommended by Associate Editor Ji Weon Kim

Table 1. Chemical composition of base and filler metals.

| Chemical composition (% weight) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Base / filler metal | C | Cr | Ni | Mn | Mo | Fe | Others |
| Inconel 625 | 0.06 | 21.1 | 62.1 | 0.24 | 8.23 | Rem. | Co - 0.024; Cu - 0.01; Al - 0.004; Ti - 0.016; V - 0.02; W - 0.15; P -0.009; S - 0.014; Si - 0.434; Nb - 3.3 |
| AISI 316L | 0.03 | 17.4 | 8.1 | 1.23 | 2.3 | Rem. | P -0.032; S -0.01; Si - 0.28 |
| ER2209 | 0.02 | 23.0 | 8.5 | 1.6 | 3.1 | Rem. | N -0.17; Si - 0.5; Nb - 0.58 |
| ERNiCr-3 | 0.08 | 21.5 | 67.0 | 2.5 | --- | Rem. | Ti - 0.75; Cu - 0.5; Si - 0.015; P - 0,03; S - 0.5; Nb - 2.24 |

Table 2. Process parameters employed in CCGTA and PCGTA welding of Inconel 625 and AISI 316L.

| Process | Filler | Voltage (V) | Current (A) | Base current $I_{base}$(A) | Peak current $I_{peak}$(A) | Frequency HZ |
|---|---|---|---|---|---|---|
| CCGTAW | ERNiCr-3 | 13.0 | 140 | --- | --- | --- |
| PCGTAW | ERNiCr-3 | 13.5 | --- | 86-88 | 146 | 6 |
| CCGTAW | ER2209 | 13.0 | 140 | --- | --- | --- |
| PCGTAW | ER2209 | 13.9 | --- | 75-85 | 142 | 6 |

Du Pont et al. [10] reported that the selection of welding process and process conditions also have an influence on cracking susceptibility. Further the authors recommended the use of low heat input welding processes and conditions which would be favorable in avoiding such types of cracking. Jeng et al. [13] reported the precipitation of Cr-carbides at the interdendritic regions could be mitigated by using Nb added filler wire. Devendranath et al. [14] investigated the bimetallic joints of Monel 400 and AISI 304. The authors claimed that the use of E309L filler would result in the formation of secondary phases which could deteriorate the metallurgical and mechanical properties of the weldments. Further the authors recommended that the use of pulsed mode of GTA welding process for eliminating the formation of these phases. Several researchers reported about the advantageous aspects such as improvement in strength and ductility, while employing the pulsed current GTA welding on different materials [12, 15-17]. Devendranath et al. [18] investigated the comparative analysis on the CCGTA and PCGTA weldments of Inconel 718 and AISI 316L using ER2553 and ERNiCu-7 fillers. The authors concluded that PCGTA welding aided in controlling the deleterious laves phase and also facilitated for enhanced mechanical properties.

As evident from the open literatures, the scope and application of joining Inconel 625 and AISI 316L is wider and requires thorough analysis in terms of the joint's performance in ambient conditions. The present study features the weldability, metallurgical and mechanical properties of these bimetallic joints obtained by continuous and pulsed current GTA welding techniques employing ER2209 and ERNiCr-3 filler metals. The welded samples were characterized for the optical macro/micrograph, SEM/EDS analysis, micro-hardness, impact test and tensile test to understand the metallurgical and mechanical behavior. The results elucidated in this paper will be highly useful to the manufacturers operating with these bimetallic joints.

## 2. Experimentation

### 2.1 Base metals and welding procedure

The as-received base metals employed in this study were solution annealed Inconel 625 and AISI 316L. These plates were joined by CCGTA and PCGTA welding processes employing two different filler metals such as ER2209 and ERNiCr-3. The chemical composition of the base and filler metals employed in this study is represented in Table 1. The base plates were cut and machined to the dimensions of 155 mm long × 50 mm wide × 5 mm thick using wire-cut electrical discharge machining (EDM). standard butt configurations (single V-groove having a root gap of 2 mm, size land of 1 mm and included angle of 70°) were employed on the plates before welding. The process parameters employed for joining these dissimilar metals were obtained based on the existing open literatures as well as confirmed by the bead on plate welding and shown in Table 2. These dissimilar weldments were subjected to different metallurgical and mechanical tests to investigate the structure - property relationships.

### 2.2 Characterization of weldments

After welding, the dissimilar weldments were investigated for any flaws using gamma ray NDT technique. Ensuing to the results, these weldments were cut to coupons of different dimensions using wire-cut electrical discharge machining (EDM) process for performing various metallurgical and mechanical tests to arrive at the structure - property relationships. Coupons of the transverse sections of the welded samples having the dimensions of 30 mm × 10 mm × 5 mm known as "composite region" covering all the zones of the weldments were metallographically etched to investigate the macro and microstructure. Macrostructure studies were carried out to examine the weld fusion with respect to the welding techniques and filler wires employed. Standard metallographic procedures were employed to examine the microstructure of the weldments. Electrolytic etching (10% oxalic acid - 10 V DC supply; 30 - 40 s; current density of 1 A/cm$^2$) process was employed to reveal the microstructure of the various zones of the weldments. The micro-structural features were examined using the combined techniques of optical microscopy and a SEM equipped with EDS point analysis. Furthermore Vicker's micro-hardness tests were carried out across the weldments with a load of 500 gf for a dwell period of 10 s duration at regular intervals of 0.25 mm. Tensile tests were performed using Instron Universal testing machine by employing a cross head velocity of 2 mm/min to induce uniform strain rate across the weldments, prepared as per the ASTM: E8/8M - 13a standard. The tensile specimens were cut perpendicular to the welding direction and tested to assess the strength of the weldments.

Charpy V-notch impact test was conducted on the sub-sized specimens of the weldments as per ASTM: E23-12C standards at room temperature. The specimens were machined perpendicular to the welding direction with the notch in the center of the weld metal in the cap zone of the weldments. Both these mechanical tests were carried out on three samples in each case to ascertain the reproducibility of the results. Further these fractured samples obtained from tensile and impact tests were investigated for SEM fractography to determine the mode of fracture. The data obtained from the microstructure and mechanical 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.

Fig. 1. Photographs of the dissimilar weldments of Inconel 625 and AISI 316L employing CCGTA welding using: (a) ER2209 filler; (b) ERNiCr-3 filler and PCGTA welding employing; (c) ER2209 filler; (d) ERNiCr-3 filler, respectively.

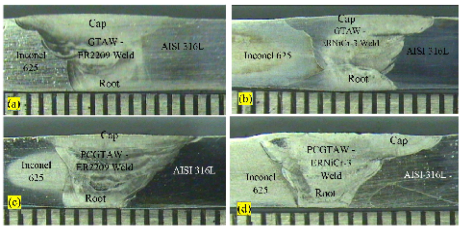

Fig. 2. Macrostructure of the dissimilar weldments of Inconel 625 and AISI 316L employing CCGTA welding using: (a) ER2209 filler; (b) ERNiCr-3 filler and PCGTA welding employing; (c) ER2209 filler; (d) ERNiCr-3 filler, respectively.

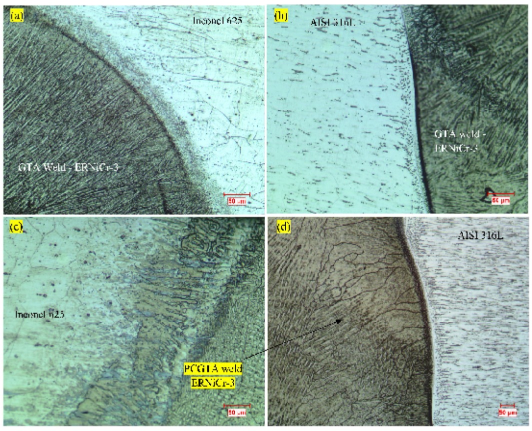

Fig. 3. Microstructure examination showing: (a), (b) CCGTA weldments; (c) and (d) PCGTA weldments employing ERNiCr-3 in the middle/filler pass region.

## 3. Results

### 3.1 Macro-structure examination

The photographs and macro-structure of both CCGTA and PCGTA weldments of Inconel 625 and AISI 316L are depicted in Figs. 1(a)-(d) and Figs. 2(a)-(d). The results showed a proper weld bead with complete penetration of the base metals and filler metals in all the cases. Macrostructure examination showed that narrow weld beads were obtained on employing PCGTA welding technique. It could also be inferred that the width of the fusion zone is found to be varying with respect to the filler wires and the welding techniques.

### 3.2 Microstructure studies

#### 3.2.1 CCGTA and PCGTA weldments employing ERNiCr-3

Interface microstructures of the dissimilar combinations obtained from CCGTA and PCGTA welding techniques employing ERNiCr-3 are represented in Figs. 3(a)-(d). The formation of secondary phases was well observed at the HAZ of Inconel 625 for both the weldments. However the amount of segregation was found to be minimal for the PCGTA weldments. Grain coarsening effect was also been observed at the HAZ(s) of both the weldments. Moreover the Migrated Grain Boundaries (MGBs) were distinctly observed at the weld zone of both weldments (Figs. 5(a) and (b)). No solidification cracking was observed at the weld zone in spite of the presence of migrated grain boundaries. Also it was inferred that the weld zone resulted in a complete austenitic weld due to the formation of MGBs at the weld zone.

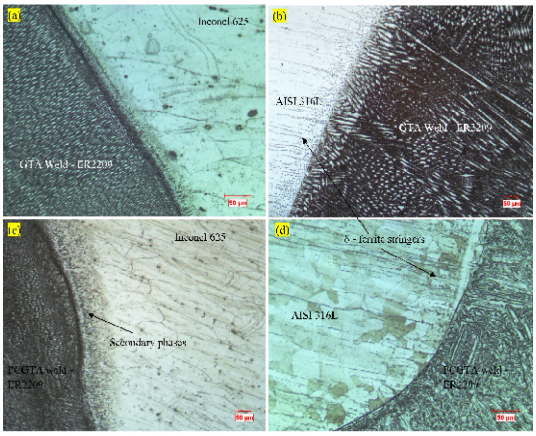

Fig. 4. Microstructure examination showing: (a), (b) CCGTA weldments; (c), (d) PCGTA weldments employing ER2209 in the middle/filler pass region.

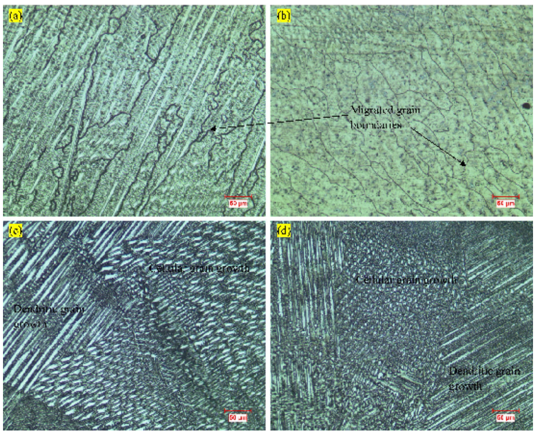

Fig. 5. Weld microstructure of CCGTA weldments employing: (a) ERNiCr-3; (c) ER2209 filler; PCGTA weldments employing; (b) ERNiCr-3 and; (d) ER2209 filler respectively in the middle/filler zone.

### 3.2.2 CCGTA and PCGTA weldments employing ER2209

Interfacial micrographs of CCGTA and PCGTA weldments employing ER2209 filler are represented in Figs. 4(a)-(d). Grain coarsening has been vividly seen in the CCGTA weldments compared to the PCGTA weldments. Multi-directional grain growth such as the presence of cellular, columnar and dendritic growth was observed at the weld zone for both the weldments (Figs. 5(c) and (d)).

## 3.3 Line mapping analysis

### 3.3.1 CCGTA and PCGTA weldments employing ERNiCr-3

EDAX line mapping analysis was carried out on the weldments to infer the movement of elements and is represented in Figs. 6(a)-(d). It was well inferred that the elemental migration was almost minimal and from Inconel 625 to weld zone or vice-versa (Figs. 6(b) and (d)) for both CCGTA and PCGTA weldments. On the other hand, Fe has migrated from the HAZ of AISI 316L side to the weld zone; whereas Ni has migrated vice-versa for both the weldments. Even though the content of Cr is almost equal in parent and filler metal, slight variations occurred at the weld interface and the HAZ of AISI 316L (Figs. 6(a) and (c)). On closer observation, it was found that Cr content has slightly lowered in the weld interface for both CCGTA and PCGTA weldments.

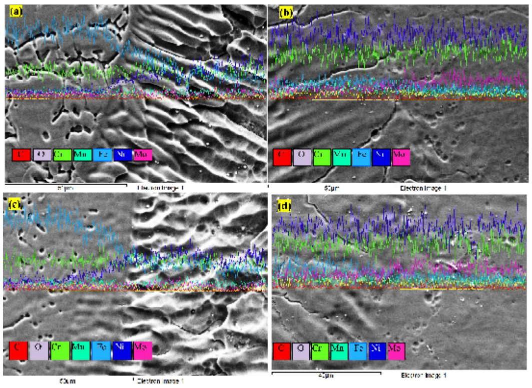

Fig. 6. Line Mapping EDS analysis on the dissimilar weldments employing ERNiCr-3 filler: (a), (b) CCGTA weldments; (c), (d) PCGTA weldments.

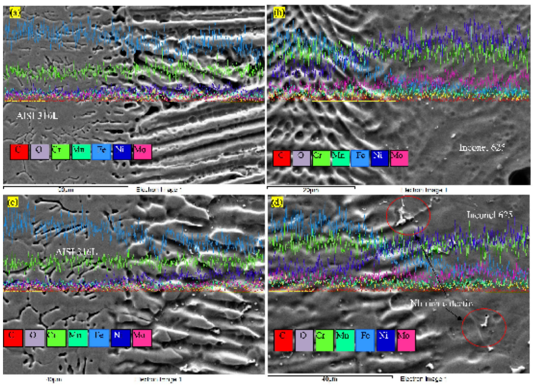

Fig. 7. Line Mapping EDS analysis on the dissimilar weldments employing ER2209 filler: (a), (b) GTA weldments; (c), (d) PCGTA weldments.

### 3.3.2 CCGTA and PCGTA weldments employing ER2209

Line mapping analysis on the CCGTA and PCGTA weldments employing ER2209 filler is represented in Figs. 7(a)-(d). The results showed the migration of elements from HAZ of AISI 316L to the weld zone or vice-versa for both the cases (Figs. 7(a) and (b)). It was also inferred that the weld zone has been enriched with Ni, Mo and Fe and these elements were highly predominated in CCGTA weldment (Fig. 7(c)) compared to PCGTA weldment (Fig. 7(d)). Tiny white phases were clustered at the HAZ of Inconel 625 in case of PCGTA weldment.

## 3.4 SEM/EDAX analysis

### 3.4.1 CCGTA and PCGTA weldments employing ERNiCr-3

SEM/EDAX point analysis was also carried out at the vari-

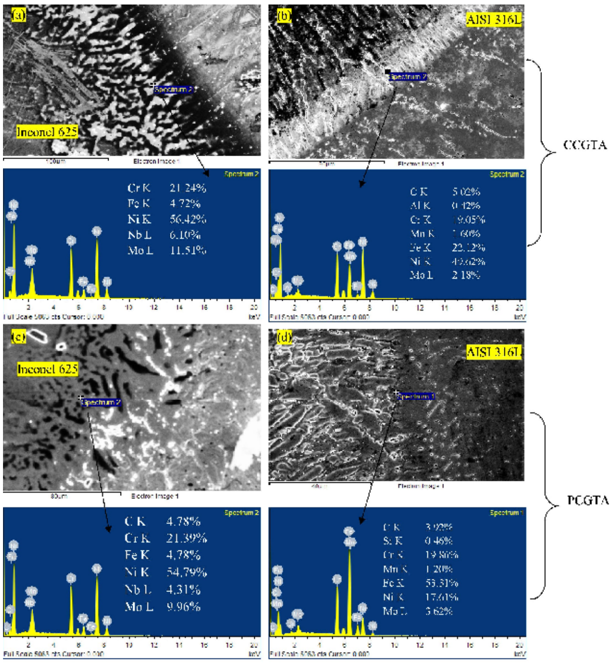

Fig. 8. SEM/EDAX point analysis on the dissimilar weldments of Inconel 625 and AISI 316L employing ERNiCr-3: (a), (b) CCGTA weldments; (c), (d) PCGTA weldments.

ous zones of the weldments and is shown in Figs. 8(a)-(d). More specifically, the analyses were focused at the weld interface of both the metals. It was inferred that the secondary phases observed at the Inconel 625 contained rich amounts of Nb, Ni, Mo and Cr for both the weldments (Figs. 8(a) and (c)). However Nb and Mo content in the PCGTA weldments were found to be slightly lower than the CCGTA weldments. The HAZ of AISI 316L was observed to have greater amounts of Cr, Ni, Fe and Mo.

### *3.4.2 CCGTA and PCGTA weldments employing ER2209*

The point analysis on the ER2209 weldments showed the presence of Nb, Mo, Ni and Cr along with other elements. In these weldments also, as discussed in Sec. 3.4.1, the Mo and Nb content appeared in the secondary phases were minimal in case of PCGTA weldments. The weld interface of Inconel 625 of both these weldments (Figs. 9(a) and (c)) showed higher amounts of Ni and Cr whereas Fe, Ni and Cr dominated at the weld interface of AISI 316L (Figs. 9(b) and (d)).

## *3.5 Mechanical characterization of the weldments*

### *3.5.1 Micro-hardness test*

Hardness trend of the dissimilar weldments obtained from the different welding techniques and filler wires is represented in Fig. 10. The hardness plot clearly envisaged that the weld zones exhibited slightly higher hardness compared to the base metal of AISI 316L, while it is observed to be lower as compared to Inconel 625. The average hardness at the weld zones were found to be 207 HV, 207 HV for CCGTA weldments and 210 HV and 219 HV for PCGTA weldments employing ER2209 and ERNiCr-3, respectively. Further, the weld interface of Inconel 625 side was observed to have the peak hardness while using ERNiCr-3 filler for both welding techniques.

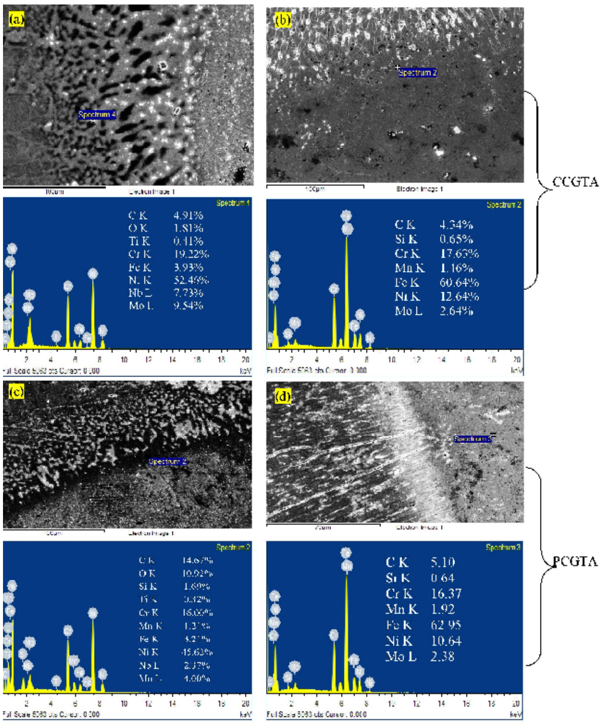

Fig. 9. SEM/EDAX point analysis on the dissimilar weldments of Inconel 625 and AISI 316L employing ER2209: (a), (b) CCGTA weldments; (c), (d) PCGTA weldments.

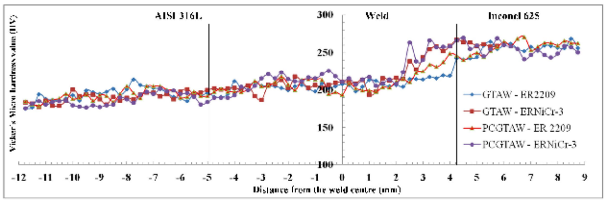

Fig. 10. Hardness profile of the dissimilar weldments of Inconel 625 and AISI 316L obtained by CCGTA and PCGTA welding processes employing ER2209 and ERNiCr-3 filler.

### *3.5.2 Tensile test*

Tensile studies corroborated that the fracture occurred at the parent metal side of AISI 316L for all the weldments in all the trials. The photograph of fractured samples is represented in Figs. 11(a)-(d).

The average ultimate tensile strength and ductility values were observed to be 602.7 MPa, 616.7 MPa and 41.3%, 37.8% for the CCGTA weldments employing ER2209 and ERNiCr-3 filler metals respectively; whereas the average tensile strength of 599.7 and 632.7 MPa and the ductility values of 40.0%, 42.2% were observed for the PCGTA weldments employing ER2209 and ERNiCr-3 filler metals. The cumulative mechanical properties of these dissimilar weldments are

Table 3. Cumulative tensile properties of the dissimilar weldments of Inconel 625 and AISI 316L.

| Weldment | Average UTS (MPa) | Average ductility (%) | Fracture zone |
|---|---|---|---|
| CCGTAW - ER2209 | 602.7 ± 6 | 41.3 ± 3 | Parent metal side of AISI 316L |
| CCGTAW - ERNiCr-3 | 616.7 ± 5 | 37.8 ± 2 | Parent metal side of AISI 316L |
| PCGTAW - ER2209 | 599.7 ± 5 | 40.0 ± 2 | Parent metal side of AISI 316L |
| PCGTAW - ERNiCr-3 | 632.7 ± 4 | 42.2 ± 1 | Parent metal side of AISI 316L |

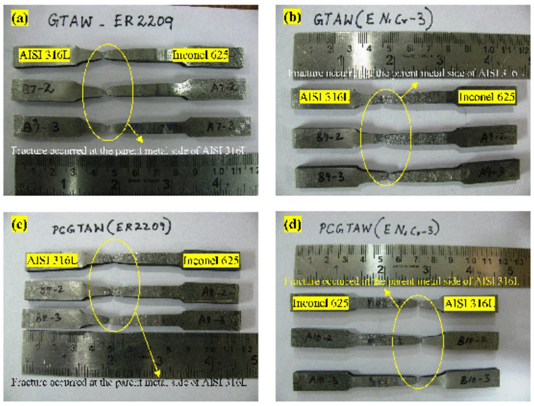

Fig. 11. Photographs of fractured tensile samples of CCGTAW employing: (a) ER2209; (b) ERNiCr-3 and PCGTAW employing; (c) ER2209; (d) ERNiCr-3 filler metals, respectively.

shown in Table 3.

Further SEM fractographs of the CCGTA and PCGTA weldments employing ERNiCr-3 are shown in Figs. 12(a) and (c). The fractographs showed the presence of scarce voids in the CCGTA weldments and bulk voids with fibrous network in case of PCGTA weldments. On the other hand, the CCGTA weldments employing ER2209 filler divulged the presence of voids which were running across the ductile tearing ridges; whereas clustery dimple facets spread uniformly in the fractured surface were witnessed for PCGTA weldments employing ER2209 filler as shown in Figs. 12(b) and (d).

### 3.5.3 Impact test

The photograph of impact tested samples is represented in Figs. 13(b) (i)-(iv). The impact test results showed that both the CCGTA weldments ruptured completely upon impact loading. Whereas notch deformation was occurred in the PCGTA weldments, which had given a clear indication that the deformation had not transpired completely.

The results showed that the impact resistance was much lesser for both CCGTA and PCGTA weldments employing ER2209 and the average impact toughness reported by these weldments was 8 J and 10 J respectively. Conversely the average toughness obtained for the ERNiCr-3 weldments was greater and found to be 77 J (CCGTAW) and 69 J (PCGTAW). SEM micrographs of the impact test samples envisaged the formation of dimples, tiny voids for the CCGTA and PCGTA weldments employing ERNiCr-3 welds (Figs. 14(c)-(d)). Whereas negligible amount of voids with cracked boundaries were observed at the CCGTA and PCGTA weldments of ER2209 which may influence in the deterioration of the impact energy (Figs. 14(a)-(b)).

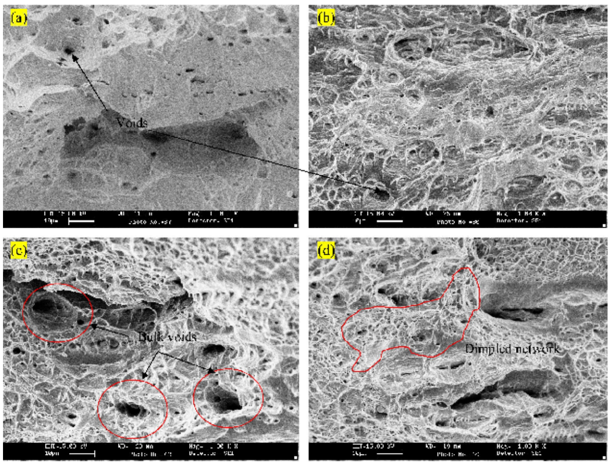

Fig. 12. SEM fractographs of CCGTAW employing: (a) ER2209; (b) ERNiCr-3 and PCGTAW employing; (c) ER2209; (d) ERNiCr-3 filler metals, respectively.

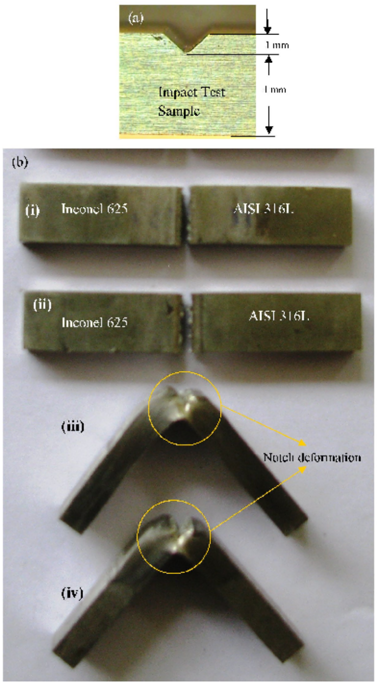

Fig. 13. (a) Impact test sample; (b) fractured samples of CCGTA weldments and PCGTA weldments employing: (i) and (ii) ER2209 filler; (iii) and (iv) ERNiCr-3 filler, respectively.

The following chapter encompasses the discussion on the structure-property relationship of these bimetallic combinations in detail. The cumulative impact toughness values are represented in Table 4.

Table 4. Impact test results of the dissimilar weldments of Inconel 625 and AISI 316L at room temperature.

| Weldment | Average impact strength (J) |
|---|---|
| CCGTAW - ER2209 | 8.0 ± 3 |
| CCGTAW - ERNiCr-3 | 77.0 ± 5 |
| PCGTAW - ER2209 | 12.0 ± 4 |
| PCGTAW - ERNiCr-3 | 69.0 ± 7 |

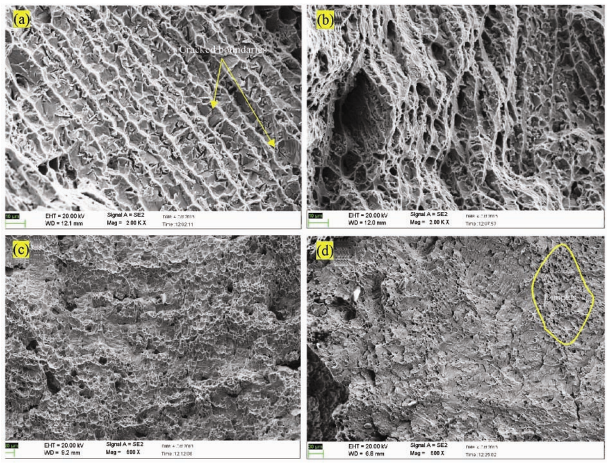

Fig. 14. Fractographs of Charpy Impact test samples of GTA weldments and PCGTA weldments employing: (a) and (b) ER2209 filler; (c) and (d) ERNiCr-3 filler respectively.

## 4. Discussion

The study outlines the investigation of the weldability, microstructure and mechanical properties of Inconel 625 and AISI 316L using two different welding techniques and filler wires. It is well inferred from the macrostructure studies that the dissimilar welds obtained from both the welding techniques were found to be free from any macroscopic defects. Further the gamma ray NDT inspection technique also confirmed the absence of weld defects such as porosity, undercuts, inclusions etc. in all the weldments. A closer view of the macrostructure depicted the formation of narrow beads on employing PCGTA welding technique in comparison with CCGTAW for both filler wires. This could be reasoned out because of the controlled heat input developed during the PCGTA welding process [15-18].

Microstructure examination clearly divulged the formation of secondary phases at the HAZ of Inconel 625 in case of CCGTA and PCGTA weldments employing ERNiCr-3. However the amount of secondary phases present in PCGTA weldments was found to be meager compared to CCGTA weldments. These secondary phases appeared as tiny white precipitates were inferred to be precipitates richer in Nb and Mo. These phases could be well established from the SEM/EDAX line mapping analysis in such a way that the Nb and Mo content found in the secondary phases were found to be minimal for PCGTA weldments. The lower amounts of Nb and Mo also indicated that these elements were dissolved in the matrix to the extent possible and remaining elements segregated as secondary phases. From this, it is vividly concluded that PCGTA weldments resulted in lower segregation compared to CCGTA weldments.

Migrated grain boundaries (MGBs) could be prominently seen in both the weld zones employing ERNiCr-3 filler. MGBs are prevalent in the fully austenitic welds and migration of the boundary is possible during reheating, such as during multi-pass welding [10]. Moreover the presence of higher amounts of Ni in the weld zones employing ERNiCr-3 clearly stated that the mode of solidification would be completely austenitic. The presence of Nb consituent in the filler wire also stabilizes the austenitic matrix.Also it was stated that MGBs normally resulted in ductility dip cracking (DDC) in the welded structures. As the filler wire consisted of higher amounts of Cr, it combated the DDC problem as evident from the microstructure. It could be seen that the filler wire chosen for the study was found to be reasonable for joining these metals.

Microstructures of ER2209 weldments showed the grain coarsening effect at the HAZ of Inconel 625 for CCGTA weldments. Whereas due to the controlled heat input generated during PCGTA welding, the grains were not much coarsened. Also it could be envisaged from the weld microstructure that the weld zone witnessed multi-directional grain growth. Except the presence of Mo and N, the major elements present in the composition of the ER2209 filler metal were Fe, Cr and Ni those have lower tendency to segregate in the interdendritic and inter-granular regions. Hence, there is a minimal driving force (constitutional under-cooling) to change the solidification mode from cellular to dendritic. Similar observations were reported by Shah Hosseini et al. [9]. Moreover the presence of delta ferrite stringers was evident at the HAZ of AISI 316L for all the weldments. It was reported that the delta ferrite stringers control the grain growth and minimize the susceptibility to HAZ liquation cracking [4, 10, 19].

Hardness measurements showed that there were not much differences observed for the various cases of the weldments. The hardness was slightly higher at the HAZ of Inconel 625. This could be well inferred to the presence of secondary phases containing Nb rich eutectics such as NbC, (Nb, Ti) C, $Mo_2C$ as evident from the microstructure and SEM/EDAX analysis. This is well in agreement with the earlier works of the author [18]. As the samples were etched by electrolytic process before SEM/EDAX analysis, there would be more chances of distortion of the elements and hence more reliable data could not be ascertained. Similarly the tensile studies showed that both CCGTA and PCGTA weldments employing ER2209 and ERNiCr-3 offered sound tensile properties. Since the fracture had occurred at the parent metal of AISI 316L in all the trials for all the weldments, it is difficult to arrive at a conclusion to recommend the suitable welding technique and filler wire for joining these bimetallic joints. However it was accrued from the study that the weld strength was found to be greater than one of the parent metal i.e. AISI 316L. This could be well explained with the microstructures such that the presence of ferrite stringers at the HAZ region was observed after these welding trials. It could be observed that fracture occurred at this zone where the ferrite stringers were not observed. This could be reasoned out to the CCGTA and PCGTA welding process resulted in slower cooling rate owing to higher heat inputs resulted in the formation of ferrite as the austenite to ferrite transformation takes place very slowly. The presence of ferrite at the HAZ contributed for better strength at the HAZ of AISI 316L and the tensile failures were occurred at the parent metal where the ferrite constituent was lowered after welding. Also the tensile strength of the welds could be determined either by v-notch tensile test or the tensile sample should be obtained in the longitudinal direction of the weld runs, which will be focussed in the future studies. SEM fractographs further corroborated that the mode of fracture was found to be ductile in nature by showing the micro/macro-voids with ductile tearing ridges. Moreover the weld zone showed the presence of Nb and traces of Ti and Cu apart from other alloying elements in the ERNiCr-3 filler, which contributed for greater strength by forming the complex inter-metallics. Also it is well proven that the welds produced using ERNiCr-3 were free from cracking in spite of the presence of MGBs. This could also be confirmed via the tensile test results by observing the fracture at the parent metal side.

Similarly all the tensile fractures occurred at the parent metal for both CCGTA and PCGTA weldments employing ER2209. It is a known fact that the filler wire ER2209 offered duplex structure containing both austenite and ferrite. Also the presence of Mo and N in the filler wire enhanced the strength of the weld zone. Furthermore researchers addressed that the enhanced weld properties could be achieved on having the optimal ferrite count. It is well elucidated from these studies that the selection of process parameters and filler wires for joining these bimetals provided pensive results.

To assess the behaviour and response of the weldments towards impact loading, Charpy V-notch tests were carried on these joints. Further as the tensile data supported all the filler wires to recommend a suitable method and filler wire for joining these bimetals the impact test was carried out to support the discussion. It could be well examined that the CCGTA and PCGTA weldments employing ERNiCr-3 offered better impact toughness compared to ER2209 weldments. This shall be reasoned again to the presence of austenitic structure prevailing in the weld zones of ERNiCr-3 and ferritic-austenitic structure for ER2209 weld zones. This is well in agreement with the investigations of Barnhouse and Lippold [20] stated that fully austenitic fusion zone offered better impact toughness than the welds with high ferrite number (FN). Joseph Davis [21] reported that the strength of the weld increases due to the presence of nitrogen additions however with the loss of toughness. Further in the welds containing ferrite, the ferrite exhibited secondary-phase strengthening with a concomitant decrease of ductility and toughness. This is well in agreement with the present work as well as supported by other researchers [22-24].

In a nutshell, the objective of the present study is to obtain successful dissimilar weldments of Inconel 625 and AISI 316L. The metallurgical and mechanical properties have been determined carefully to interpret the structure - property relationships. The outcomes of the study will be accolade to the industries employing these bimetallic combinations.

## 5. Conclusion

This study aimed to investigate the weldability and structure - property relationships of the dissimilar combinations of Inconel 625 and AISI 316L using Continuous and Pulsed Current GTA welding techniques employing ER2209 and ERNiCr-3 fillers. The outcomes of the study are summarized as follows:

(1) Successful dissimilar joints of Inconel 625 and AISI 316L could be achieved by CCGTA and PCGTA welding techniques using these filler wires.

(2) Microstructure studies showed the presence of secondary phases at the HAZ of Inconel 625 for the weldments employing ERNiCr-3; however these phases were found to be minimal for PCGTA weldment. Weld microstructures exhibited the formation of migrated grain boundaries on employing ERNiCr-3 however without the ductility-dip cracking. This tendency was achieved due to the presence of Nb in the filler.

(3) Tensile test results showed that the fracture occurred at the parent metal of AISI 316L for all the trials in all the cases.

(4) Although there were not much differences observed in the hardness profile and the tensile strengths, the impact test data clearly portrayed that both the CCGTA and PCGTA weldments employing ERNiCr-3 filler exhibited better impact toughness.

(5) Based on the metallurgical and mechanical property investigations, the present study recommends the use of pulsed current GTA welding technique employing ERNiCr-3 filler for joining these bimetallic combinations.

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**K. Gokul Kumar** received his Bachelor's degree in Mechanical Engineering 1990 and Master's Degree in Design during 2000 from University of Madras. He is currently pursuing his Ph.D. in the area of characterization of dissimilar weldments in VIT University. He has published five pioneered International journal papers. He is currently serving as Assistant Director (Students welfare) at VIT University.

**K. Devendranath Ramkumar** received his Bachelor's degree in Mechanical Engineering in 2001 and Masters and Doctoral Degree from VIT University in the year 2004 and 2012 respectively. He has published more than 35 research papers in the pioneered International Journals.

**N. Arivazhagan** obtained his B.E. degree in Production Engineering from University of Madras in 1997. He received his Master's Degree M.E. in Industrial Metallurgy from NIT Warangal in 2002 and PhD from IIT Roorkee in 2007. His areas of interest are dissimilar metal welding, high temperature corrosion and welding metallurgy. He has published more than 50 International Journal Papers. He is currently serving as Professor in the School of Mechanical & Building Sciences at VIT University.