Chapter 5

Welding Metallurgy of Corrosion-Resistant Superalloy C-276

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Abstract

Microsegregation occurs during solidification of fusion zone in alloy C-276. The concomitant precipitation of topologically close-packed phases P and μ has been reported to be responsible for the hot cracking observed in this alloy during welding. The clue to preventing hot cracking hence lies in suppressing microsegregation in the fusion zone. An important avenue towards this is the introduction of current pulsing during gas tungsten arc welding. Current pulsing was found to be effective in mitigating microsegregation; it was also found to refine the microstructure in the weld zone and improve the mechanical behavior of weld joints. Judicious choice of filler wire is of paramount importance to get weld joints free from segregation and with a good combination of mechanical properties. Joints made using arc welding methods were found to be highly resistant to corrosion in salt spray tests. Non-arc-based methods—laser welding and electron beam welding—were found to be effective in largely keeping the microsegregation at bay. This chapter elaborates on these issues.

Keywords: Superalloy C-276, Fusion weld joints, Microsegregation, Microstructure, Mechanical behavior, Corrosion resistance

1. Introduction

Alloy C-276 is a highly corrosion-resistant Ni-based superalloy. It has good resistance to corrosion in both oxidizing and reducing conditions. The alloy exhibits excellent resistance to corrosion in various environments encountered during chemical processing and allied industries and, as such, finds widespread application in these industries [1]. It has also been a highly attractive material for naval/marine applications owing to its excellent resistance to corrosion in seawater environments, especially under crevice corrosion conditions [1]. Testing for crevice corrosion in both quiescent seawater and flowing seawater showed that C-276 did not corrode. Critical crevice and critical pitting temperatures in tests conducted as per ASTM G48 methods C and D showed higher resistance of the alloy to crevice and pitting corrosion compared to stainless steel 304 SS, Incoloy 825 and 925, Inconel 625 and 725 [1].

Alloy C-276 is a nickel-based single phase superalloy. The nominal chemical composition of the alloy is given in Table 1. The main alloying elements are Cr, Mo, Fe and W. The alloy is designed based on solid solution strengthening; there is no precipitation hardening operating in this alloy [2].

Base/Filler Metal	Chemical Composition (% Wt.)								
	Ni	Mo	Cr	W	Co	Mn	Fe	Nb	Others
Hastelloy C-276	Bal	16.36	15.83	3.45	0.05	0.41	6.06	—	0.17 (V), 0.005(P), 0.002 (S), 0.02 (Si), 0.005(C)
ERNiCrMo-3	Bal	10.0	22.0	—	—	0.5	1.0	4.5	0.015 (P), 0.015 (S), 0.5 (Si), 0.5 (Cu), 0.4 (Al), 0.4 (Ti), 0.1 (C)
ERNiCrMo-4	Bal	17.00	16.5	4.5	2.50	1.0	7.0	—	0.04 (P), 0.03 (S), 0.5 (Cu), 0.02(C)

Table 1. Chemical Composition of Base Metal and Filler Wires

Chromium facilitates the formation of passive films in a wide range of oxygen-bearing environments, thereby contributing to alloy's corrosion resistance. Chromium also contributes to solid solution strengthening. Molybdenum imparts alloy resistance to reducing chemicals. In addition, by virtue of its large atomic size compared to that of nickel, it has a strong solid solution strengthening effect [3]. The behavior of W is similar to that of Mo. It is, in fact, an even more effective solid solution strengthener than Mo.

Alloy C-276 is generally supplied in the solution annealed condition. Solution annealing leads to the dissolution of the alloying elements in the austenitic matrix. Standard solution annealing treatment is comprised of soaking at 1120°C followed by rapid quenching to room temperature to prevent the formation of carbides and/or embrittling phases. Representative microstructure of the alloy in the solution treated condition is shown in Fig. 1.

Welding is a very important process which is used for the manufacturing of various products out of this alloy. Arc welding is a commonly used technique. The most common arc welding methods are gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). The choice of filler wire is an important part of the weld design process. Two types of filler wire have been employed: (i) filler wire with composition matching with that of base metal and (ii) overalloyed filler wire where alloying elements are present in the filler wire material at a level

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higher than in base metal. For a majority of applications, the filler wire with base metal composition is adequate [4]. For situations where the weld joints are expected to serve in highly aggressive environments, overalloyed filler wire is selected [4].

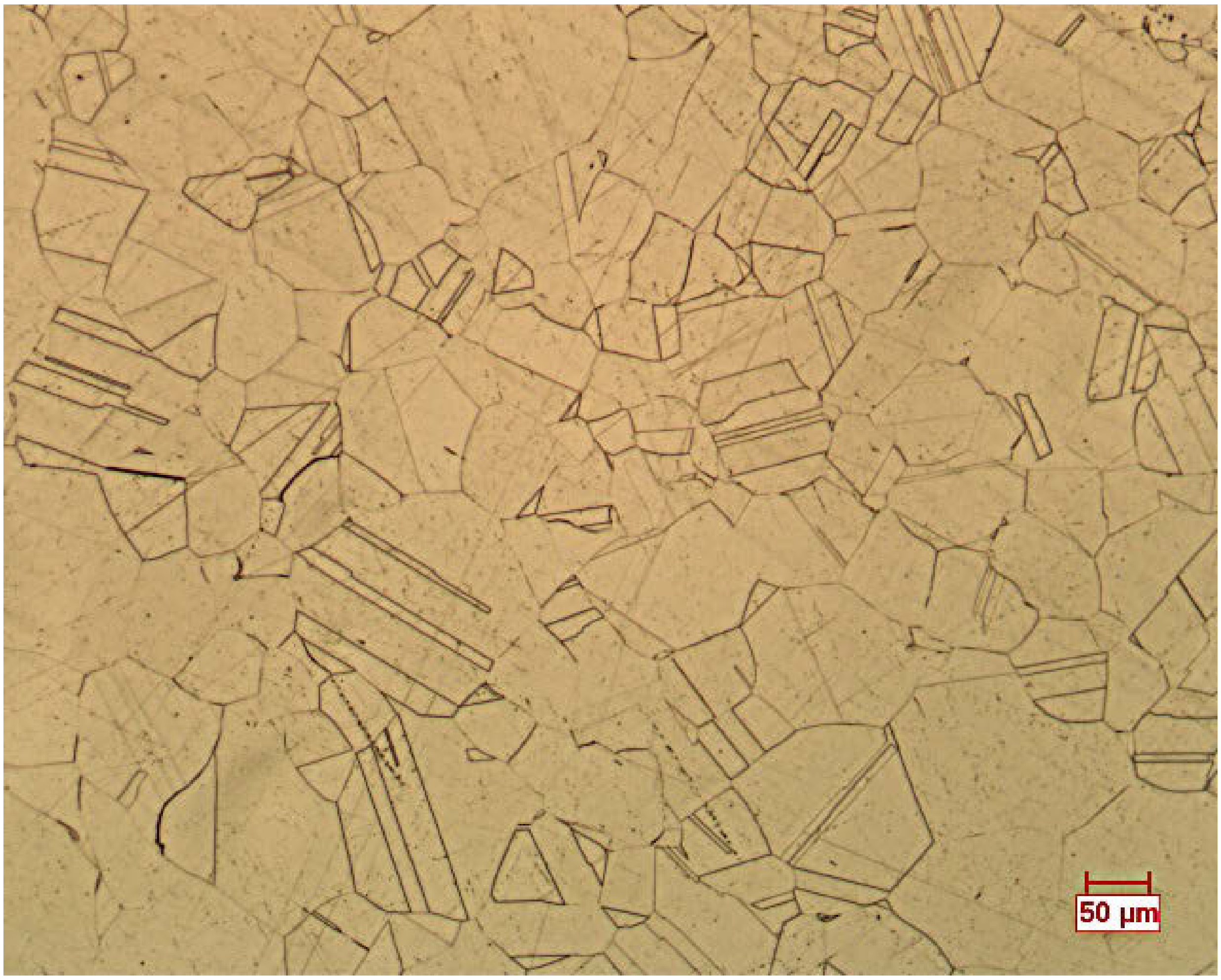

Figure 1. Microstructure of Hastelloy C-276 in as-received condition.

The performance of alloy C-276 can become adversely affected under certain circumstances and these were documented in the literature by different workers. It was emphasized that deleterious phases appear when the material is exposed to high temperatures. Tawancy [5] reported the precipitation of M_2C and μ phases in the form of a continuous layer at the grain boundary when the alloy is aged at 537°C for a long time, leading to a reduced tensile elongation and higher corrosion rate in boiling sulfuric–ferric sulfate solution. Akhtar et al. [6] reported the precipitation of molybdenum-rich μ phase after aging at 850°C, leading to a drop in impact energy; a completely intercrystalline brittle fracture occurred after aging for 120 h. Raghavan et al. [7] observed the formation of three distinct phases when the alloy was aged in the temperature range 650°C–900°C. Most abundant was the molybdenum-rich μ phase. The next most abundant phase was molybdenum-rich M_6C carbide. The third phase was tentatively identified as P phase, with a composition remarkably similar to that of μ phase.

Both μ and P phases belong to the group of topologically close-packed (TCP) phases. In general, the TCP phases in superalloys have a detrimental effect on several properties. Their rupture strength, tensile ductility and impact toughness at room temperature and corrosion resistance suffer a reduction when TCP phases appear in the microstructure [8].

The welding metallurgy of alloy C-276 gets complicated by the appearance of these TCP phases in fusion zone during welding. Cieslak et al. [9] carried out arc welding studies on alloys C-4, C-22 and C-276. All these grades are highly corrosion-resistant Ni-based alloys derived from Ni-Cr-Mo ternary system. Cieslak et al. [9] found that elemental segregation occurs during welding, leading to the formation of brittle TCP phases P and μ in alloys C-22 and C-276. The authors reported that alloy C-276 shows the highest susceptibility to hot cracking among the three alloys. They established that weld metal hot cracks are associated with intermetallic secondary solidification constituents P and μ. Perricone and Dupont [10] reviewed the subject of TCP phases in superalloys based on Ni-Cr-Mo system and summarized that the occurrence of TCP phases μ and P in alloy C-276 adversely affects weldability and other properties of interest.

The TCP phases P and μ are both rich in Mo and W, i.e., these elements preferentially partition into P and μ phases, depleting the gamma matrix of these elements to that extent. The higher the level at which Mo and W are present in the Ni-Cr-Mo-based alloy, the higher is the propensity for the formation of these brittle phases. For example, Perricone and DuPont [10] found no evidence for the occurrence of these phases in the weldments of a 12% Mo containing Ni-Cr-Mo alloy. However, upon increasing the Mo level to 24% at the expense of Ni, P and μ phases appear in the weld microstructure. Zheng [11] also reported that high concentration of Mo and W in Ni-Cr-Mo alloys leads to the occurrence of TCP phases during solidification. These phases find a place in the ternary equilibrium diagram for the Ni-Cr-Mo system. P phase forms at relatively high temperatures compared to μ phase. The latter phase is believed to be the product of a solid state transformation from the former.

2. Problem statement and critical review of the work done

Microsegregation in the weldment is the root cause of the problem and if it can be minimized by judicious selection of the welding process and parameters, the problem of hot cracking gets mitigated. Different approaches have been taken to suppress microsegregation in C-276 weldments.

Researches have been carried out to examine if pulsing of current during GTAW can be adopted to mitigate the problem of microsegregation in alloy C-276 weldments. In case of autogenous GTAW, there is significant segregation of Mo and Ni in the weld zone. The subgrain boundary shows higher levels of Mo and lower levels of Ni compared to subgrain interior (Figs. 2 a and 2b). In the case of autogenous pulsed current gas tungsten arc welding (PCGTAW), such segregation is essentially absent (Figs. 3 a and 3b).

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Figure 2. EDAX analysis of autogenous GTA welded alloy C-276: (a) subgrain boundary and (b) subgrain body.

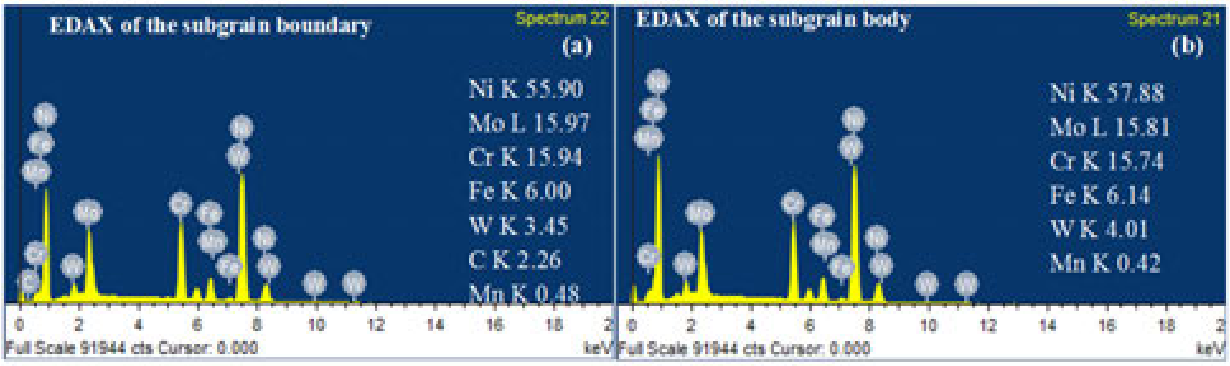

Figure 3. EDAX analysis of autogenous PCGTA welded alloy C-276: (a) subgrain boundary and (b) subgrain body.

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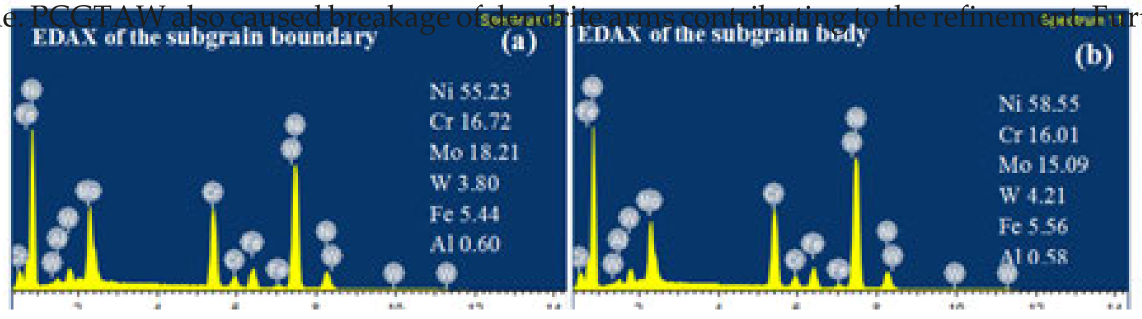
When welding was done using matching filler wire ERNiCrMo-4, the situation was the same. The chemical composition of the filler is also included in Table 1. In case of GTAW, it is seen that the subgrain boundary is enriched in Mo and impoverished in Ni and W compared to subgrain body (Figs. 4 a and 4b). In case of PCGTAW, in contrast to the case of GTAW, there is no significant difference between the subgrain boundary and subgrain body with reference to levels of any of the elements (Figs. 5 a and 5b). The microsegregation that was noticed in GTA fusion zone is thus essentially absent in the PCGTA fusion zone. It is believed that the occurrence of secondary constituents *P* and *μ*, deleterious in the context of hot cracking susceptibility of the alloy, also comes down to that extent. There is indeed some evidence to this effect. Welds made with GTAW, both autogenous and with filler wire, show indications suggestive of the occurrence of secondary phase(s) in weld interface regions. Welds made with PCGTA, in contrast, did not show any secondary phases. PCGTAW also resulted in refinement of microstructure in fusion zone. Figure 6 shows scanning electron microscope (SEM) images of weld zones of C-276 produced by autogenous welding using GTAW and PCGTAW respectively. The lower heat inputs coupled with higher instantaneous cooling rates associated with PCGTAW are considered responsible for the refinement of microstructure in the fusion zone. PCGTAW also caused breakage of dendrite arms contributing to the refinement. Further,

There have been other process/parameter changes attempted for welding of alloy C-276 to bring down the extent of microsegregation in the fusion zone of C-276 weld joints. For example, electron beam welding and pulsed laser welding have been shown to improve the quality of weldments. Guangyi et al. [12] reported that microsegregation in C-276 joints produced by pulsed laser beam welding is relatively less compared to the situation obtained with arc welding process. Manikandan et al. [13] studied laser-welded C-276 joints and found that microsegregation was within acceptable limits. The higher cooling rates and shorter solidification times associated with laser welding are believed to be responsible for the reduced elemental segregation.



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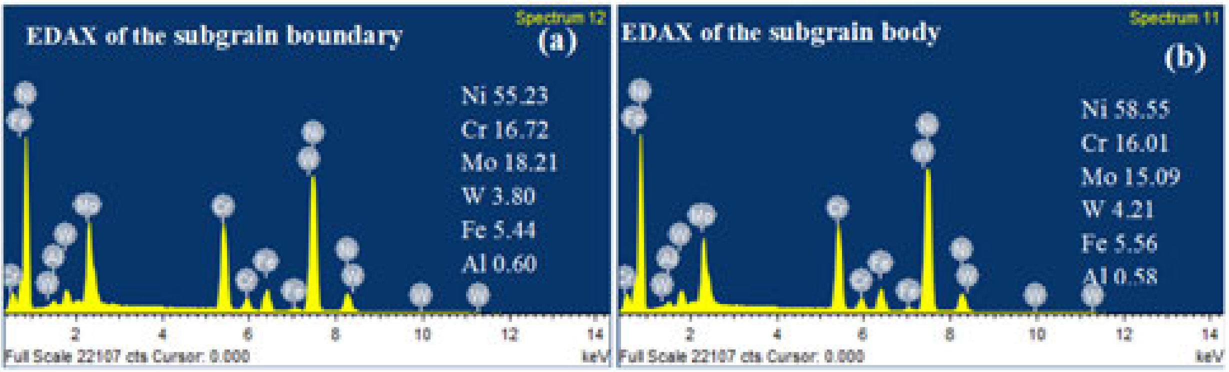

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Figure 4. EDAX analysis of GTA welded alloy C-276 with ERNiCrMo-4 filler wire: (a) subgrain boundary and (b) subgrain body.

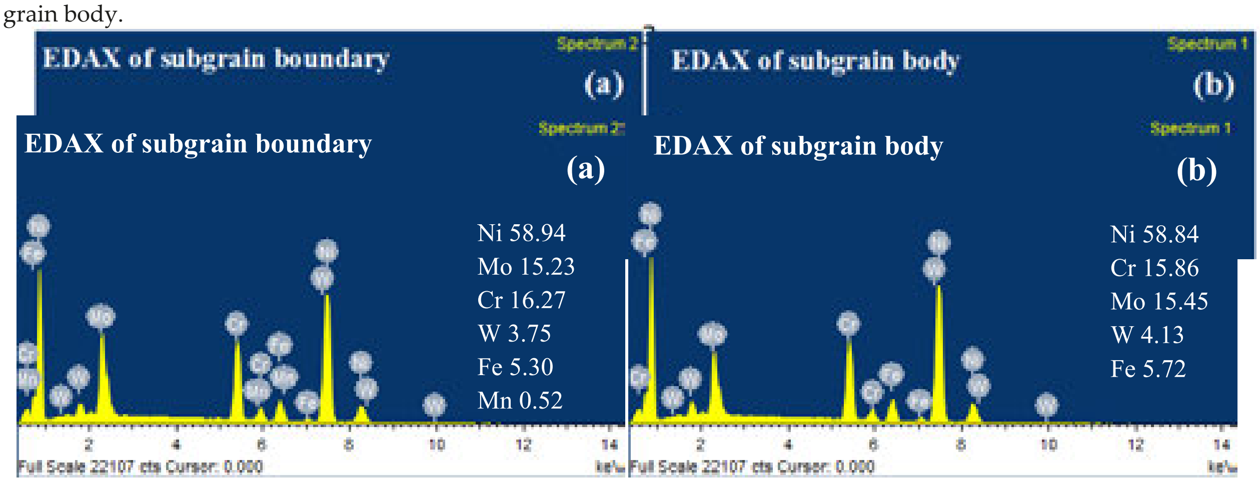

Figure 5. EDAX analysis of PCGTA welded C-276 alloy with ERNiCrMo-4 filler wire: (a) subgrain boundary and (b) subgrain body.

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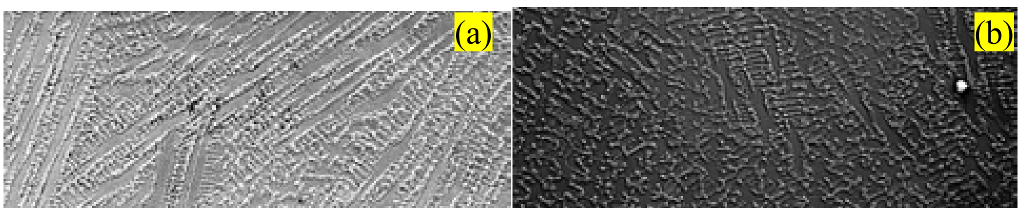

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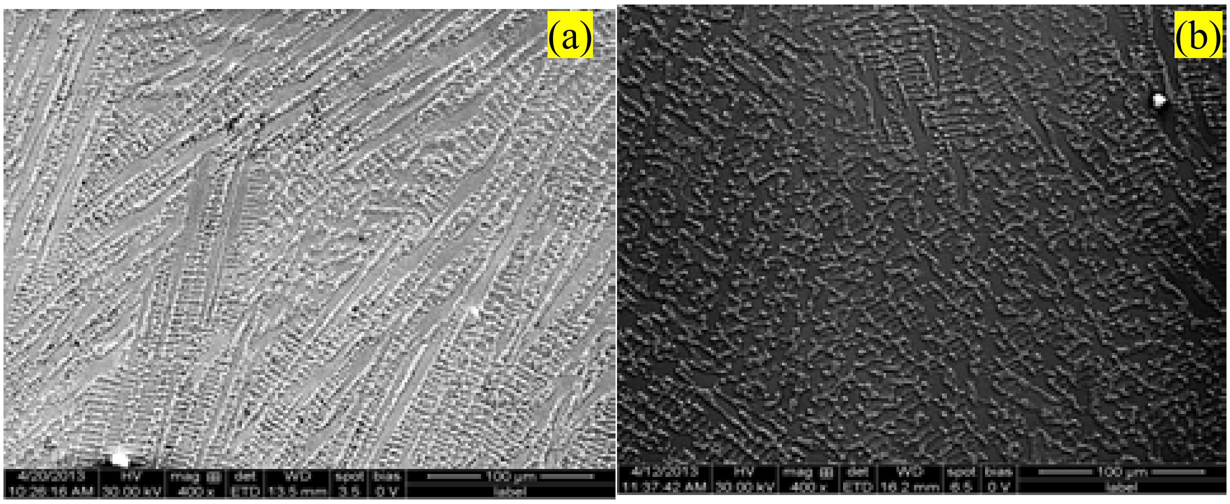

Figure 6. SEM micrograph of autogenous welded alloy C-276 (a) GTA and (b) PCGTA.

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Welding Process	Results of Tensile Testing			Impact Toughness
	Average UTS (MPa)	Average Yield Strength (MPa)	Average % Elongation	Average Energy (J)
Autogenous GTA	746	394	53	54
Autogenous PCGTA	763	405	66	56
GTA ERNiCrMo-4	766	403	34	53
PCGTA ERNiCrMo-4	815	413	41	56

Table 2. Results of Tensile and Impact Tests of Autogenous and ERNiCrMo-4 Weldments of Alloy C-276 Produced by GTAW and PCGTAW

The choice of the appropriate filler wire composition is also very important in restricting the elemental segregation in fusion zone of C-276 weld joints. Manikandan et al. [14, 15] carried out welding of C-276 using two different filler wire compositions: ERNiCrMo-3 with a nonmatching composition (lower Mo and Fe, higher Cr and Nb than the base metal) and ERNiCrMo-4 with a matching composition. There was much higher segregation of alloying elements in the fusion zone in case of the former filler wire, as shown in Table 3. Both the GTA and PCGTA weldments made with the filler wire ERNiCrMo-4 showed distinctly superior strength-toughness combinations than those made with filler wire ERNiCrMo-3. Table 4 gives the results of tensile testing and impact testing of ERNiCrMo-3 and ERNiCrMo-4 weldments produced using GTAW and PCGTAW. The relatively high degree of segregation in the fusion zone of welds made with the nonmatching filler wire are believed to be contributing to the poor mechanical behavior of weld joints.

Welding Process	Results of Tensile Testing			Impact Toughness
	Average UTS (MPa)	Average Yield Strength (MPa)	Average % Elongation	Average Energy (J)

Table

Results of Tensile and Impact Tests of Autogenous and ERNiCrMo-4 Weldments of Alloy C-276 Produced by GTAW and PCGTA

Type of Welding	Zone	Ni	Cr	Mo	W
GTAW ERNiCrMo-3	Weld subgrain boundary	40.81	16.50	29.87	3.79
	Weld subgrain body	55.25	19.17	15.31	1.89
GTA ERNiCrMo-4	Weld subgrain boundary	55.23	16.72	18.21	3.80
	Weld subgrain body	58.55	16.01	15.09	4.21

Table 3. Element Levels in Subgrain Boundary and Body of ERNiCrMo-3 and ERNiCrMo-4 GTA Weldments, Determined by EDAX

Welding Process	Results of Tensile Testing		Impact Toughness
	Average UTS (MPa)	Average Yield Strength (MPa)	Average Energy (J)
GTA ERNiCrMo-3	688	380	48
GTA ERNiCrMo-4	766	403	53
PCGTAW ERNiCrMo-3	706	388	50
PCGTA ERNiCrMo-4	815	413	56

Table 4. Results of Tensile and Impact Tests of ERNiCrMo-3 and ERNiCrMo-4 Weldment of Alloy C-276 Produced Using GTAW and PCGTAW

The excellent resistance of alloy C-276 to marine corrosion has been highlighted in the Introduction. The weld joints made of C-276 showed no weight loss when subjected to salt spray testing for 120 h as per ASTM B117. This was true whether it was autogenous welding or welding with filler wire ERNiCrMo-3 or ERNICrMo-4 and whether it was GTAW or PCGTAW. Prima facie, there appears no need for adopting special welding methods or overalloyed filler wire for producing welded structures of C-276 for marine applications [16].

3. Conclusions

1. PCGTAW of alloy C-276 resulted in reduced severity of microsegregation compared to GTAW. It is believed that the occurrence of secondary constituents P and μ, deleterious in the context of hot cracking susceptibility of the alloy, also comes down to that extent.

2. PCGTAW gave rise to superior mechanical properties—higher strength and at the same time better toughness—compared to GTAW. The refined grain structure with reduced severity of microsegregation is believed to be responsible for the improved mechanical properties of the PCGTA weld joint.

3. Laser welding of alloy C-276 can be done to produce weld joints with acceptable level of microsegregation and a good combination of mechanical properties.

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4. Appropriate choice of filler wire composition is important in the context of restraining the microsegregation in C-276 weld joints and realizing a good combination of strength and toughness of the weld joints.

5. Weld joints produced in alloy C-276 showed good corrosion resistance when subjected to salt spray testing as per ASTM B117.

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