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The Influence of Square and Hexagonal Array of Cylindrical Holes on the Elastic and Strength Properties of EN AW-5754 Aluminium Alloy Sheet Metal

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ABSTRACT

The paper presents research results on the influence of a regular perforation pattern on the modulus of elasticity (Young's modulus) and on the strength properties of EN AW-5754 aluminium alloy sheet. Square and hexagonal array of cylindrical (in the plane of the sheet metal – round) holes was considered, maintaining a constant hole diameter and pitch value. The reference material was solid sheet metal (without perforation) of the same grade and thickness. It was found that hexagonal perforation pattern reduces the Young's modulus and strength of the material to a greater extent compared to square array of holes, while maintaining a higher uniformity of the distribution of these parameters in the plane of the sheet metal. The comparative analysis of the elastic and strength properties of sheet metal with straight and hexagonal perforation was also carried out accounting for mass loss ratio.

Keywords: effective modulus of elasticity (effective Young's modulus), strength properties, perforated sheet metal, aluminium alloy EN AW-5754.

INTRODUCTION

The combination of mechanical and functional properties of perforated sheet metals determines their wide range of applications in various industries. These materials can constitute an essential part or an element of a given structure. The mechanical characteristics of perforated sheet metals are determined by the type of base material and perforation parameters. Therefore, in the context of the design requirements related to the use and application of perforated sheet metals, it is important to properly understand not only the mechanical properties of the base material (solid sheet metal) but also the impact of the perforation itself on these properties.

Numerous perforation variants related to the hole shape, profile, and size, as well as their arrangement in the sheet metal plane, require special attention to the method of determining the properties of these materials [1, 2]. In the case of regular perforations, such as a square array (straight perforation) or an equilateral triangular array (hexagonal perforation), it is possible to distinguish characteristic directions with the densest packing of holes and directions perpendicular to them [3]. Knowing the parameters for these directions significantly enhances the understanding of the mechanical characteristics of perforated sheet metal. For an even more thorough analysis, other orientations in the sheet metal plane, not typical for the examined perforation, can also be considered. Adopting such a methodology for determining specific properties of perforated sheet metal seems appropriate, especially considering the practical aspect related to the use of these materials.

In addition to their functional properties (e.g., filtration, sound-absorbing, anti-slip, etc.), perforated sheet metal as a construction material, characterised by a certain amount of open area and mass loss, must meet certain requirements, including those regarding elastic and strength properties. Hence, it is crucial to investigate the impact of a given perforation on the change in the mechanical properties of the base solid sheet metal. A specific array of holes not only modifies selected parameters describing the elasticity or strength of the sheet metal but also determines their distribution in its plane to some extent [4]. Therefore, it can be concluded that perforation allows, in a way, to control the mechanical properties of the sheet metal, but without exceeding their level for the base material. Through perforation, it is possible to shape the material properties to a certain extent also in the elasticity area, influencing the value of Young's modulus (longitudinal modulus of elasticity). As is known, this parameter depends primarily on the type of bonds between atoms, chemical composition and crystal structure [5, 6]. Therefore, if, for example, metal forming and heat treatment do not change them, these methods are not efficient enough and are ineffective in modifying this elasticity constant [7]. An important benefit resulting from perforation is the reduced mass of the sheet metal compared to the base material, which, combined with the right stiffness and strength, determines the suitability of this specific material in various types of structures where, in addition to the required mechanical characteristics, the material must also have specific functional properties. It is worth adding that the versatility of uses of perforated sheet metals also results from the possibility of shaping them using metal forming [8, 9]. They can also constitute the inner layer (core) of the so-called composite materials [10, 11].

The study examined the influence of square and hexagonal perforation (equilateral triangular perforation, in production terms also referred to as a staggered 60° array) on the elastic and strength properties of EN AW-5754 aluminium alloy sheet. The distribution of the considered parameters in the perforated sheet metal plane is presented against the background of the reference material (the base solid sheet metal). The comparative analysis of both perforations was extended by taking into account the mass loss of the sheet metal caused by a grid of holes. The significant application importance of perforated sheet metals in a square and hexagonal array determined the selection of this type of perforation for research.

SCOPE AND METHODOLOGY OF RESEARCH

The elastic and strength properties of EN AW-5754 alloy sheet metal with a square and hexagonal array of cylindrical holes were determined by considering the characteristic directions of the tested perforations. The reference material was solid sheet metal of the same grade and thickness. When analysing the change (decrease) in the mechanical properties of sheet metal with a regular array of holes, the loss of its mass caused by perforation was also taken into account.

Tested material

The tests were carried out on 1 mm thick EN AW-5754 sheet metal. This alloy is highly susceptible to metal forming (especially in a soft state 0/H111, H112). It is characterised by very good corrosion resistance (including in seawater conditions), good weldability, and fatigue resistance. It can be anodised. Moreover, the low density of aluminium-magnesium alloys (2.6 g/cm^3), combined with specific sheet metal perforation, allows to minimise the mass of a given structure even further [12]. Compared to various steel grades, aluminium alloys (including the 5XXX series) are among the most frequently used materials for the production of perforated sheet metals.

A straight and hexagonal perforation system was considered for a constant hole diameter of 2 mm and a pitch value twice that diameter. Thus, the open area of the perforated sheet was 19.625% for the square hole array (1) and 22.75% for the hexagonal hole array (2), respectively.

$$P = 0.785 \times \frac{d^2}{s^2} \times 100\% \quad (1)$$

where: P – open area of sheet metal with straight perforation, d – hole diameter [mm], s – pitch [mm].

$$P = 0.91 \times \frac{d^2}{s^2} \times 100\% \quad (2)$$

where: P – open area of sheet metal with hexagonal perforation, d – hole diameter [mm], s – pitch [mm].

Therefore, it can be noted that for the assumed mesh diameter and pitch value, greater open area can be obtained in the case of a hexagonal hole array compared to a square array of holes. The consider perforations diagrams are shown in Figure 1 and Figure 2.

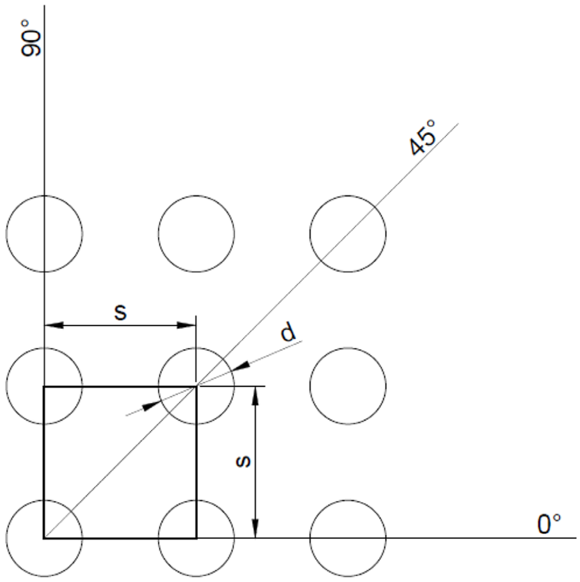

Figure 1. Diagram of straight perforation (square array of holes)

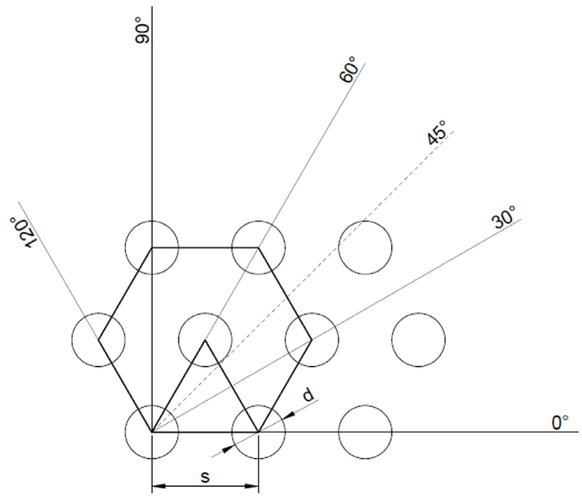

Figure 2. Diagram of hexagonal perforation (equilateral triangular array of holes)

For a straight perforation, the densest packing of holes occurs in the directions of 0° and 90° (Figure 1), while for a hexagonal system, these are the directions of 0° and 60° (Fig. 2). Periodicity is maintained for both perforations: every 90° for straight perforation and every 60° for hexagonal perforation. Characteristic directions also include those located perpendicular to the directions with the densest perforation, as well as a 45° diagonal orientation in the case of a straight arrangement of holes (Fig. 1). It should be noted that in the case of straight perforation, the directions with the densest packing of holes are perpendicular to each other.

Following the coding method adopted in work [3], a sheet metal with a square and hexagonal array of cylindrical holes is marked as Po2s4 and Ho2s4, respectively, where P and H denote the straight and hexagonal arrangements, o2 indicates a round hole with a diameter *d* of 2 mm and s4 denotes a pitch *s* of 4 mm.

Methodology

The ability of materials containing voids in their structure (e.g. porous materials) to transfer external loads depends on their active cross-section, the surface of which does not include any discontinuities in the medium. Similarly, in the case of perforated sheet metals, the active and total cross-section (including voids in the form of holes) can be considered.

When considering the practical aspect related to the structural purpose of the considered materials, often used in the form of a flat sheet or blank of a specific shape, it is important to recognise their elastic response and strength properties. In this context, when defining the mechanical properties of perforated sheet metal, it is reasonable and appropriate to use its entire cross-section. Moreover, in numerous applications of materials of this type, knowledge of their selected properties from a global (macroscopic) perspective is required. This results from the so-called equivalent continuum approach (of equivalent solid material), according to which the perforated material is considered as an equivalent solid material (without perforations) with the same external dimensions but with appropriately modified (effective) properties compared to the base material [13, 14].

In order to determine the strength properties and the Young's modulus of the tested materials, samples were taken from sheet metal with the longitudinal axis oriented towards the direction of the densest packing of holes (made by punching) at angles of 0°, 45°, and 90° for straight perforation (Fig. 3a) and 0°, 30°, 45°, 60°, and 90° for hexagonal perforation (Fig. 3b). In the case of the reference material (sheet metal without perforations), samples were prepared for all mentioned orientations (Fig. 3c). The rolling direction (RD) of the sheet metal was always consistent with the direction of the densest perforation. Strips of sheet metal were cut using the electric spark method, preventing the material from strengthening at the separation surface. The measurement base of each sample was 70 mm, but determining

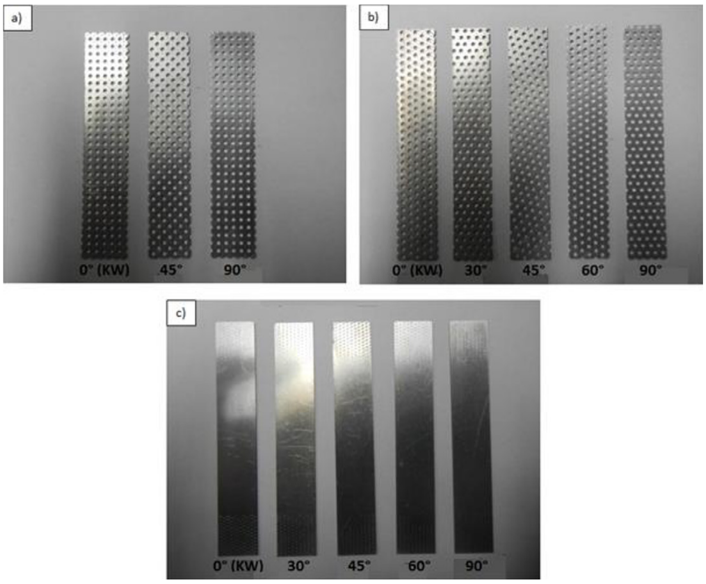

Figure 3. Examples of sets of specimens made of aluminium alloy EN AW-5754: a) with straight perforation (Po2s4), b) with hexagonal perforation (Ho2s4), c) without perforation

the same width for the perforated sheet metal was impossible due to the adopted principle that the axis and side edges of the sample should pass through the holes' centre. While striving to ensure that the width of perforated samples is as close as possible to the width of solid sheet metal samples (without perforation) of 20 mm, the following values were set: 24 mm (0° and 90° orientation) and 22.63 mm (45° orientation) for straight perforation, as well as 20.78 mm (0°, 45°, and 60° orientation) and 20 mm (30° and 90° orientation) for hexagonal perforation.

The examined properties of the tested materials were determined based on a tensile testing on an Instron 5566 universal testing machine with a maximum pressure of 10 kN. The effective Young's modulus E^* of perforated sheet metal and the analogous parameter for solid sheet metal were established in the linear elastic range (Fig.4), determined on the basis of preliminary tensile testing up to the point of material rupture. Uniaxial stretching in the area of reversible strains was carried out in three cycles, each cycle including a stress and strain stage.

A biaxial Instron extensometer was used to measure elastic longitudinal strain (Fig. 5). The strain rate was 10^{-5} s^{-1}. The measurement base was 12.5 mm, which corresponded to the extensometer spacing. The obtained results allowed for the

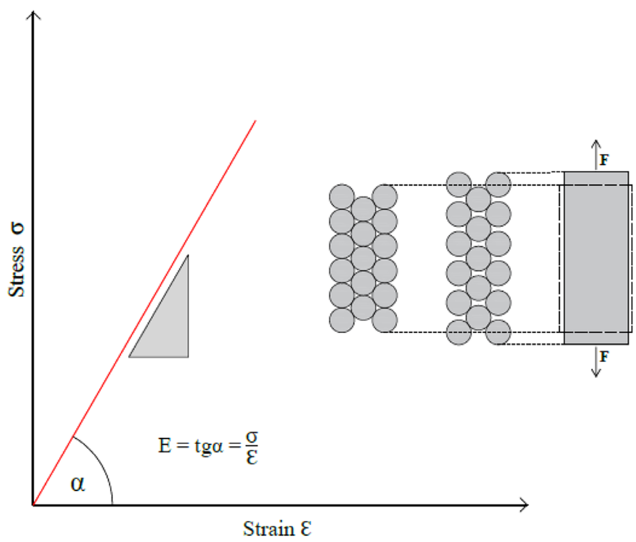

Figure 4. Stress-strain relation within linear elastic range [7]

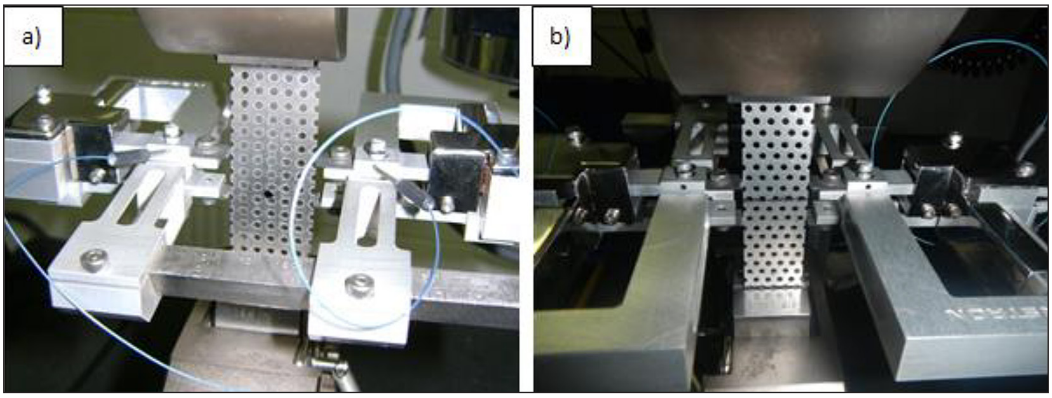

Figure 5. Measurement of elongation of specimens: a) with straight perforation (Po2s4) and b) with hexagonal perforation (Ho2s4) in elastic range on an Instron 5566 testing machine using an extensometer

preparation of graphs in σ–ε coordinates, which were used to determine the longitudinal modulus of elasticity. The yield strength $R_{p0,2}$ and tensile strength R_m were determined in a full uniaxial tensile test (until the sample broke) with a strain rate of $10^{-3}s^{-1}$ (Fig. 6). The value of the longitudinal strain was determined based on the displacement of the testing machine crossbeam.

RESEARCH RESULTS

The analysis of the elastic and strength properties of the tested materials was carried out based on the results presented, among other formats, in the form of polar charts ranging from 0° to 90°, visualising their distribution in the sheet metal plane. The impact of straight and hexagonal perforation on the change in the considered parameters is presented against the background of the base solid sheet metal, and also taking into account the mass (loss) ratio W_m.

The average values of the examined characteristics in the perforated sheet metal plane were determined according to the following relation:

$$x = \frac{x_0 + 2x_{45} + x_{90}}{4} \text{ for straight perforation} \quad (3)$$

$$x = \frac{x_0 + x_{30} + x_{45} + x_{60} + x_{90}}{5} \text{ for hexagonal perforation} \quad (4)$$

where: x denotes the parameter under consideration and the subscripts denote individual directions in the sheet metal plane.

Mechanical properties and effective Young's modulus of Po2s4 and Ho2s4 perforated sheet metal

Figure 7 shows example curves obtained in a static uniaxial tensile test of perforated sheet

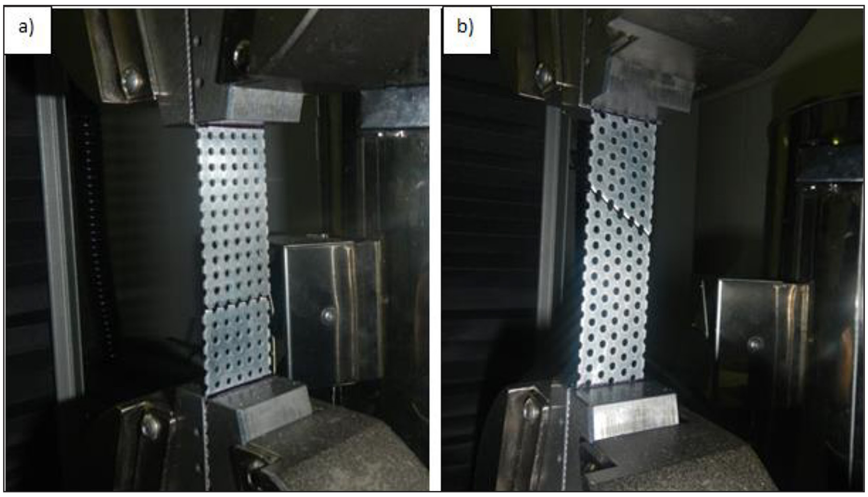

Figure 6. Examples of photographs of specimens after breaking with: a) straight perforation (Po2s4) and b) hexagonal perforation (Ho2s4)

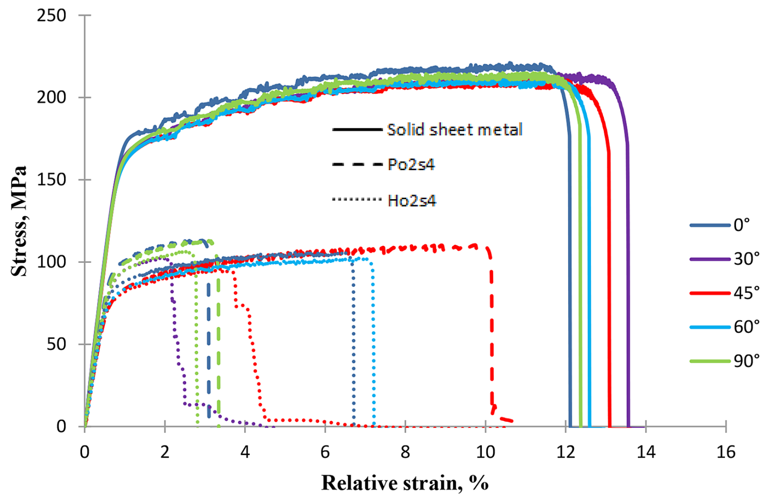

Figure 7. Examples of tensile stress-strain curves for solid and perforated sheet metal (Po2s4 and Ho2s4)

metal (Po2s4 and Ho2s4) for the considered directions in its plane, which were compared with analogous curves for the reference material (solid sheet metal). As a result of perforation, there was a change in the nature of the material's deformation. The stretching of perforated sheet metal occurs not only at lower stress values but also with lower obtainable strain values. However, in the case of the diagonal direction (45°) of straight perforation, the relative strain (elongation) is relatively large and most similar to the strain of solid sheet metal. Moreover, characteristic faults may appear on the tensile curves of perforated sheet metal, resulting from the propagation of material cracks between the holes. The mechanics (process) of perforated sheet metal cracking in relation to straight and hexagonal perforation is discussed in [3]. Regardless of the direction considered, a similar shape of the tensile curves of solid sheet metal is observed, while perforated sheet metal in a straight and hexagonal arrangement shows greater variation in this respect. It should be noted, however, that the curves for the 0° and 90° orientation of straight perforation and the curves for the 0° and 60°, as well as for 30° and 90° directions of hexagonal perforation have a similar course.

Figure 8 presents example lines illustrating the dependence of stress σ on strain ε (relative elongation) in the linear elastic range for the tested materials. Based on these lines, the values of the effective Young's modulus of perforated sheet metals (Po2s4 and Ho2s4) were determined, and an analogous parameter was determined for sheet metals without perforations. The slope of the lines clearly indicates a higher value of the analysed

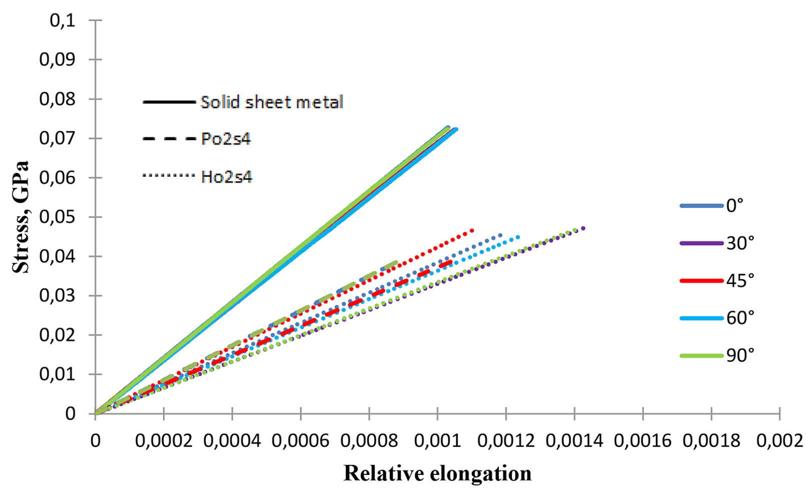

Figure 8. Examples of stress-strain lines in the elastic range for solid and perforated sheet metal (Po2s4 and Ho2s4)

elastic constant in the case of solid sheet metal. The distribution of elastic and strength properties in a sheet metal plane with straight and hexagonal perforation, compared to the base solid sheet, is shown in Figure 9 and Figure 10 based on the results in Table 1 and Table 2.

The EN AW-5754 solid sheet metal shows high uniformity in the considered properties (especially the longitudinal modulus of elasticity). As a result of perforation, their anisotropy increased. Straight perforation caused a decrease in the average value of Young's modulus in the sheet metal plane by 42%, while for hexagonal perforation it was 48%. The greatest reduction in the analysed elastic constant was recorded for the 30° and 90° directions of the hexagonal hole system (by 52% and 53%, respectively). The smallest reduction was for the 0° and 90° directions of straight perforation (by 38%). In the remaining cases, the decrease in Young's modulus was as follows: 40%

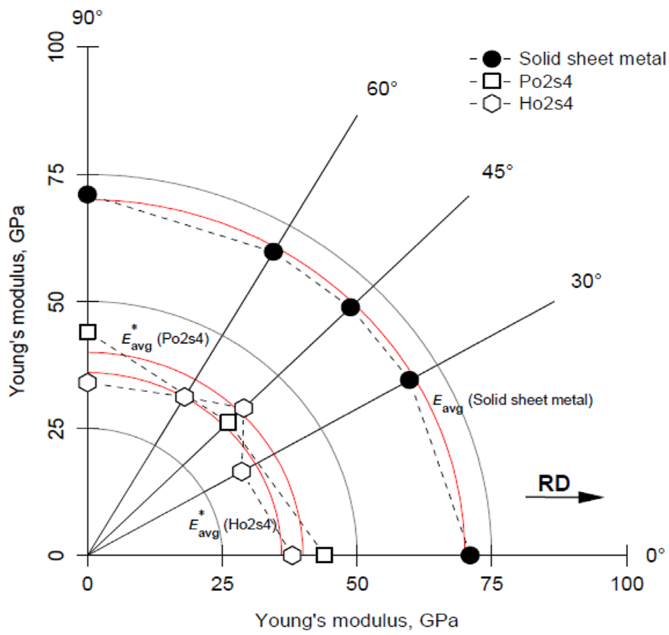

Figure 9. Distribution of effective Young's modulus of sheet metal with straight (Po2s4) and hexagonal (Ho2s4) perforation on the background of solid sheet metal

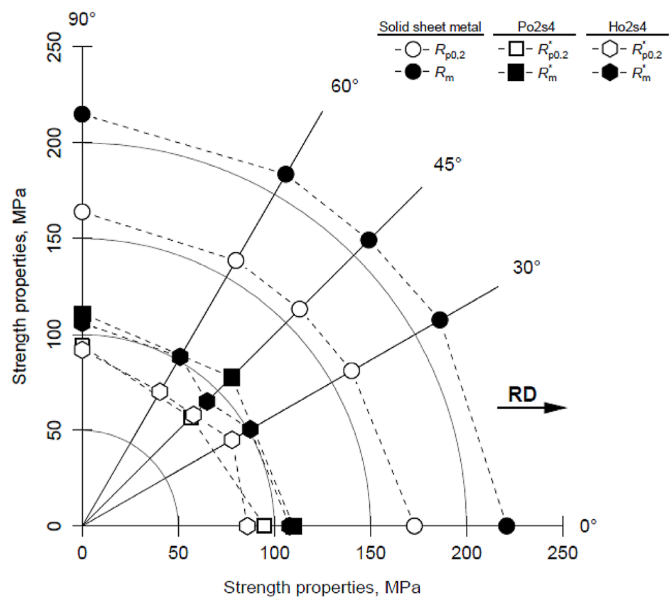

Figure 10. Distributions of strength properties of sheet metal with straight (Po2s4) and hexagonal (Ho2s4) perforation against the background of solid sheet metal

Table 1. Young's modulus of sheet metal EN AW-5754 – perforated and without perforation

Direction of the sample axis in relation to the RD	Young's modulus *E*, GPa	Effective Young's modulus *E**, GPa	
	Solid sheet metal	Perforated sheet metal	
		Po2s4	Ho2s4
0°	71	44	38
30°	69	-	33
45°	69	37	41
60°	69	-	36
90°	71	44	34
Average value	70	40	36

Table 2. Strength properties of sheet metal EN AW-5754 – perforated and without perforation

Direction of the sample axis in relation to the RD	Strength properties, MPa					
	Solid sheet metal		Perforated sheet metal			
			Po2s4		Ho2s4	
	$R_{p0,2}$	R_m	$R_{p0,2}^*$	R_m^*	$R_{p0,2}^*$	R_m^*
0°	173	221	95	110	86	108
30°	162	215	-	-	90	101
45°	160	211	80	110	82	92
60°	160	212	-	-	81	102
90°	163	215	94	111	92	106
Average value	164	215	87	110	86	102

(45° direction of hexagonal perforation), 46% (0° direction of hexagonal perforation, and 45° direction of straight perforation), and 48% (60° direction of hexagonal perforation). For straight perforation, the effective Young's modulus in the diagonal direction (45°) constitutes approximately 84% of the parameter obtained for the directions with the densest hole packing (0° and 90°). Perforated sheet metal in a hexagonal array is characterised by a fairly uniform distribution of the effective longitudinal modulus of elasticity, although for the intermediate direction (45°), its value was slightly higher in relation to the other considered orientations of this array. Comparing corresponding directions of both perforations, i.e. those that form the same angle with the direction of the densest packing of holes, it should be concluded that for 0° and 90° orientations, a straight array of holes reduces the Young's modulus of the sheet to a lesser extent (by 8% and 15%, respectively), while in the 45° direction, a smaller decrease in the considered parameter was recorded for hexagonal perforation (by 6%).

A straight perforation system resulted in a reduction in the average values of yield strength and tensile strength in the sheet metal plane by 47% and 49%, respectively. In the case of hexagonal perforation, the average values of these parameters were lower by 47% and 52%, respectively, compared to the reference material. The greatest decrease of 50% in yield strength occurred for the 45° direction of straight perforation and for the 0° and 60° directions of hexagonal perforation, with the 45° direction showing a slightly smaller decrease in this parameter (49%). In the remaining cases, the value of yield stress was reduced by 45% and 42%, respectively, for the 0° and 90° directions of the square array of holes, and by 45% and 44%, respectively, for the 30° and 90° directions of the hexagonal array. The average value of tensile strength of the perforated sheet metal was reduced relative to the base material by 49% for straight perforation and by 52% for hexagonal perforation. For the 0°, 45°, and 90° directions of the square array of holes, the decrease in this parameter was 50%, 48%, and 48%, respectively, while for each considered hexagonal perforation direction it exceeded 50%, being the highest for the 45° orientation (56%). Moreover, it can be generally stated that perforated sheet metal in a square array of holes is characterised by slightly higher strength properties compared to sheet metal with a hexagonal array of holes (except for the 45° orientation). Considering the characteristic directions of both perforations, a fairly uniform distribution of tensile strength in the sheet metal plane is observed, while in the case of yield strength it is less uniform, especially for a straight perforation.

Effective Young's modulus and strength properties of perforated sheet metal, taking into account the mass loss ratio

An important aspect often considered in the design of a structure is ensuring its sufficiently low mass while maintaining the required strength. In this case, it is worth referring to the so-called specific strength, which expresses the ratio of strength to material density. To minimise the mass of the structure, a higher value of this parameter is more beneficial. However, for perforated sheet metals, it is difficult to determine this type of material density and, consequently, to use the concept of specific strength in relation to these materials. In this context, when considering the structural purpose of perforated sheet metal, the so-called mass loss ratio W_m (5), clearly defined in [4], can be used. This ratio expresses relation between the perforated sheet metal mass m_p and the base solid sheet metal mass m:

$$W_m = \frac{m_p}{m} \quad (5)$$

In the case of perforated and solid sheet metals made of the same material (the same density of material) and the same thickness, the mass loss ratio W_m can be expressed as follows:

$$W_m = 1 - P \quad (6)$$

where: P - open area, i.e. the ratio of the area with holes to the total surface of the sheet metal covered by perforation. The argument coming from the general definition (5) to the dependency (6) is presented in [4].

As follows from Equation 6, the mass loss ratio W_m for solid sheet metal with zero open area ($P = 0$) is 1, while for perforated sheet metal it is in the range: $0 < W_m < 1$. This ratio helps to account for the impact of mass loss caused by perforation on the change in mechanical properties of the sheet metal.

Moreover, the mass loss ratio W_m compensates for the selected parameters adequately to the open area value, according to the exemplary relation: E^*/W_m, which allows for a more effective comparison for different perforations, assuming the same type and thickness of the base sheet metal. Thus, perforated sheet metal characterised by a higher value of a given parameter, which takes into account the mass loss ratio, transfers external loads more effectively. In Figure 11 and Figure 12, based on the results presented in Table 3 and Table 4, the distribution of the effective Young's modulus and strength properties of perforated sheet metal in a square and hexagonal array is presented, taking into account the mass loss ratio W_m through the relation: E^*/W_m, $R^*_{p0.2}/W_m$ and R^*_m/W_m. With sufficient accuracy, it can be assumed that for sheet

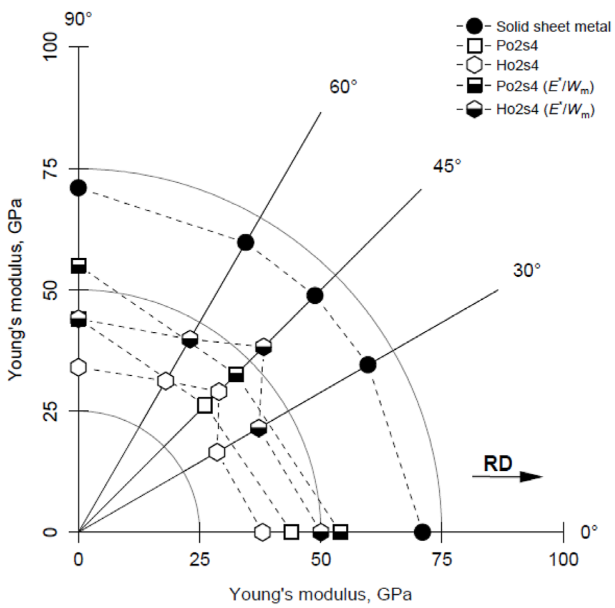

Figure 11. Distribution of effective Young's modulus accounting for the mass loss ratio W_m in comparison to the distributions for solid and perforated (Po2s4 and Ho2s4) sheet metal

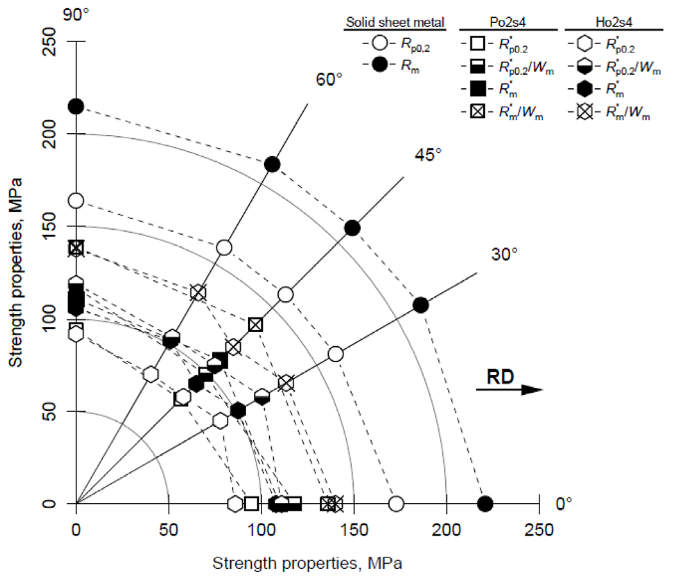

Figure 12. Distributions of strength properties accounting for the mass loss ratio W_m in comparison to the distributions for solid and perforated (Po2s4 and Ho2s4) sheet metal

Table 3. Young's modulus of sheet metal EN AW-5754 – perforated and without perforation accounting for mass loss ratio W_m

Direction of the sample axis in relation to the RD	Young's modulus E, GPa	Effective Young's modulus E^*/W_m, GPa	
		Perforated sheet metal	
	Solid sheet metal	Po2s4	Ho2s4
0°	71	54	50
30°	69	-	43
45°	69	46	54
60°	69	-	46
90°	71	55	44
Average value	70	50	47

Table 4. Strength properties of sheet metal EN AW-5754 – perforated and without perforation, accounting for the mass loss ratio W_m

Direction of the sample axis in relation to the RD	Strength properties, MPa					
	Solid sheet metal		Perforated sheet metal			
			Po2s4		Ho2s4	
	$R_{p0,2}$	R_m	$R_{p0,2}^*/W_m$	R_m^*/W_m	$R_{p0,2}^*/W_m$	R_m^*/W_m
0°	173	221	118	136	111	140
30°	162	215	-	-	116	131
45°	160	211	99	137	106	120
60°	160	212	-	-	104	132
90°	163	215	117	139	119	138
Average value	164	215	108	137	111	132

metal with straight perforation $W_m = 0.80$, and for sheet metal with hexagonal perforation $W_m = 0.77$.

After taking into account the mass loss ratio W_m, the effective Young's modulus values and the strength parameters of the perforated sheet "increased" in accordance with its open area (by approx. 20% and approx. 23%, respectively, for a square and hexagonal array of holes), while the nature of the distribution of the analysed properties in the sheet metal plane has been maintained. Obviously, the considered parameters of perforated sheet metal have become closer to the analogous characteristics of solid sheet metal. In this respect, the increase in the average values of the effective Young's modulus, yield strength, and tensile strength compared to the reference material was 14%, 13%, and 13% for straight perforation, and 15%, 15%, and 14% for hexagonal perforation, respectively. Nevertheless, the obtained values of the analysed parameters, resulting from the adopted method of taking into account the sheet metal mass loss caused by perforation (using the W_m ratio), should be considered mainly in the context of a direct comparative analysis of the mechanical properties of the tested perforated sheet metals (with different arrays of holes and open area). It can therefore be concluded that among the perforations discussed the sheet metal with a square array of holes transfers loads slightly more effectively in the elastic region, as proved by higher (in this case) values of the effective Young's modulus for the 0° and 90° directions, as well as the average value of this parameter. By taking into account the mass ratio $W_{m,}$ the strength properties of sheet metal with straight and hexagonal perforations became very similar (except for the 45° orientation). In this case, it is more difficult to clearly indicate which of the considered regular hole arrays shows higher strength properties.

CONCLUSIONS

Perforated sheet metals are a specific type of engineering materials with a wide characteristics profile. Favourable mechanical properties combined with suitable functional features, obtained through the appropriate selection of the raw material and perforation parameters, determine the broad application significance of these materials. Perforated sheets made of aluminium and its alloys are used, among others, in architecture and building construction as facade panels. They can also be a structural element of acoustic or photovoltaic panels. Despite a certain decrease in elastic or strength properties compared to the base material, perforated sheet metal can still be an attractive construction material, characterised by, among other things: reduced mass – an important criterion in many engineering solutions – and specific open area, enabling controlled flow of various substances.

Considering the multitude of parameter variants related to perforation, the method of determining the properties of perforated sheet metal requires special attention. In the case of a regular perforation system, characteristic directions can be distinguished such as directions with the densest packing of holes and the directions perpendicular to them. This approach was incorporated into the research methodology of this study when analysing the impact of straight and hexagonal perforation on the elastic and strength properties of EN AW-5754 sheet metal. Based on the results obtained, it can be concluded that for a constant hole diameter (2 mm) and pitch value (4 mm), a sheet with a straight array of holes shows slightly higher elastic and strength properties compared to the hexagonal array. However, it should be noted that this does not apply to the diagonal direction (45°) of straight perforation, for which a noticeably lower value of the effective Young's modulus and yield strength was recorded compared to the 0° and 90° directions of this system of holes. Moreover, considering the characteristic directions of the discussed perforations, a fairly high uniformity in the distribution of the analysed parameters in the perforated sheet metal plane in a hexagonal arrangement is observed. After accounting for the mass loss caused by perforation, the considered characteristics were compensated to some extent, and as a result, the tested properties, especially strength ones, of sheet metals with straight and hexagonal perforation are very similar, although the nature of their distribution remained unchanged.

To conclude, as a result of perforation, the elastic and strength properties of the EN AW-5754 aluminium alloy sheet metal decreased, and this decrease varied depending on an array of holes and the considered direction in the sheet metal plane. The average value of the effective Young's modulus, yield strength and tensile strength decreased by 42%, 47%, and 49%, respectively, for straight perforation, and by 48%, 47%, and 52%, respectively, in the case of hexagonal perforation. The conducted research allows us to conclude that the analysed mechanical properties and their distribution in the perforated sheet metal plane strongly depend on the geometric features of the hole grid.

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