 DOI: 10.1002/maco.200804149

Corrosion Concepts

In this forum readers will be able to present practical problems for discussion. It is envisaged that these contributions will include not only discussion of general problems and incidents of corrosion but that suggested remedies will also be presented and discussed. It is hoped that this exchange of knowlegde and experience will become a permanent feature of this periodical. We are particularly anxioux that both Senior Scientists and those with more practical experience will make use of this forum to exchange information, problems and potential remedies.

Mechanic treatment of fastener holes: The influence of compressive residual stress on the corrosion behaviour of aluminium alloys

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Corrosion has a significant impact on the life cycle cost of military aircraft. Fleet experiences show that structural areas around joining elements (rivets, bolts) and faying surfaces are particularly sensitive to corrosion. During the repair currently performed the corrosion usually is blended out, the surface protection applied, the fastener inserted and a new top coat applied. Blending out corrosion often results in a reduction of fatigue life. To restore fatigue life the induction of compressive stress in the area affected is common practice. It is generally accepted that the induction of compressive residual stress extends fatigue life but its impact on the overall corrosion behaviour of alloys is discussed controversially in the literature. For this reason the influence of compressive residual stress on the corrosion behaviour was investigated in a joint experimental project. The compressive residual stress was introduced in different ways on laboratory scale and the specimens artificially weathered to simulate the effect of corrosion.

1 Introduction

As a consequence of the increasing age of aircraft and the need to use aircraft beyond the original design life, there will be an increasing degree of corrosion in the future. So corrosion repair will become more and more necessary in the years to come.

Experience shows that especially in the areas of joining elements (riveted joints, bolts) no way of effective long-term corrosion protection has been found yet. Detected corrosion damage has to be removed. New surface protection systems have to be applied to prevent corrosion from restarting.

During corrosion repair residual compressive stress is induced in many cases, sometimes intentionally to restore fatigue life, and sometimes unintentionally as a result of the working process. In the literature there are different opinions about the effect of compressive residual stress on the corrosion resistance of alloys.

For this reason the influence of residual stress on the corrosion behaviour was investigated in a joint experimental project for two aluminium alloys widely used in aircraft design. The compressive residual stress was introduced in different ways.

The corrosion behaviour of the specimens was tested using aggravating corrosion test conditions. The tested specimens were evaluated by metallographic investigations.

2 Literature research

If corrosion fatigue is the problem, the generation of compressive residual stress is a possibility to extend the lifetime. The effectiveness of the life extension technique depends on the stage of the implementation related to the baseline life. However, if only the influence of residual stress to corrosion resistance is to be estimated, different opinions about the correlation of residual stress and the corrosion behaviour can be found in the literature.

Looking at the theory, the conditions for the appearance of corrosion are

– a difference in the local electrochemical potential;
– an electrolyte;
– a conducting connection between the areas of different potential.

Crevice corrosion is caused by a local dissolution of a passive layer. The mechanism of crevice corrosion is not

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influenced by cold forming, but the number of weak points in the passive surface can increase due to plastic deformation, and in that way the extent of crevice corrosion can be influenced.

Generally, the occurence of corrosion is dependent on several individual parameters.

Multiphase materials often show areas of different potential, which can cause corrosion. However, macroscopically uniform metallic surface shows a lot of microscopic cathodic and anodic areas. For example, there exists a potential difference between the metallic grains and the grain boundaries, which frequently causes the dilution of the grain boundaries and leads to intercrystalline corrosion. Therefore, grain boundaries are weak points as far as corrosion resistance is concerned and as few grain boundaries as possible shall be in contact with the electrolyte to avoid corrosion.

Strongly deformed areas of a material will become more anodic compared to non-deformed areas [1–3].

To sum up, there are two different opinions about the influence of compressive residual stress on corrosion resistance:

- Arguments in favour of an increase in corrosion resistance:

- the process which generates compressive residual stress (shot peening, rolling, cold expansion of holes) also produces a high surface quality.
- The tool marks caused by the manufacturing process disappear by processes like rolling or split sleeve treatment.
- The surface exposed to the corrosive environment is reduced by processes cited above.
- The grain boundaries at the surface of the components are closed by the compression process.
  So no accumulation of corrosion is expected.

- Arguments for a reduction of the corrosion resistance

- Generating compressive residual stress brings the material to a higher imperfection of structure and so to a higher level of energy. The density of dislocations is increasing.
- The material itself wants to obtain a lower level of energy by corrosion.
- No stable state of the material is obtained by cold working.

A research of the specialized literature for different metallic materials and different test conditions yielded no consistent result.

Regarding to corrosion fatigue a clear positive effect of compressive residual stress is established. For stress corrosion cracking an improvement of the corrosion resistance was found in most cases. If only corrosion behaviour was tested, sometimes the resistance to corrosion is improved by compressive residual stress, and sometimes it is diminished.

The results are different because of the individual specific test conditions like:

- material
- electrolyte
- testing conditions (like temperature, time)
- different ratios between the anodic and the cathodic areas, etc.

If an improvement of the corrosion resistance was stated, the reason was mostly due to surface effects caused by the working process. If a reduction of the corrosion resistance was stated, the reason mostly was seen in lattice dislocations.

A survey of selected literature is given in ref. [1–21]. This literature survey was evaluated in an internal report of the company IABG.

3 Specimen material

For the investigation two aluminium alloys very common for fighter aircraft were selected:

- 3.1354 T 351 (AA 2024 T351) and
- 3.4364 T 7351 (AA 7075 T7351).

3.1 Parameters of treatment

The different specimens simulated typical problem areas for corrosion like fastener holes with joining elements and areas with corrosion removed. The residual stress has been produced by three typical repair methods.

- Rolling of holes (Fig. 1)

The cold expansion is applied using a rotating tool. The diameter of the tool can be expanded to produce compressive stress at the inner surface of the hole. The rolling conditions used for the investigation (diameter, tooling, machine parameters like pressure, velocity, etc.) are qualified for specific aircraft applications.

- Cold expansion of holes (Fig. 2)

The cold expansion is applied using a split sleeve system. The split sleeve cold expansion is accomplished by pulling a tapered mandrel, prefitted with a lubricated sleeve, through a hole. The function of the disposable split sleeve is to reduce mandrel pull force, ensure correct radial expansion of the hole, preclude damage to the hole and allow one-sided processing.

The applied expansion of the hole by the mandrel and the sleeve is nominally 4% of the hole diameter for aluminium. The desired finished hole diameter is normally obtained by reaming the cold expanded hole.

Also these expansion conditions (diameter, tooling, etc.) used for the test specimens were used for aircraft maintenance.

Fig. 1. Rolling tool (comm. Ecoroll). Compressive residual stress is produced by increasing the diameter of the tool

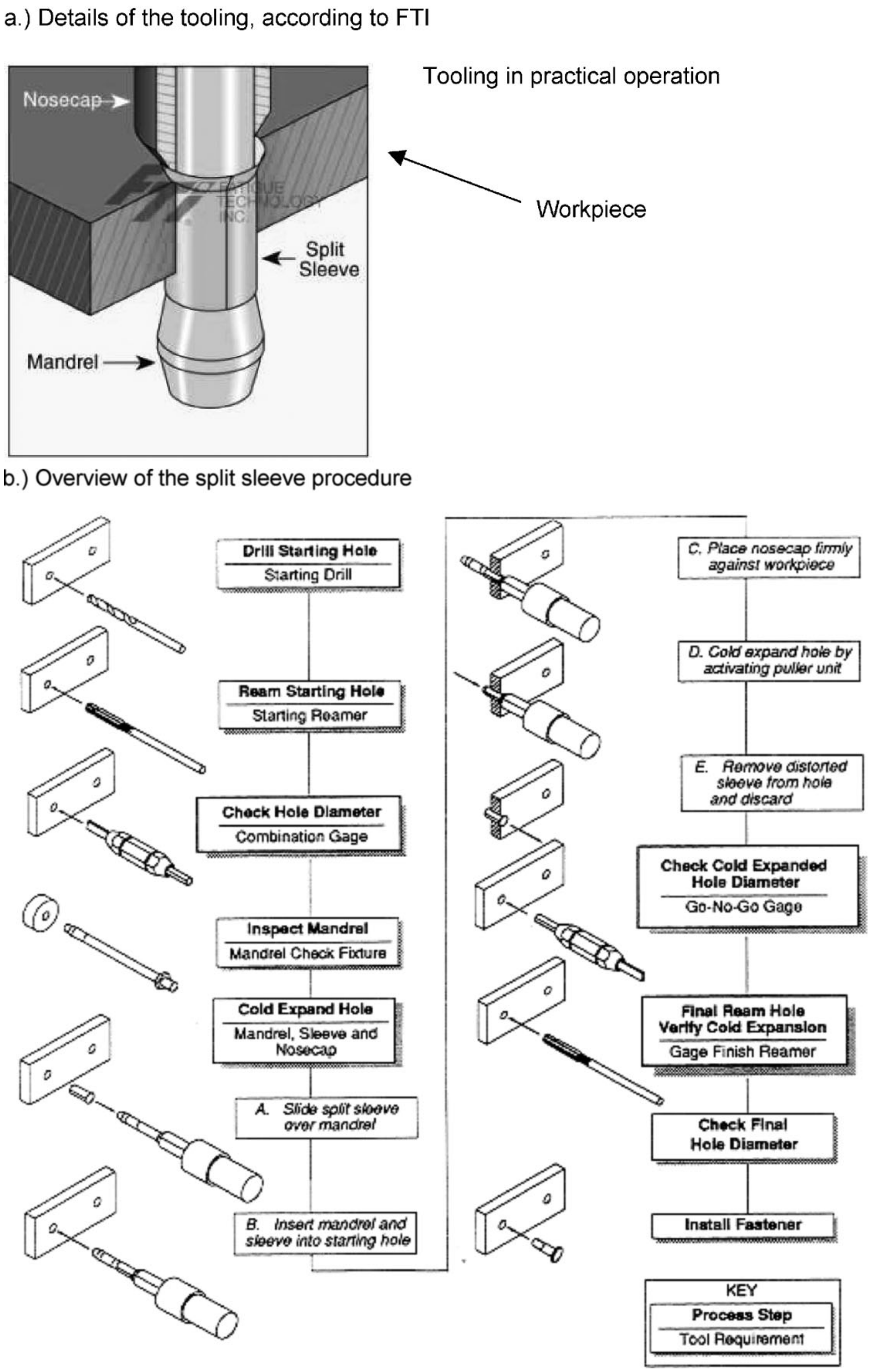

Fig. 2. Cold expansion of holes using a split-sleeve system, according to FTI: (a) details of the tooling and (b) overview of the split-sleeve procedure

Parameter	Specimen				
Hole (∅ 30mm) **Reference**	X		X		
Hole (∅ 30mm) + **rolling**		X		X	X
Chem. **Surface protection** with chromate containing wash primer on all areas with residual stress					X
Bushing (Bush stainless steel passivated, cadmium plated)			X	X	X

Fig. 3. Parameters for the rolled specimens, holes Ø 30 mm

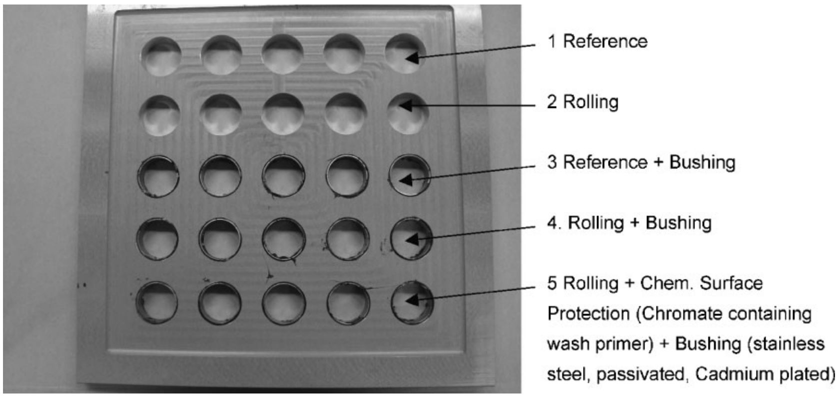

Fig. 4. Specimen plate with rolled and partially bushed holes, condition before test

- Shot peening

The cold expansion is applied by a plastic deformation of the surface using spherical particles. The shot peening shall simulate the conditions after the removal of corrosion damage at the surface. The blasting conditions are qualified for repair schemes for different aluminium aircraft components.

So the specimens will be subjected to the repair methods under realistic conditions. Additionally the specimens were prepared according to different steps of surface restoration. Descriptions of all different test parameters and pictures of the specimens before weathering are given in:

Combination of Parameters:																			
Hole with no modification (Ø 6,0 ^{R8}mm) - reference- (U)	x	x	x	x	x	x													
Simulation of corrosion removal: Grinding about 1,5 mm deep, afterwards Al_2O_3 blasting (S)			x			x						x	x	x	x	x	x		x
Shot Peening of the surface around the holes (Intensity 0,15 Almen), glass beads (P0,15)				x						x	x				x	x			
Shot Peening of the surface around the holes (Intensity 0,20 Almen), glass beads (P0,20)					x	x						x					x	x	x
Cold expansion by split sleeve procedure (A)							x	x	x	x	x	x	x	x	x	x	x	x	x
Chemical surface protection on all areas with residual stress (wash primer) (W)									x						x				x
Installation of Ti-Hi-lok (HL)		x						x	x		x			x	x		x	x	x

Fig. 5. Cold expansion by peening and/or split-sleeve treatment, list of test parameters for both alloys respectively: corrosion removal—shot peening—split sleeve—Ti-Hi-Lok—chemical surface protection

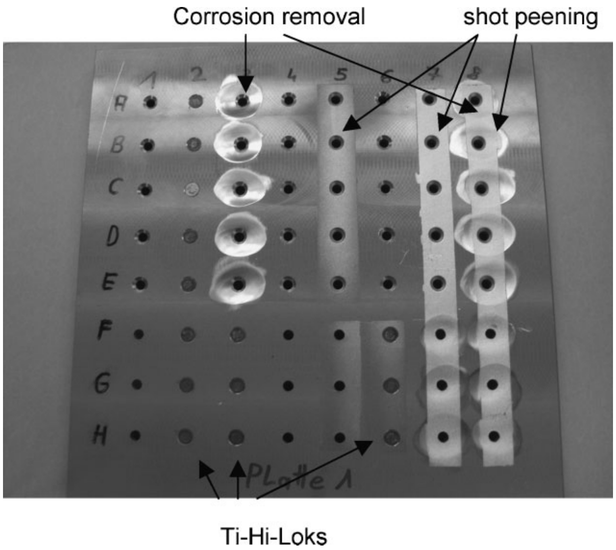

Fig. 6. Specimen plate: front view, condition before test; parameters: corrosion removal, cold expansion by split sleeve, shot peening, Ti-Hi-Lok

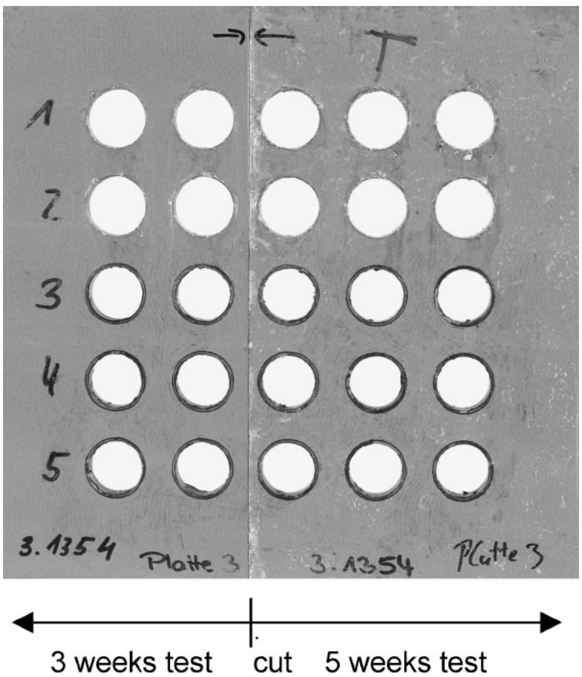

Fig. 7. Specimen plate, AA 2024, rolled holes, parameters according to Fig. 3, after 3 or 5 weeks corrosion test according to VDA 621-415

Figures 3 and 4 for the test parameters of the rolled specimens;
Figures 5 and 6 for the test parameters of the split sleeve specimens.

3.2 Test parameters

The specimens were subjected to artificial weathering according to VDA-Test 621-415.

One cycle consists of: 24 h salt spray, 96 h condensating humidity and 48 h drying. So, 1 cycle is equivalent to a testing period of 1 week.

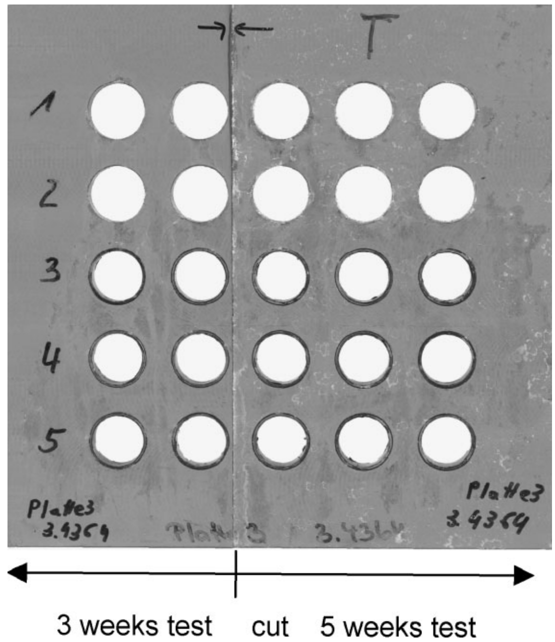

Fig. 8. Specimen plate, AA 7075, rolled holes, parameters according to Fig. 3, after 3 or 5 weeks corrosion test according to VDA 621-415

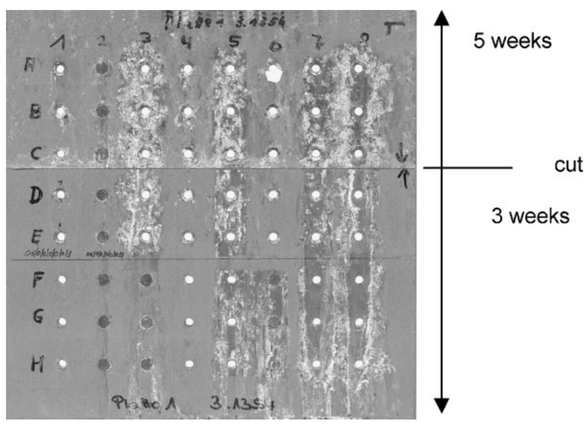

Fig. 9. Specimen plate, AA 2024, peening and/or split sleeve specimens, parameters according to Fig. 5, after 3 or 5 weeks corrosion test according to VDA 621-415

After first tests to optimize the weathering parameters, test periods of 3 and 5 weeks were chosen depending on the initial corrosion test. The results of the corrosion tests were assessed by comparative metallographic investigations.

4 Results of the corrosion tests according to VDA 621-415 for AA 2024 and AA 7075

4.1 Results of the visual inspection

4.1.1 Rolled specimens

The rolled AA 2024 test specimens are shown in Fig. 7, the AA 7075 specimens are shown in Fig. 8 for test periods of 3 and 5 weeks. The results of the visual inspection are listed below:

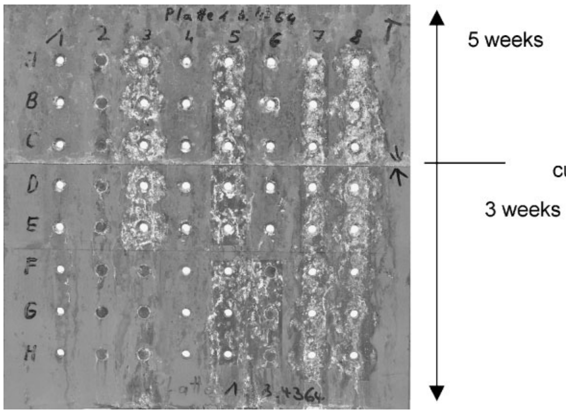

Fig. 10. Specimen plate, AA 7075, peening and/or split sleeve specimens, parameters according to Fig. 5, after 3 or 5 weeks corrosion test according to VDA 621-415

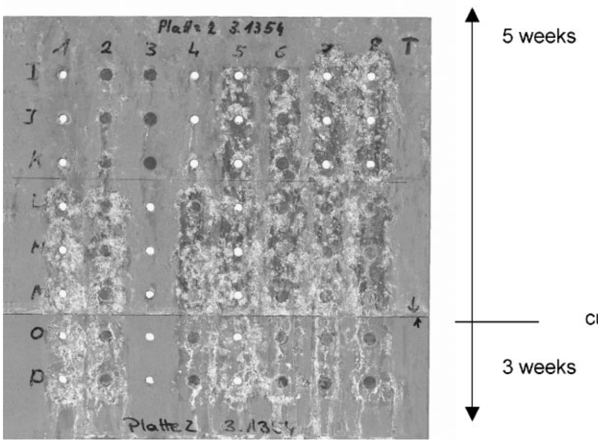

Fig. 11. Specimen plate, AA 2024, peening and/or split sleeve specimens, parameters according to Fig. 5, after 3 or 5 weeks corrosion test according to VDA 621-415

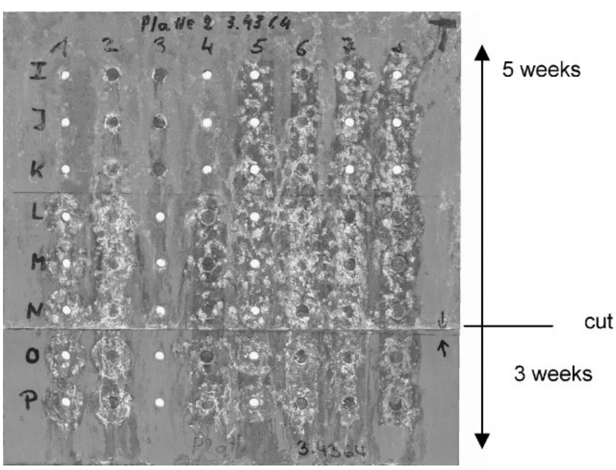

Fig. 12. Specimen plate, AA 7075, peening and/or split sleeve specimens, parameters according to Fig. 5, after 3 or 5 weeks corrosion test according to VDA 621-415

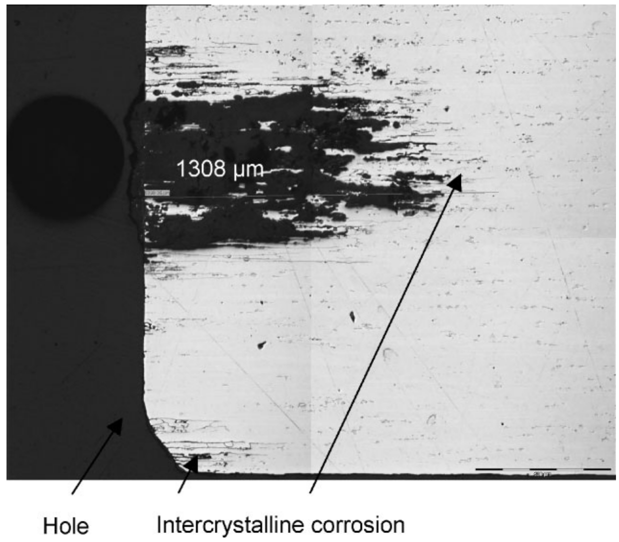

Fig. 13. AA 2024 (3.1354), Reference (not rolled) of a 30 mm hole, after 3 weeks corrosion test according to VDA 621-415

- by visual inspection the behaviour of both alloys is comparable;
- best results were achieved by the combination rolling – wash primer – bushing;
- there was no difference in the corrosion behaviour between the reference specimens and the rolled only specimens by visual inspection.

4.1.2 Peened and/or split sleeve treated specimens

The specimens subjected to a peening and/or split sleeve treatment according to Fig. 5 are shown in Figs. 9–12 after test periods of 3 or 5 weeks. The results of the visual inspection are listed below:

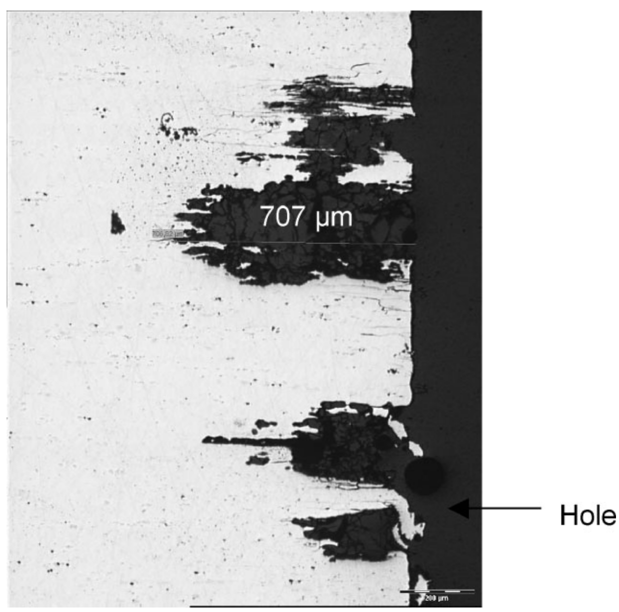

Fig. 14. AA 2024 (3.1354), rolled specimen of a 30 mm hole, after 5 weeks corrosion test according to VDA 621-415, comparable appearance and extent of the corrosion of rolled and not rolled specimens

- by visual inspection the behaviour of both alloys is comparable;
- simulated corrosion removal and subsequent Al_2O_3 blasting results in an increasing degree of corrosion;
- the use of chromate containing wash primer diminishes the degree of corrosion;
- the holes with a Hi-lok inserted show a smaller degree of corrosion;
- there is no effect of split sleeve treatment on the degree of corrosion;
- there is no effect of shot peening on the degree of corrosion.

4.2 Results of the metallographic investigation

To obtain a detailed knowledge of the corrosion behaviour, metallographic investigations were performed. Most of the holes were examined by metallographic cross-sections.

4.2.1 Rolled specimen

4.2.1.1 Results of the rolled specimen, AA 2024

For the evaluation the degree of corrosion was classified as follows:

slight corrosion: <200 μm
moderate corrosion: <500 μm
strong corrosion: <1000 μm
very strong corrosion: >1000 μm
(depth of corrosion attack)

Reference	Strong corrosion in all areas of the holes independent of the duration of the corrosion test
Rolled	From moderate to very strong corrosion in particular at the burred edges, especially after 5 weeks of corrosion test
Bushed	No corrosion
Rolled and bushed	No corrosion
Rolled, surface protection with wash primer and bushed	No corrosion

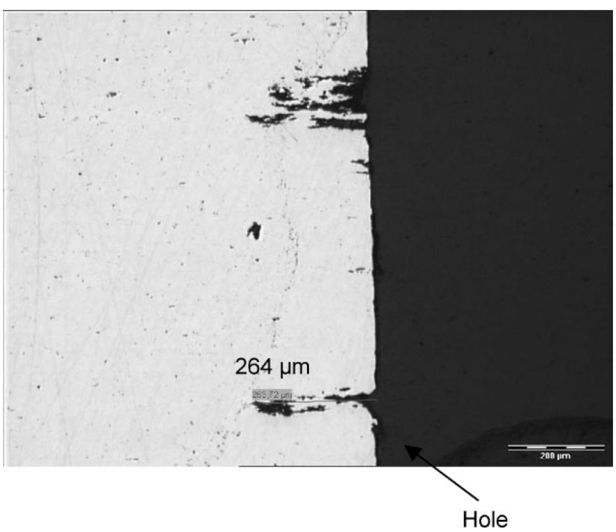

Fig. 15. AA 7075, rolled specimen of a 30 mm hole, after 3 weeks corrosion test according to VDA 621-415

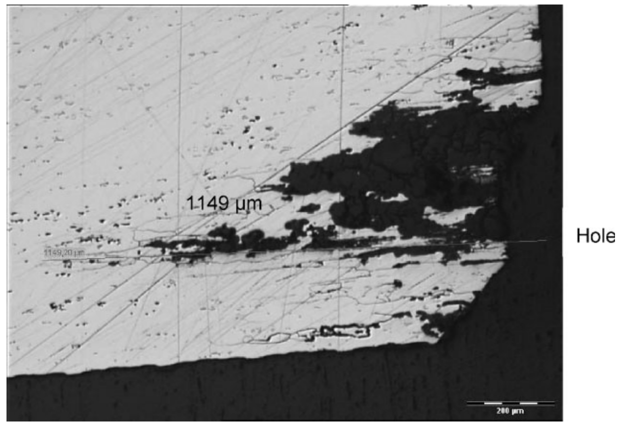

Fig. 16. AA 2024, (3.1354), split sleeve specimen, reference (no cold expansion) after 3 weeks corrosion test according to VDA 621-415, very strong corrosion at the hole

Examples of the metallographic investigation of the Ø 30 mm holes for the AA 2024 are shown in Figs. 13 and 14.

4.2.1.2 Results of the rolled specimen (plate no. 3/II), AA 7075

Reference	Moderate corrosion in the holes independent of the duration of the corrosion test
Rolled	Slight up to moderate corrosion at the holes and the burred edges independent of the duration of the corrosion test
Bushed	Slight corrosion only at one hole
Rolled and bushed	No corrosion
Rolled, surface protection with wash primer and bushed	No corrosion

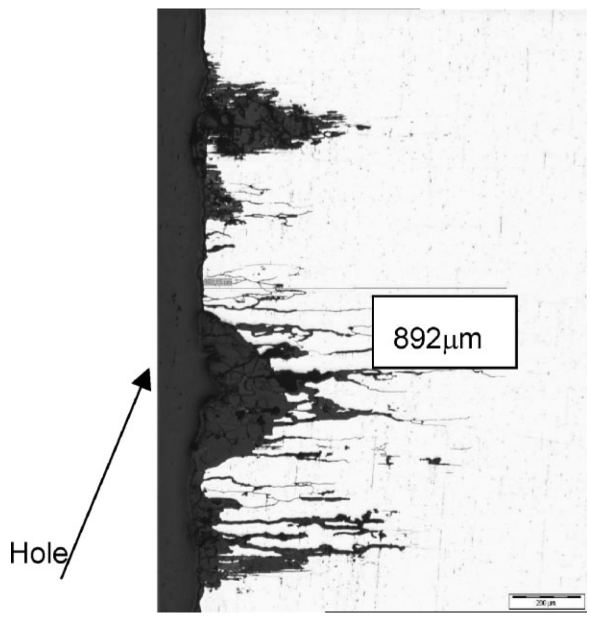

Fig. 17. AA 2024, (3.1354), Reference (no cold expansion), peening 0.15 A after 5 weeks corrosion test according to VDA 621-415, strong corrosion at the hole

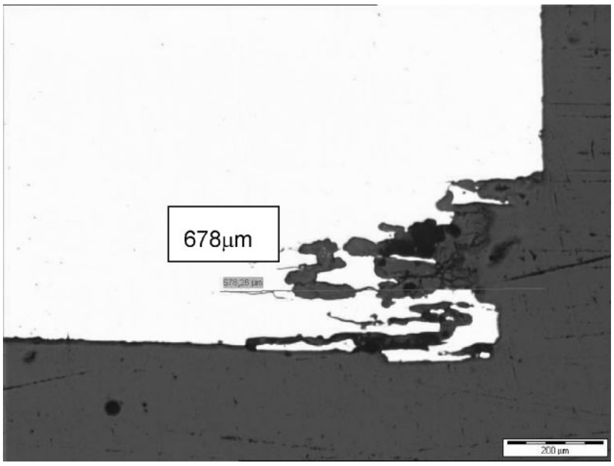

Fig. 18. AA 2024, (3.1354), specimen expanded by split sleeve; strong corrosion at the hole, after 3 weeks corrosion test according to VDA 621-415

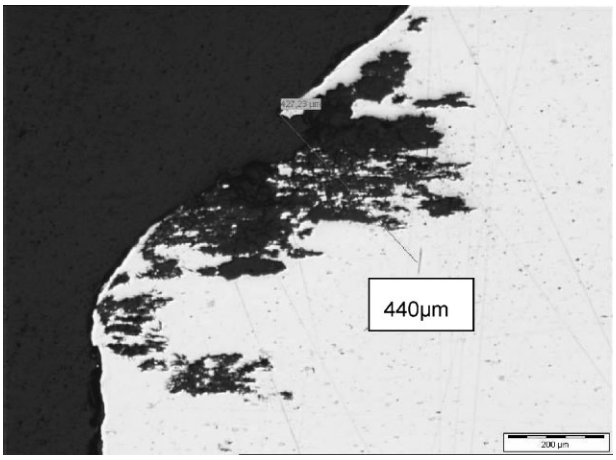

Fig. 19. AA 7075, reference (no cold expansion), peening 0.15 A after 5 weeks corrosion test according to VDA 621-415, moderate corrosion at the hole near the countersink

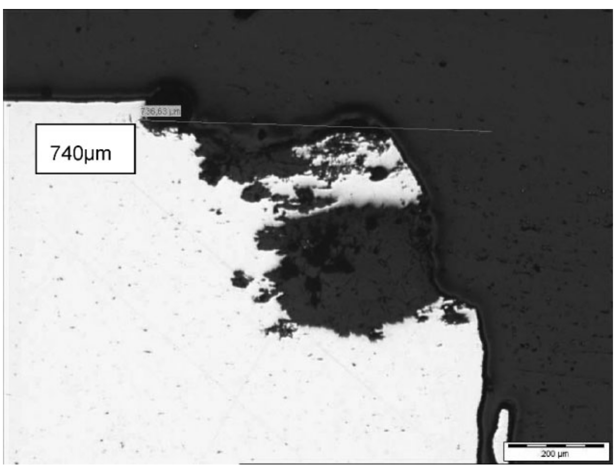

Fig. 20. AA 7075, specimen, expanded by split sleeve, strong corrosion at lower end of the hole, after 3 weeks corrosion test according to VDA 621–415

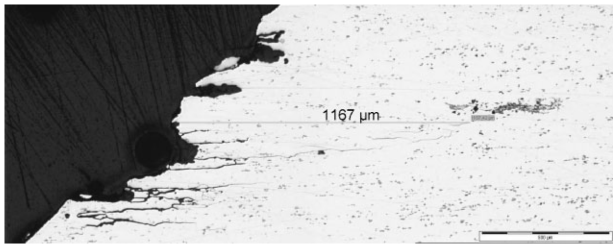

Fig. 21. AA 2024, expanded by split sleeve, after 5 weeks corrosion test according to VDA 621-415. Simulation of corrosion removal, peening 0.2 A, Hi-Lok, – (no wash primer) – very strong corrosion at the countersink (in spite of using a Hi-Lok)

An example of the metallographic investigation of the Ø 30 mm hole for the AA 7075 is shown in Fig. 15.

4.2.1.3 General results of the metallographic investigation of the rolled specimens (Ø 30 mm)

The general results of the metallographic investigations of the corroded rolled specimens for both alloys (2024 and 7075) are listed below:

- There was a smaller degree of corrosion on the AA 7075 in comparison to AA 2024.
- A considerable scatter in the results was observed for specimens of both alloys with identical parameters of preparation and treatment.
- The degree of corrosion was comparable for rolled holes and untreated holes which means the degree of corrosion was not accelerated by the rolling process.
- There was no significant difference in the degree of corrosion after 3 or 5 weeks of weathering.
- With a minor exception no corrosion at any of the bushed and sealed holes was detected.

4.2.2 Peened and/or split sleeve treated specimens

The results of the metallographic investigations of specimens treated according to the test parameters described in Fig. 5 (peening and/or split sleeve process) are listed below for both alloys.

- Surface protection by using a chromate containing wash primer on all areas with compressive residual stress significantly diminishes the degree of corrosion.
- The degree of corrosion was not increased by the peening and/or split sleeve process (Figs. 16–20).
- Corrosion was detected in the countersink areas in spite of a Hi-Lok being inserted (Fig. 21).
- All areas with simulated corrosion removal by grinding and subsequent Al_2O_3 blasting were susceptible to corrosion.
- There were very different degrees of corrosion on specimens with the same test parameters.

Comparing the corrosion behaviour of AA 2024 and AA 7075, AA 7075 tends to show a better corrosion resistance in the metallographic examinations (based on the method of artificial weathering described above).

5 Conclusions

To sum up, the general results of the corrosion behaviour for the specimens with residual stress will be described:

- In many cases different degrees of corrosion were detected for specimens with the same test parameters.
- The degree of corrosion is not increased by compressive residual stress introduced by rolling or by expansion by split sleeve.
- An additional surface protection of the treated surface using a chromate containing wash primer significantly diminishes the degree of corrosion.

From the point of corrosion resistance, it is practical to introduce compressive residual stress into the surface of aluminium components to increase or restore the original fatigue life. The sensitivity to corrosion does not increase according to the results obtained.

6 References

[1] Kh. G. Schmitt-Thomas, Metallkunde für das Maschinenwesen, Vol. II, Springer Verlag, Berlin, **1989**.
[2] Kh. G. Schmitt-Thomas, *Metallkunde für das Maschinenwesen, Vol. I*, Springer Verlag, Berlin, **1988**.
[3] H.-J. Bargel, G. Schulze, *Werkstoffkunde*, VDI-Verlag, Berlin, **1988**.
[4] Z. Lisowski, S. Guzowski, O. Krettek, *ZEV-Glas, Ann.* **1981**, *105*, 347.
[5] P. O'Hara, *Anti-Corrosion*, October **1986**, 8.
[6] M. P. Müller, A. Atrens, J. E. Allison, *Mater. Tech.* **1987**, *1*, 3.
[7] J. Horowitz, *Oberfläche-Surface* **1980**, *21*, 93.
[8] P. Gümpel, T. Vollmer, M. Blaise, W. Racky, *Stainless Steel Europe*, **1995**, *7*, 47.
[9] G. Grötsch, *Aachener Schweißtechnik Kolloquium* **1993**, 16-17 03, 341–358.
[10] H. Werner, C. Voigt, G. Riedl, J. Müller, K. Feist, *Korrosion* **1991**, *22*, 175.
[11] P. O'Hara, *Br. Corros. J.* **1989**, *24*, 3.
[12] N. S. Rengaswamy, S. Ramu, S. Govindarajan, K. Balakrishnan, *Corros. Prev. Contr.* **1991**, *8*, 101.
[13] P. O'Hara, *Corros. Prev. Contr.* **1989**, *12*, 163.
[14] W.-T. Tsai, C.-S. Chang, J.-T. Lee, *Corrosion 50*, S.98.
[15] W. Koehler, *2. International Conference on Shot Peening*, Chicago, **1984**, 126–132.
[16] J. Horowitz, *Schweiz. Alum. Rundsch.* **1981**, *31*, 207.
[17] P. Gümpel, T. Vollmer, M. Blaise, W. Racky, *Stahl* **1995**, *4*, 50.
[18] S. Matsumoto, Y. Nakano, C. Shiga, A. Narumoto, S. Kikukawa, *International Confonference On Evaluation of Materials Performance in Severe Environments*, Kobe, Japan, 20–23 11 1989, **1989**, 1, p.159.
[19] B. Mazza, P. Pedeferri, D. Sinigalia, U. Della Sala, L. Lazzari, *Werkstoffe und Korrosion* **1974**, *25*, 239.
[20] I. Garz, *Korrosionsverhalten plastisch verformter Metalle*, Sitzungsberichte der Akkademie der Wissenschaften der DDR, **1984**, 7/N.
[21] X. Zhang, Z. Wang, *Int. J. Fatigue* **2003**, *25*, 1249.

(Received: September 14, 2007) W4149
(Accepted: October 24, 2007)