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Short Communication

Use of Aerospace Fasteners in Mechanical and Structural Applications

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Abstract

The intention of the present short review is to introduce to the non-specialist reader the feasibility of the use of alternative materials not generally considered by engineers working in mechanical and structural applications. That is, the use of specialised aerospace rivets in the more general area of construction is considered. To this end, the text briefly overviews the different types of fasteners used in the construction industry and their common mechanisms of failure. The most common types of fasteners used for conventional mechanical and structural applications are all-steel rivets and pop rivets consisting of aluminium shank and mandrel of a higher strength alloy. In contrast, the aerospace industry makes universal use of pop rivets consisting of high-strength aluminium alloys, the design and installation of which are illustrated. These more specialised rivets are suitable for implementation because the aluminium alloys used exhibit superior mechanical properties and corrosion resistance compared to those of other rivets. For comparison, the mechanical properties of the aluminium alloys used in both conventional and aerospace rivets are surveyed in tabular form.

Since environmental failure by galvanic corrosion owing to exposure to seaspray is a frequent occurrence, the factors that affect galvanic corrosion are discussed. A relatively comprehensive graphic survey of the galvanic series for corrosion of metals and alloys in seawater, drawn from a variety of sources, is provided. While this provides a well known ranking of the susceptibility to corrosion, this version of the series is unusual in that it illustrates the series generically for alloys and it differentiates the metals and alloys into four ranges of corrosion resistance rather than as a continuous series. More specifically, since the susceptibility to corrosion of chemically similar alloys can be subtly shaded and hence difficult to rank, the galvanic series for corrosion in seawater of an extended range of aluminium alloys, including some effects of the alloy temper, also is provided. Finally, an example of the successful 10-year performance of aluminium alloy aerospace rivets for the rectification of the failure of a major rooftop structure, which failed rapidly owing to steel shank-aluminium alloy workpiece corrosion from seaspray, is mentioned.

Fasteners

In the construction industry, which regularly involves mechanical and structural applications, metallic materials are utilised heavily. One major area of application is mechanical fasteners or connections, which include rivets, bolts/nuts, lock bolts, and pins [1,2]. More broadly, fasteners are categorised generally as follows:

Threaded fasteners

Bolt/nut systems are designed with threads, which allow this fastener to be removed without damage to the system.

Rivets

Rivets are permanent fasteners that constrain the joint with a head (*factory-head*) and an expanded tail (*shop-head* or *buck-tail*) on the opposite end of the shank.

Blind fasteners

Blind fasteners are those that are installed and can be accessed on one side of the joint only, such as pop rivets.

Pin fasteners

Pin fasteners typically are of a single elongated piece (solid or tubular), although they may include a malleable collar.

Special-purpose fasteners

Specialised fasteners often are designed for quick removal and replacement and may include studs, latches, slotted springs, and retaining rings.

Fasteners for composites

In the joining of composites, specialised design considerations often are required for joints subject to high stresses, tight tolerance requirements, thermal expansion mismatch, galvanic corrosion, and/or leakage.

Failure

Failure of fastening systems usually is from static loading (overload in tension, bending, shear, or torsion), dynamic fatigue (from cyclic loading or repeated impact), or corrosion (galvanic, chemical, or stress) [1]. Typical locations of failure of the most

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common mechanical fasteners are directly beneath the head(s) of rivets, at the thread-shank transition (in bolts), at the first inner thread (in nuts), and at microstructural imperfections. Alternatively, failure of the plates or sheets being joined regularly is by dynamic fatigue [3].

Although it usually is straightforward to design for static and dynamic loads in mechanical and structural systems, the potential effects of corrosion are more difficult to predict. This is partly because they depend on factors that are intrinsic to the product, such as the chemical composition and the microstructure, the latter of which is dependent on the processing. It also is because they depend on factors that are extrinsic to the product, particularly the environmental conditions to which it is exposed. Consequently, these effects often can be overlooked when specifying materials for such applications.

Most conventional threaded fasteners are fabricated from various grades of alloy steel, which may have protective coatings, sometimes sacrificial, such as zinc, tin, cadmium, or aluminium [1]. In contrast, pop rivets are constructed from alloys in all-steel, all-aluminium, and aluminium shank/steel mandrel configurations. In most construction applications, the joined plates and sheets also consist of alloys of steel and aluminium. Therefore, the potential for galvanic corrosion resulting from the apposition of dissimilar metals is clear [4].

The principles of galvanic corrosion are well known [5-8]. Since many mechanical and structural applications are exposed to rainwater, condensed humidity, seawater, and seaspray, the metals used in these systems are subject to anodic corrosion by electrochemical reactions during which at least one of the metals is altered from the metallic to the non-metallic state. In terms of galvanic corrosion, there are five general issues of consideration:

Galvanic series

In galvanic reactions, dissimilar metals act as cathode and anode while the water acts as electrolyte. This configuration is sufficient to establish an electrical circuit involving a potential (voltage) difference between the electrodes and associated current (amperage) flow. The electromotive force (EMF) series [5], which ranks the potential for corrosion between pure bimetallic couples in water in terms of electrochemical cell voltages, is well known. Another, perhaps more practical, variant is the galvanic series, which provides the same ranking for commercial metals and alloys in seawater, which is a more conductive electrolyte than water. The data, which are drawn from a range of sources [9-13], are shown in Figure 1. This information can be used to determine the probable location of corrosion (*i.e.*, oxidation). For example, if structural steel members (*i.e.*, mild steel) are fastened with a zinc-plated bolt and nut, their relative vertical locations in Figure 1 indicate that the former acts as the cathode (lower in Figure 1 → decelerated corrosion) and the latter acts as the anode (higher in Figure 1 → accelerated corrosion). The greater the separation of the two in Figure 1, the more severe the corrosion. Since electrons are conducted to the anode and cause reaction, then the zinc-plated bolt and nut will corrode (where the contact surface areas of both electrodes are identical) and hence form zinc oxide (ZnO). In this case, the zinc acts as a sacrificial coating, which is intended to corrode preferentially rather than the more important structural components.

Similar EMF ranges

Since commercial metals and alloys exhibit a range of EMF values,

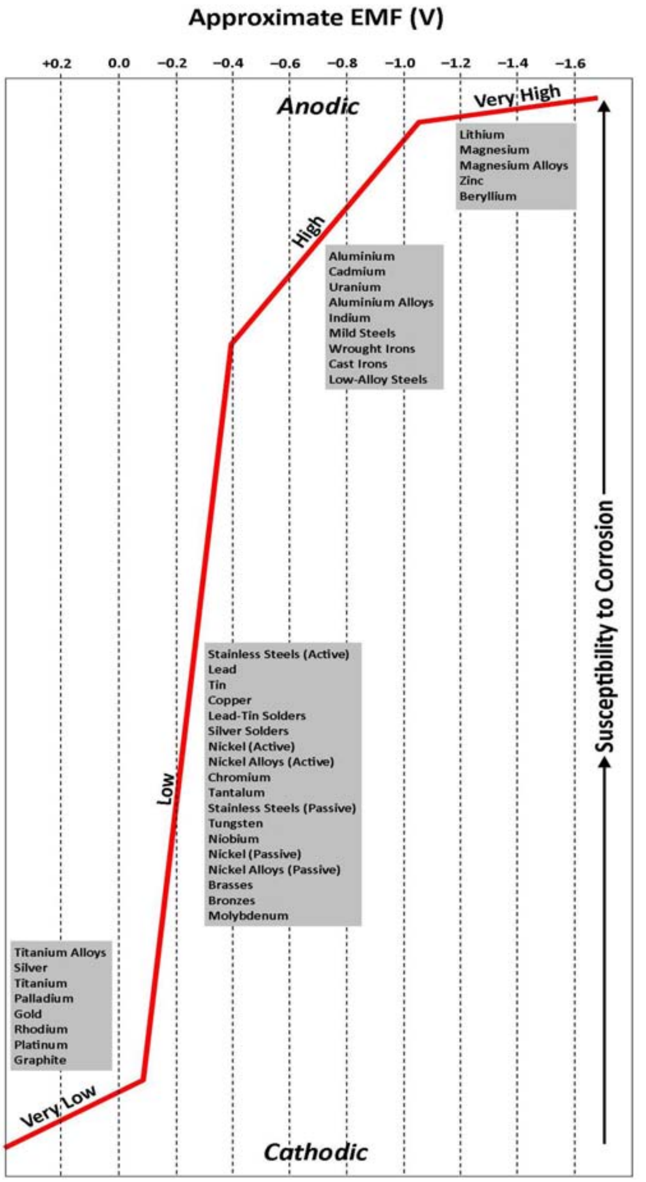

Figure 1: Generalised galvanic series in seawater [9-13].

rather than specific consistent values, when two metals in contact have EMF ranges that overlap, it many become uncertain which acts as cathode and which acts as anode.

Surface area effect

When the surface areas of the electrodes are dissimilar, then an area effect becomes important. That is, when the anode is small relative to the cathode, then the concentration of electrons being conducted to the anode becomes high, which enhances reaction. Therefore, it is desirable to ensure that the anodic metal surface area is large compared to that of the cathodic metal surface area. The greater the difference in areas, the more severe the corrosion. So, when a coating is pitted or scratched and the underlying metal is exposed, the latter becomes an electrode of very small surface area. In this case, it is essential for the underlying metal to be cathodic relative to the anodic surface coating. Figure 1 shows that zinc-plated bolts and nuts, the coatings of which can be damaged relatively easily, meet

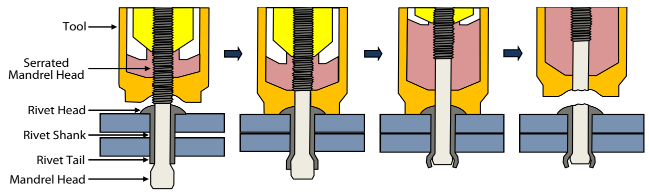

Figure 2: Schematic of operation of *Huck Magna-Lok*® [17] rivet system.

this criterion. Again, this is why the zinc is considered to provide a sacrificial coating.

Biocorrosion

Marine slimes or biofilms often form, which can facilitate bacterial corrosion [14]. As the films grow, bacteria can release corrosive species or establish conditions conducive to corrosion, both of which can increase corrosion rates significantly.

Contact resistance

Consideration of the effect of the galvanic series on the probability of corrosion relies on the assumption of two dissimilar metals in contact and subsequent *active* corrosion [15]. However, the resultant electrical circuit may be broken through the formation of an electrically insulating layer consisting of an oxide or another corrosion product [16], which typically results in *passive* corrosion [15]. This has the effect of hindering further corrosion and so reducing its severity and/or rate.

Rivets

There are five main types of conventional rivets, which are bifurcated or split, compression, full tubular, solid, and semitubular [1]. All of these rivets require access to both sides of the joint and, with the exception of compression rivets, they require the use of a *bucking bar*, which is a specially shaped metal piece that expands and work hardens the tail upon impact to the head (*bucking* or *upsetting*). Compression rivets have two heads and they form the join from radial compressive stress and deformation.

In contrast, blind rivets require access to only the head side of the join. There are four main types of blind rivets, which are chemically expanded, drive-pin, pull-mandrel, and threaded [1]. Of these, the most commonly used and the most convenient is known as the *pop rivet*, which consists of a tubular shank (sleeve) and contains an interior mandrel (pin). When the mandrel is drawn into the rivet shank with the appropriate tool, the mandrel causes the exposed shank tail to expand, after which the mandrel snaps off, leaving the mandrel head (or head + part of the mandrel) locked into the tail (or tail + shank). The design and installation of an *open-end break mandrel* is illustrated in Figure 2 [17].

There are two main considerations concerning the failure of rivets in the environment:

Corrosion

Since the mandrels are made from aluminium alloy, low-carbon steel, stainless steel, copper, and Monel (63Ni31Cu) alloy, the potential for galvanic corrosion with what typically is an aluminium alloy tubular shank within the rivet itself is clear. Consequently, two common problems in mechanical and structural applications exposed to the environment near the ocean are shank-workpiece corrosion in the joint and mandrel-shank corrosion in the rivet.

Table 1: Mechanical Data for Aluminium Alloys Commonly Used in Pop Rivet Shanks [18].

Aluminium Alloy Grade	Temper	Tensile Strength (MPa)	Yield Strength (MPa)	Shear Strength (MPa)	Fatigue Strength (MPa)
5050	O	145	55	105	83
	H32	170	145	115	90
	H38	220	200	138	97
5052	O	195	90	125	110
	H32	230	195	140	115
	H38	290	255	165	140
5056	O	290	152	179	138
	H18	434	407	234	152
	H38	414	345	221	152

Mechanical properties

Stresses deriving from periodic wind loading, cyclic thermal expansion/contraction, and continuous static loading can be significant since the mechanical strengths of the aluminium alloys of different tempers typically used as the shank, which must carry a substantial portion of the load, are relatively low, as shown in Table 1 [18].

Aluminium in Aerospace Applications

History

Aluminium metal was first isolated by Hans Christian Ørsted in Denmark in 1825 [19] and a commercial process for its manufacture was developed simultaneously by Charles Martin Hall in America and Paul Héroult in France in 1886 [20]. Aluminium in aerospace applications goes back to the earliest days of successful flight, where the crankcase of the engine used in the Wright Brothers' inaugural flight of 1903 was fabricated using an aluminium alloy [21]. The first mass-produced aeroplane to make extensive use of aluminium was the Bréguet 14 bomber of 1916 [22]. The first all-aluminium aircraft was produced in the following year in the form of the Junkers J7 fighter [23]. In 1936, aluminium rivets were used in aircraft construction for the first time in both the US by *Cherry Aerospace* [24] and the UK by *Aviation Developments* (now *Avdel*) [25].

Applications of Aerospace Rivets in Mechanical and Structural Applications

The use of rivets in aerospace construction is well established [26-29]. This high-performance application requires superior performance in terms of corrosion resistance and mechanical stability. However, the use of aerospace rivets in more conventional mechanical and structural applications has remained very limited probably owing to lack of familiarity and higher costs. Consequently, the main purpose of the present work is to introduce to the reader the potential to use these more specialised rivets in conventional applications for which they may not have been considered. Table 2 [14,29-32] gives some of the mechanical properties of aluminium alloys that are used commonly in aerospace rivets.

Table 2: Mechanical Data for Aluminium Alloys Commonly Used in Aerospace Rivets.

Aluminium Alloy Grade	Temper	Tensile Strength (MPa)	Yield Strength (MPa)	Shear Strength (MPa)	Fatigue Strength (MPa)	References
1100	O	90	34	62	34	14
	H14	124	117	76	48	
	H18	165	152	90	62	
2017	T4	427	276	262	124	30
2024	T3	483	345	283	138	30
2117	T4	296	165	193	97	31
2219	T851	455	352	285	103	30
5056	O	290	152	179	138	14
	H18	434	407	234	152	
	H38	414	345	221	152	
7050	T7451	524	469	303	240	30,32
7075	T6	572	503	331	159	29

Alloy	Temper	Anodic
Al 7072	Coating	
Al 2014	T3	
Al 1160	H14	
Al 7079	T6	
Al 218	Die Cast	
Al 5056	O	
Al 5052	O	
Al 5052	H12	
Al 5456	O, H353	
Al 5052	H32	
Al 1100	O	
Al 6053	Not Stated	
Al 3004	Not Stated	
Al 3003	H25	
Al 6061	T6	
Al A360	Die Cast	
Al 7075	T6	
Al 1160	H14	
Al 6061	O	
Al 2014	O	
Al 2117	Not Stated	
Al 2017	Not Stated	
Al 2024	T4	
Al 5052	H16	
Alloy	Temper	Cathodic

Increasing Conrrosion Resistance

Figure 3: Galvanic series for some aluminium alloys in seawater [33-35].

The most successful aerospace rivet probably is the *Huck Magna-Lok*® [17], which is manufactured by *Alcoa Fastening Systems*. In light of the previous comments concerning the importance of corrosion and mechanical properties, it is clear that there are advantages in the use of these all-aluminium rivets, which consist of aluminium alloy grades 5056 for the shank and 7075 for the mandrel, both of which are coated with zinc chromate.

Following installation, the partially retained mandrel, as shown in Figure 2, carries the majority of the mechanical load, so the optimal mechanical properties of alloy grade 7075 are a major advantage. A second major advantage is the resistance to corrosion in the rivet and, in the case of joining of aluminium sheet, at the shank-workpiece interface, where the chemical similarities of the aluminium alloys minimise the chemical differences and hence the EMF differences. Although Figure 1 is simplified in terms of metal and alloy groups for the benefit of the non-specialist reader, a more comprehensive list of aluminium alloys in the galvanic series in seawater is as shown in Figure 3 [33-35]. A qualitative assessment of the corrosion resistance of a more comprehensive range of aluminium alloys is available elsewhere [36].

Table 3: Mechanical Data for Aluminium Alloys Used in Louvre System.

Aluminium Alloy Grade	Temper	Tensile Strength (MPa)	Yield Strength (MPa)	Shear Strength (MPa)	Fatigue Strength (MPa)	References
6060	T5	220	185	140	90	38,39
6063	T6	241	214	152	69	30
6351	T6	310	283	200	90	31

Finally, it is noted that *Huck Magna-Lok*® [17] rivets have been used by the authors in a major construction rectification of an aluminium louvre system installed on the roof of a high-rise building located ~2 km from the Pacific Ocean [37]. The louvre system failed principally owing to galvanic corrosion initiated by the use of steel rivets that had been used to join the louvre mullions and profiles, which were constructed from aluminium grades 6063 (T6) and 6060 (T5), respectively. The original louvre system was replaced with mullions and profiles of aluminium grades 6351 (T6) and 6063 (T6). The mechanical properties of these aluminium alloys and their tempers are contrasted in Table 3 [30,31,38,39]. While the original system failed within 1 year of installation, the rectification using all-aluminium rivets has performed without corrosion for nearly 10 years.

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