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# Evaluation of Alloy C276 for High Strength Fastener Applications in Marine Environments

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**Abstract:** The nickel-base alloy C276 holds promise as a high strength fastener material for use in marine environments. The resistance of the material in annealed condition to pitting and crevice corrosion in seawater environments has been well documented. The strength of the alloy can be increased substantially by strain hardening, but this may have an adverse effect on the corrosion resistance. Slow strain rate testing (SSRT) was carried out on the material in strain hardened condition to evaluate its resistance to corrosion in seawater environment. Limited SSRT was also carried out on a comparative basis on cold drawn Alloy 686, a nickel-base alloy demonstrated to be an excellent material for high strength fastener applications in seawater environments. Test results for the alloys C276 and 686 are similar. The study suggests that Alloy C276 is an adequate material for high strength fastener applications in seawater environments.
**Key Words:** Nickel-base alloy C276, Fastener application, Degradation in seawater environment, Slow strain rate testing.

## 1. Introduction

Fasteners with a high degree of corrosion resistance are required while working with very aggressive marine environments. The construction of ships, other marine vessels and equipment requires the use of corrosion resistant fasteners. Often the designer has also the requirement to work with materials with high strength levels. The high strength level inevitably brings along with it a high degree of susceptibility to environmental degradation. Fasteners are generally much smaller than the components which they hold together; they should accordingly be more corrosion resistant to offset any effects of galvanic corrosion. A severe state of stress occurring in the fasteners would facilitate environment induced cracking – in particular stress corrosion cracking and hydrogen embrittlement – potentially leading to failure of the component. Fasteners based on stainless steels such as AISI 316 stainless steel and nickel-copper alloys (Monels) have proved to be inadequate for service in severe marine environments[1]. Literature reveals that failures of the Monel alloy K-500 fasteners have occurred due to corrosion from galvanic interaction and hydrogen embrittlement[2]. For this reason, highly resistant nickel-base fasteners become candidate materials in marine service. However, nickel-base alloys such as Alloy 625 have also been found not capable of withstanding the arduous conditions encountered in aggressive marine environments[2]. Severe crevice corrosion has taken place when fasteners made of the alloy 625 were used for marine construction[1].

Fasteners made of the nickel based superalloy Alloy 686 have been extensively evaluated by Special Metal Corporation, USA for service in aggressive marine environments[2-5]. The alloy was found to exhibit excellent corrosion resistance to seawater and hydrogen embrittlement as well. High strength can be realized by subjecting the material to cold working, with ductility and fracture toughness remaining at respectable levels even after cold working. Fasteners made of Alloy 686 have been reported to solve many of the problems encountered with existing grades of corrosion resistant fasteners.

Alloy C276 is very similar in chemical composition to Alloy 686. It has high levels of Mo and W like Alloy 686. These elements increase the resistance to localized corrosion – notably pitting and crevice corrosion. Further, yield strength values of Alloys C276 and 686 in the annealed condition are comparable and yield strength of Alloy C276 can be increased substantially by cold working, as is the case with Alloy 686. Alloy C276 and its equivalents are available from a number of manufacturers in the world market. Hence, it is considered necessary to study the corrosion behavior of the Alloy C276 for evaluating it as a high strength fastener material in marine environments involving severe corrosive conditions.

There have been some concerns raised on the corrosion resistance of Alloy C276 in the published literature. Kane and Greer[6] identified hydrogen embrittlement of Alloy C276 at room temperature as a possible failure mode in long term charging. Ahluwalia[7] brought out that cold working of Alloy C276 could make the alloy susceptible to hydrogen embrittlement. Ahluwalia also pointed out that Alloy C276 was shown to be susceptible to stress corrosion cracking. However these concerns were raised based on the testing carried out on the alloy simulating oil and gas production environments and environments encountered in hot sour gas production. It is necessary to evaluate the Alloy C276 with specific reference to naval environments.

Slow strain rate testing (SSRT) has remained as an excellent, reliable and reproducible accelerated laboratory test for evaluation of environmentally induced degradation of high performance alloys. A wide spectrum of materials has been studied using this test technique. It can address both hydrogen embrittlement and stress corrosion cracking, degradation mechanisms of concern to this material, as brought out in the previous paragraph. The study reported here involves SSRT of cold worked Alloy C276 with specific reference to its use as a high strength fastener material in marine environments. Susceptibility to environment induced degradation has been evaluated by conducting SSRT in laboratory air environment and synthetic seawater environment. Testing was done under free corrosion conditions as it is truly representative of hydrogen entry conditions, unless when a cathodic protection system is in place. Three different strain rates were used for the testing.

Limited SSRT was also carried out on cold worked Alloy 686 under comparable conditions to use the data thereby obtained for reference purposes. Recognizing that Alloy 686 has been shown to demonstrate excellent performance for application in highly aggressive marine environments, this would enable ranking of Alloy C276 with reference to Alloy 686 for critical marine fastener applications.

## 2. Experimental

Alloy C276 was received from Mishra Dhatu Nigam Limited, Hyderabad, India in the form of sheet. It was in cold rolled and annealed condition. The material was cold rolled to impart a reduction of 30 %. The optical microstructure of the material in the cold rolled condition is shown in Fig. 1. The elongated grain structure can easily be made out. Some amount of twinning is also seen.

The mechanical properties in the as-received condition are given in Table 1.

**Table 1: Mechanical properties of Alloy C276 in the as-received condition**

| Property | Value as reported in Test Certificate of Supplier |
|---|---|
| Ultimate tensile strength (MPa) | 800 |
| Percent elongation | 65 |
| Percent reduction in area | 73 |

Alloy 686 was supplied by Special Metals Corporation in the form of 35 mm diameter bars. They were in cold drawn condition; the extent of cold drawing was 30 %. The chemical composition of the two alloys, as reported by the respective suppliers, is given in Table 2.

**Table 2: Chemical Composition of Alloys C276 and 686 (in weight %)**

| Alloy | Cr | Mo | Fe | W | Mn | Co | Si | C | S | P | V | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C276 | 16.01 | 15.5 | 5.78 | 4.12 | 0.46 | 0.35 | 0.05 | 0.006 | 0.003 | 0.005 | <0.1 | Bal |
| 686 | 20.5 | 16.3 | 1 max | 3.9 | 0.75 max | 0.01 max | 0.08 max | 0.01 max | 0.02 max | 0.04 max | 0.01 max | Bal |

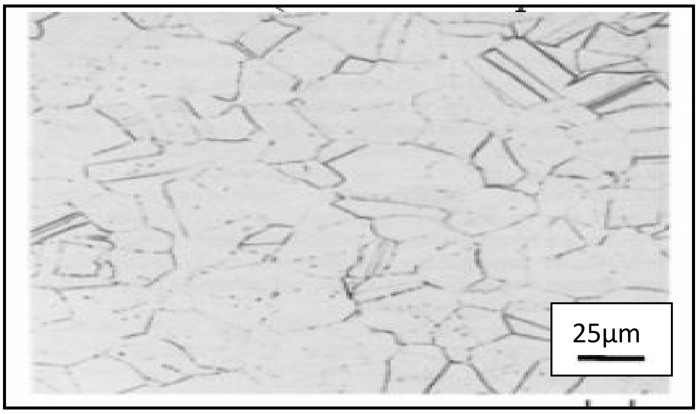



**Figure 1 Optical microstructure of Alloy C276 after cold rolling. Etchant: Glyceregia 15cc HCl + 10cc Glycerol + 5cc $HNO_3$.**

The strength and ductility values for the two alloys in cold worked condition are shown in Table 3. Values for Alloy 686 are extracted from the Test Certificate supplied by Special Metals Corporation. No tensile testing was done on Alloy C276 after cold rolling. For a comparative appreciation of the mechanical properties of the two alloys, values for 30% cold worked Alloy C276 were extracted from the website www. corrosionmaterials.com[8] and included in Table 3.

**Table 3 Strength and ductility values of the alloys taken up for SSRT**

| Material | Yield strength (MPa) | Ultimate tensile strength (MPa) | % Elongation | Source of data |
|---|---|---|---|---|
| 30 % cold rolled Alloy C276 sheet | 1068 | 1158 | 15 | www.corrosionmaterials.com |
| 30 % cold drawn Alloy 686 rod | 1069 | 1198 | 20.6 | Supplier's Test Certificate |

The drawing of notched tensile specimen adopted for conducting SSRT is shown in Fig. 2. The specimens were machined out of the cold rolled sheet in case of Alloy C276. Specimens conforming to the same drawing were machined out of the 35 mm diameter cold drawn bar in case of Alloy 686.

The notches were polished with a cotton thread with application of diamond paste. The value of stress concentration factor $k_t$ works out to 2.98. The three strain rates used for testing Alloy C276 were $10^{-5}$, $10^{-6}$ and $10^{-7}$ $s^{-1}$. The Alloy 686 was however tested at only one strain rate ($10^{-6}$ $s^{-1}$). The SSRT was carried out in two different environments: (i) air having relative humidity of 30 – 40 % (henceforth referred to as 35 % RH air), and (ii) synthetic seawater. The synthetic seawater was prepared by the method devised by Kester[9]. For each combination of test parameters, one test specimen was tested. While it is advisable to test more than one specimen to arrive at an average / representative value, the limited availability of test material came in the way. The tests were all carried out at ambient temperature.

The susceptibility to cracking in synthetic seawater was calculated

(i) as the ratio of time to failure:

$$\text{Ratio of time to failure} = \frac{\text{Time to failure in synthetic seawater}}{\text{Time to failure in 35 \% RH air}} \quad (1)$$

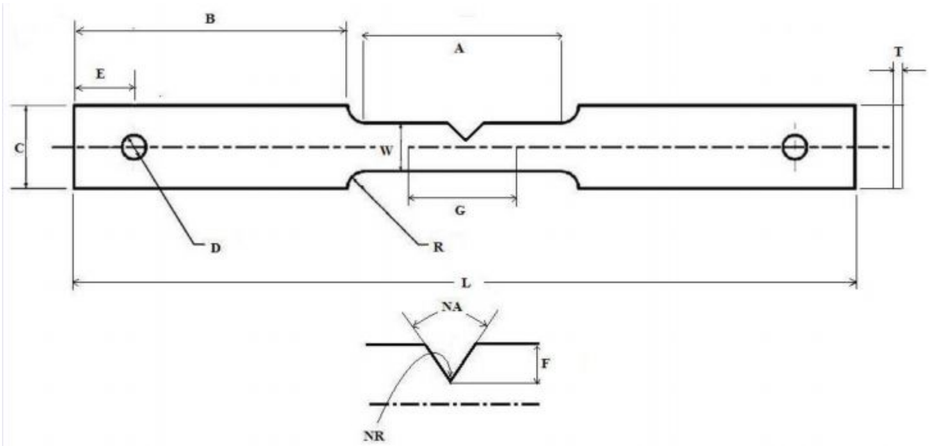
(ii) as percent loss of plasticity:

$$\% \text{ loss of plasticity} = \frac{\% \text{ Elongation in } 35\,\% \text{ RH air} - \% \text{ Elongation in synthetic seawater}}{\% \text{ Elongation in } 35\,\% \text{ RH air}} \quad (2)$$

(iii) as fractional loss of notched tensile strength (NTS):

$$\% \text{ loss of notched tensile strength} = \frac{\text{NTS (in } 35\,\% \text{ RH air)} - \text{NTS (in synthetic seawater)}}{\text{NTS (in } 35\,\% \text{ RH air)}} \quad (3)$$

At the end of SSRT, the broken tensile specimens were examined in a scanning electron microscope to get information about the operating modes of fracture.




| | |
|---|---|
| G - Gauge length | = 32 |
| W - Width of gauge section | = 6 |
| D - Diameter of hole or pin | = 6 |
| R -Radius of the fillet | = 5 |
| E - Edge distance from pin | = 12 |
| L - Over-all length | = 140 |
| F - Width of notch | = 2 |
| B - Length of grip section | = 50 |
| A - Length of reduced section | = 40 |
| T -Thickness | = 3 |
| C - Width of grip section | = 16 |
| NR - Notch root radius | = 0.125 |
| NA - Notch angle | = 60$^{o}$ |

**Figure 2 Drawing of the notched tensile specimen adopted for conducting SSRT (Dimensions are in mm)**

## 3. Results and Discussion

### 3.1 Studies on Alloy C276

Table 4 summarises the SSRT results generated on Alloy C276 in cold rolled condition. Table 5 gives values of ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength in synthetic seawater environment for C276 alloy tested in cold rolled condition. These values have been calculated from the experimental data presented in Table 4 using equations 1, 2 and 3 respectively.

**Table 4 Slow strain rate test results for alloy C276 in different environments at different strain rates**

| Strain Rate $s^{-1}$ | Medium | Elongation % | Time (h) | Max Stress (MPa) |
|---|---|---|---|---|
| $10^{-5}$ | 35 % RH Air | 6.35 | 1.73 | 797 |
| $10^{-5}$ | Synthetic Seawater | 5.54 | 1.64 | 763 |
| $10^{-6}$ | 35 % RH Air | 6.19 | 17.03 | 793 |
| $10^{-6}$ | Synthetic Seawater | 5.49 | 16.14 | 765 |
| $10^{-7}$ | 35 % RH Air | 6.58 | 162.48 | 751 |
| $10^{-7}$ | Synthetic Seawater | 5.93 | 146.26 | 732 |

**Table 5 Ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength for alloy C276 for the strain rates adopted**

| Strain Rate $s^{-1}$ | Ratio of time to failure | Percent loss of plasticity | Percent loss of notched tensile strength |
|---|---|---|---|
| $10^{-5}$ | 0.95 | 5.2 | 4.3 |
| $10^{-6}$ | 0.95 | 11.3 | 3.5 |
| $10^{-7}$ | 0.90 | 9.9 | 2.5 |

Ratio of time to failure values in the range 0.8 to 1.0 normally denote high resistance to environment-assisted degradation[10]. For all the three strain rates used for testing, the ratio of time to failure value is equal to or higher than 0.9. This suggests that the alloy shows good corrosion resistance in synthetic seawater environment.

Figures 3a and 3b show scanning electron microscopic images of fracture surfaces of C276 samples tested at $10^{-6}$ $s^{-1}$ in 30 % cold rolled condition. Figure 3a is for 35 % RH air and 3b is for synthetic seawater. It can be seen that even in synthetic seawater fracture by micro void coalescence dominates. This shows that plasticity is largely retained, in line with the relatively low percent loss of plasticity value (11.3) obtained.

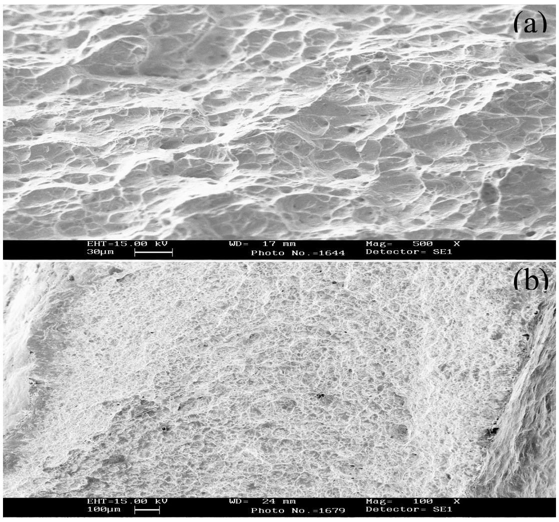



**Figure 3 SEM fractographs (a) 35 % RH air (b) synthetic seawater C276 in 30 % cold rolled condition. Strain rate $10^{-6}$ ($s^{-1}$)**

### 3.2 Studies on Alloy 686

Table 6 summaries the SSRT results generated on Alloy 686 material in the 30 % cold drawn condition. As already mentioned, testing was done at only one strain rate. There was drop in the % elongation, time to fracture and notched UTS when testing was done in synthetic seawater. The behavior is thus similar to what was observed with 30 % cold rolled Alloy C276. Included in Table 6 are the values of ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength calculated using equations 1, 2 and 3 respectively. The ratio of time to failure at the intermediate strain rate used for experimentation is 0.90, well in the middle of the range 0.8-1.0 considered safe. This is in line with the well documented good resistance of this alloy to seawater environment.

**Table 6 Results of SSRT on Alloy 686 in 35 % RH air and synthetic seawater Strain rate $10^{-6}$ $s^{-1}$**

| Medium | Elongation % | Time taken to failure (h) | Max Stress (MPa) |
|---|---|---|---|
| 35 % RH air | 4.70 | 8.73 | 709 |
| Synthetic Seawater | 4.31 | 7.88 | 681 |
| | Percent loss of plasticity = 8.3 | Ratio of time to failure = 0.90 | Percent loss of notched tensile strength = 3.9 |

### 3.3 Comparison of Alloys C276 and 686 with reference to degradation in synthetic seawater

Table 7 compares the ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength for Alloy C276 in 30 % cold rolled condition and Alloy 686 in 30 % cold drawn condition. The percent loss of notched tensile strength is essentially the same for both materials. While the ratio of time to failure is higher for C276, the percent loss of plasticity is lower for 686. Considering that the comparison is being made based on very limited quantum of data and that the mill forms from which samples for SSRT were extracted were also different (cold rolled sheet for C276 and cold drawn bar for 686), it appears reasonable to conclude that the two alloys show similar resistance to corrosion in synthetic seawater environment.

**Table 7 Comparative performance of C276 and 686 in synthetic seawater environment Strain rate $10^{-6}$ $s^{-1}$**

| Susceptibility- to-cracking index | C276 | 686 |
|---|---|---|
| Ratio of time to failure | 0.95 | 0.90 |
| Percent loss of plasticity | 11.3 | 8.3 |
| Percent loss of notched tensile strength | 3.5 | 3.9 |

Hibner and Shoemacher [2] reported studies on crevice corrosion behavior of plates of Alloy C276 and Alloy 686 in quiescent seawater environment and crevice corrosion behavior of tube sections of the two alloys in flowing seawater environment and found that none of the two alloys corroded under the test conditions used. This was in contrast to the behavior of Alloy 625, which suffered corrosion under the same test conditions[2]. The similar resistance to synthetic seawater environment shown by Alloys C276 and 686 in the present study is thus in line with the findings of Hibner and Shoemacher.

It is relevant to note from Table 3 that the two alloys after 30 % cold reduction have essentially same 0.2 % offset yield strength level. The ultimate tensile strength values are also not very different. Both materials have been evaluated in a very high strength condition. It has been well documented that the susceptibility to environmental degradation increases with increasing strength level[11]. It has also been well established that cold work impairs the corrosion resistance[12]. It is thus noteworthy that SSRT has shown high degree of resistance to corrosion in synthetic seawater environment in a high strength condition, where strain hardening contributed substantially to the overall strength of the material. Hibner and Shoemacher[2], based on corrosion studies in acidified 6 % ferric chloride solution, rated Alloy 686 as the best with Alloy C276 coming immediately next to it. The present study based on SSRT suggests that Alloy C276 compares favorably with Alloy 686 with respect to behavior in seawater environment. The Alloy C276 produced in high strength condition by exploiting strain hardening thus appears adequate for use as a fastener material in marine environments.

## 4. Conclusions

1. SSRT of 30 % cold rolled Alloy C276 in synthetic seawater results in lower values of time to failure, plasticity and notched tensile strength, compared to SSRT in 35 % RH air. However, ratio of time to failure is 0.9 or higher at all the three strain rates used for testing, indicating high resistance of the material to corrosion in seawater environment.

2. SSRT on 30 % cold drawn Alloy 686 resulted in lower values of time to failure, plasticity and notched tensile strength, compared to SSRT in 35 % RH air. The ratio of time to failure was high (0.9), in line with the documented literature that the alloy shows excellent resistance to corrosion in seawater environments.
3. Based on the values of different susceptibility-to-cracking indices obtained in the present study, it is seen that the resistance to degradation in of Alloy C276 in seawater environment compares favorably with that of Alloy 686.
4. The results suggest that cold worked Alloy C276 is suitable for use in the form of high strength fasteners for marine applications.

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