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Variability of structural aluminium alloys mechanical properties

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ABSTRACT

Content of alloying elements, type of treatment, welding and testing parameters result in variability of mechanical properties of aluminium alloys, which needs to be taken into account in design procedures. The degree of variability and current nominal values safety level were evaluated using a collection of results from published sources, expanded with experimental work. Processed results of proof and tensile strengths were fitted to distributions and cumulative function relevant fractiles for design purposes determined. It was established that ratios of characteristic to nominal values vary from 1.23 to 0.75, being unsafe or having a built in excess margin of safety, so new nominal values were proposed. These new values provide a more economical material partial factor value and a uniform reliability level.

1. Introduction

Production of aluminium alloys is done through modern industrial processes for which there are established quality control procedures and defined requirements in relevant specifications. Alloys are manufactured in eight series and hundreds of specific chemical compositions, additionally divided by type of treatment (mechanical and thermal), which provides availability in several tempers. All combinations of alloys and tempers have to be made in conformity with [1,2] for the European and with [3] for the USA market, and in Europe a manufacturer guaranties given properties with its CE (*Conformité Européene* – European Conformity) marking.

Reliable and safe performance of aluminium structures requires design procedures that depend on adequately accurate evaluation of mechanical properties of all available structural alloys. The 0.2% proof strength is the most important property for the design procedure, followed by the ultimate tensile strength and then other properties like Young's modulus and Poisson's value. All design calculations related to cross sectional resistance and instability require the 0.2% proof strength and the ultimate tensile strength is required in checks related to resistance of connections. Values of both 0.2% proof and ultimate tensile strengths presented in normative documents are not characteristic, but guaranteed (minimum), which is supposed to provide additional reliability in terms of characteristic to nominal value relation. It should be noted that the term guaranteed is of more commercial than technical value as it does not offer actual statistical information. This partially deviates from a general pattern set in EN 1990 [4] where characteristic values are used in design calculations instead of nominal ones.

The choice of partial (safety) factors is based on calibrations exercises, which should ensure that the target failure probability is met. These exercises are in most part carried out directly on the resistance associated with a specific failure mode, and no direct 0.2% proof strength or ultimate tensile strength statistical evaluation on coupons is conducted. This is justified as most of the global partial factor is influenced by the uncertainty in the engineering model and by the fact that specifications make manufacturers guarantee for the nominal values of strength. With variability of mechanical properties being induced by chemical composition deviations, heat treatment and welding procedure parameters design values reliability can be influenced. In order to quantify the extent of this influence variability of mechanical properties has to be considered on the material level itself, using uniaxial test results. Another implication regarding variability of material properties is the market area, i.e. the regional context of the use of alloys. Namely, based on the proximity of production, regional areas are supplied by different manufacturers, which due to numerous variables may produce products in conformity with related specifications but with greater or lower variability. This fact is partly introduced and recognized by differences in minimum values of strength for the same alloy and temper (Table 1). European norms are valid for all countries of the European Union, and wider, and calibration exercise should therefore be made considering this context, but can hardly do so, which is also recognized by existence of National annexes (NA) of Eurocodes that can introduce partial factor values different from recommended ones.

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Table 1
Structural wrought aluminium alloys nominal properties according to EN [6,8,9], BS [10] and AA [3].

Alloy	Temper		Product form	Thickness t (mm)	0.2% proof strength f_o (MPa)			Ultimate tensile strength f_u (MPa)		
					EN	BS	AA	EN	BS	AA
Non welded	AW-5083	0, H111	Plate	≤12,5	115	125	125	270	275	275
	AW-6060	T4	EP/H	≤25	60	70	–	120	130	–
		T6	EP/H	≤3	160	160	170	215	185	205
			EP/H	>3, ≤25	150	160	170	195	185	205
		T66	EP, EP/H	≤3	160	160	170	215	185	205
			ER/B	≤50	160	160	170	215	185	205
	AW-6061	T6	EP, EP/H, ET	≤25	240	240	240	260	280	260
	AW-6063	T5	EP, EP/H, ET	≤3	130	110	110	175	150	150
			EP	>3, ≤25	110	110	110	160	150	150
		T6	EP, EP/H	≤10	170	160	170	215	185	205
			EP	>10, ≤25	160	160	170	195	185	205
	AW-6082	T4	EP/H	≤25	110	120	–	205	190	–
		T6	EP/H	≤5	250	255	260	290	295	310
			EP/H, EP/O	>5, ≤15	260	255	260	310	295	310
			ER/B	≤20	250	255	260	295	295	310
			Plate	≤6	260	240	260	310	295	310
	AW-7020	T6	EP	≤40	290	280	–	350	340	–
	AW-7050	T7451	Plate	–	–	–	470	–	–	525
	AW-7108	T7	EP/H	≤30	260	–	–	310	–	–
		T8	EP/H	≤30	260	–	–	310	–	–
Welded	AW-5083	0	Plate	≤12,5	115	125	115	270	275	270
		F	EP	≤200	110	130	110	270	280	270
	AW-5754	H111	Plate	≤100	80	85	85	190	215	215
		H34		≤25	101	91	85	190	135	215
	AW-6060	T6	EP	>3, ≤25	60	80	55	100	93	115
		T66	ER/B	≤150	66	80	55	110	93	115
	AW-6061	T6	EP/H, ET	≤5	115	120	105	174	140	165
	AW-6063	T5	EP/H, ET	≤3	60	83	55	100	113	115
			EP	>3, ≤25	61	83	55	101	113	115
		T6	EP	>10, ≤25	66	80	55	109	93	115
	AW-6082	T6	EP/O	≤5	125	128	110	186	148	190
			EP/O	>5, ≤15	125	128	110	186	148	190
			ER/B	≤20	125	128	110	186	148	190
	AW-7020	T6	EP	≤40	206	112	–	280	136	–

Note: 1 inch = 25.4 mm; 1 ksi = 6.89 MPa; EP = extruded profile; EP/H = extruded hollow profile; EP/O = extruded open profile; ER/B = extruded rod and bar; ET = extruded tube.

Based on given facts, the purpose of this paper is to quantify variability of material properties in a global and regional context considering test results from all published sources and experimental research, and to do so in a manner that is recognized by the design requirements of partial factor approach. An additional goal is to provide reliability analysis basis for further research and considerations of current levels of safety (reliability) in valid normative documents.

2. Normative background

2.1. Structural wrought aluminium alloys

Primary and secondary structural elements made of aluminium alloys are generally wrought products from alloy series *3xxx*, *5xxx*, *6xxx* and *7xxx*, both heat-treated (HT) and non-heat-treated (NHT). Wrought aluminium alloys are more used than cast alloys as they contain a lower percentage of alloying elements and are less prone to manufacturing defects [5]. Series *3xxx* is primarily alloyed with Manganese (Mn), *5xxx* with Magnesium (Mg), *6xxxx* with Magnesium and Silicon (MgSi) and *7xxx* with Zinc (Zn). Mayor alloying elements in alloy groups are the same worldwide as most international aluminium associations have signed to use the numerical designation system administered by the USA Aluminium Association (AA). Weldability, corrosion resistance, strength, ductility and extrudability are strongly influenced by chemical composition. Additionally, treatments (tempers) exert changes to mechanical properties, and the influence of welding is a serious parameter when mechanical properties in the heat-affected zone (HAZ) are considered.

Of the wrought alloys, the most widespread are those from the *6xxx* series, which are valued for their excellent extrudability, good corrosion resistance and high strength. Extrusion is the most common production procedure and since these alloys are heat treatable, they are commonly found in a heat-treated and artificially aged state (T6). Extruded products are highly specialized so they are often shaped for a particular purpose and no claim can be made in terms of a particular profile popularity in use. It is why a narrow classification of products cannot be made, such as with steel and the division of hot rolled products. Product forms classification adopted in European norms [6] depicts available extruded forms as extruded tube (ET), extruded profile (EP), extruded rod/bar (ER/B), extruded open profile (EP/O) and extruded hollow profile (EP/H), while the USA norm [3] uses a single group, extrusions.

Although aluminium is a homogenous material, the content of alloying elements and type of treatment affect the uniformity of mechanical properties, especially when the negative influence that welding has on heat-treated alloys is considered. This variability can be high if the large number of available alloys worldwide is taken into account, with possible slight variations in minor alloying elements composition of the same alloy – even within the composition tolerance of a particular alloy.

All structural aluminium alloys for Europe specified in norms are divided according to production type, so plates, sheets and strips must be produced in conformity with EN 485 [2], extrusions with EN 755 [1] and castings with EN 586 [7]. Part 1 of each stan-