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INFLUENCE OF PERFORATION OF THE INNER LAYER ON THE PROPERTIES OF THREE-LAYER WELDED MATERIALS

Multilayered materials give a range of possibilities with regard to control of their properties through selection of layers' materials, their thickness and the layout of layers. This research is focused on examining the behaviour of three-layer material with perforated sheet as the inner layer during the stretching and drawing process. Four remove tests were carried out: Erichsen, Engelhardt-Gross, Fukui and cup drawing test. Mechanical properties and weld quality were also determined. Sheets with four perforations were used: Po2s3, Po2s4, Po2s10 and Po2s30, which corresponds to the open area values of 34.9%, 19.6%, 3.1% and 0.35%.

Keywords: multilayered material, perforated sheet, welding, drawability

1. Introduction

Modern industry, for example the automotive and aerospace industries, requires designers to use materials which often have very different properties. On the one hand, they should be characterized by good endurance properties, but on the other, they should have good formability. They also need to have good corrosion resistance. At the same time, these materials should be as light as possible and relatively cheap. One way to achieve material requirements of this type is to use multilayered materials as the construction material. The properties of materials of this type can be controlled through appropriate selection of materials for individual layers [1,2]. Their strength depends on the type of materials used and is close to the average value of components' strength [3]. Also, the number of layers affects the properties of multilayered materials [4]. It has been shown that an increase in the number of layers up to a certain point improved the impact energy of multilayer sheet. An important factor that influences the properties of multilayered materials is also the strength of the bond between layers. A high degree of bonding indicates high resistance to delamination and hence good strength of the material. However, delamination can increase the ductility of the material due to strain hardening and plastic deformation of the remaining material after the appearance of a crack between layers. Thus, the energy absorption and toughness of the material increase [5].

Perforated sheets are increasingly used as construction materials due to their relatively high strength and reduced weight compared to solid sheets [6]. The properties of perforated metal sheet strongly depend on the type of perforation and open area value. Plastic behaviour is not uniform, especially in the case of the right perforation pattern. However, by choosing the value of open area, it is possible to increase or decrease their mechanical properties and the material's behaviour during plastic deformation [7-9]. Moreover, considering the mass ratio, it turns out that the strength of this type of material is significantly higher, and the difference in the properties between solid and perforated sheet is considerably lower [6].

Drawability is an important parameter characterizing the possibility of deep drawing of sheets. Multilayered sheets with perforated sheet as the inner layer, intended as materials for drawing products, were examined in this paper. The influence of several factors was studied using Erichsen, Engelhardt-Gross, Fukui, cup drawing and tensile tests.

2. Materials and methods

A straight perforation with open area values P from 0.35% to 35% (Table 1) was selected, and two different orientations of perforated sheet, with respect to the close-packing direction of holes, were chosen: 0° and 45°. Technically pure aluminium (EN AW-1050A) and EN AW-5754 aluminium alloy were selected as the materials of the inner layer. In the case of outer layers, solid aluminium (EN AW-1050A) sheet was used. The thickness of the inner layer was constant for all studied factors and equal to 1 mm, whereas for outer layers, sheets of three different thicknesses were used: 0.25 mm, 0.5 mm and 1 mm.

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TABLE 1

Characterization of inner layer perforation

Perforation	Hole diameter *d*, mm	Distance between holes *t*, mm	Open area *P*, %
Po2s3	2	3	34.89
Po2s4		4	19.63
Po2s10		10	3.14
Po2s30		30	0.35

Three-layer sheets were obtained through the hot rolling process. First, they were heated at the temperature of 500°C for 10 (Al1050) or 15 (Al5754) minutes. Then they were hot rolled until 1 mm of sheet thickness was achieved. Mechanical properties of materials were obtained in a tensile test considering the orientation of the sample relative to the rolling direction (0°, 45°, 90°). Erichsen, Engelhard-Gross, Fukui and cup drawing tests were used to analyse the drawability of multilayer sheets.

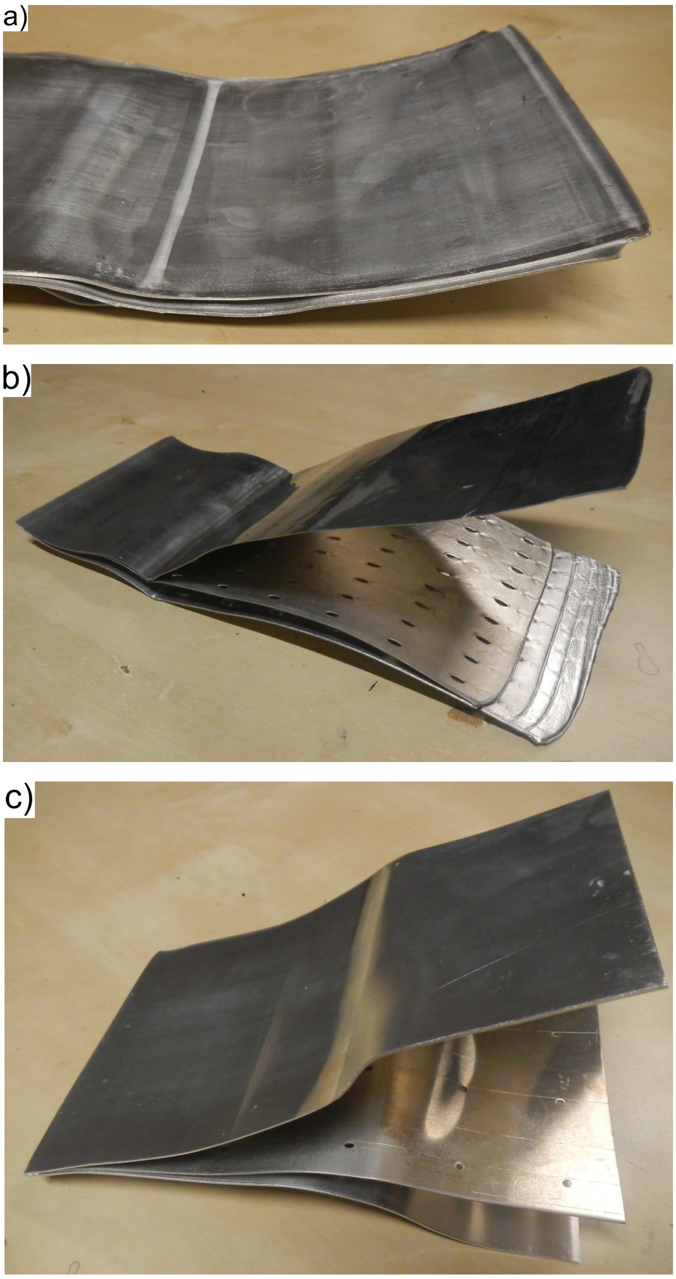

Fig. 1. Examples of multilayer sheets after hot rolling and preheated in various conditions: a) Al1050, T = 450°C, t = 15 minutes; b) Al1050, T = 500°C, t = 5 minutes; c) Al5754, T = 500°C, t = 10 minutes

3. Results and discussion

3.1. Weld quality

In this paper, the influence of several parameters on the strength and drawability of three-layer sheet was examined. Thus, it was necessary to choose the appropriate temperature and time of sample preheating. Fig. 1 shows examples of the samples after hot rolling and various conditions of preheating. The application of insufficient heating temperature and time resulted in separation of layers. In the case of the inner layer made of Al1050, a good connection between layers was obtained for heating temperature equal to T = 500°C and time t = 10 minutes. In the case of Al5754, satisfactory results were obtained for T = 500°C and heating time t = 15 minutes.

Fig. 2 shows microstructures of the welding areas. It was observed that weld discontinuities occurred at hole edge sites

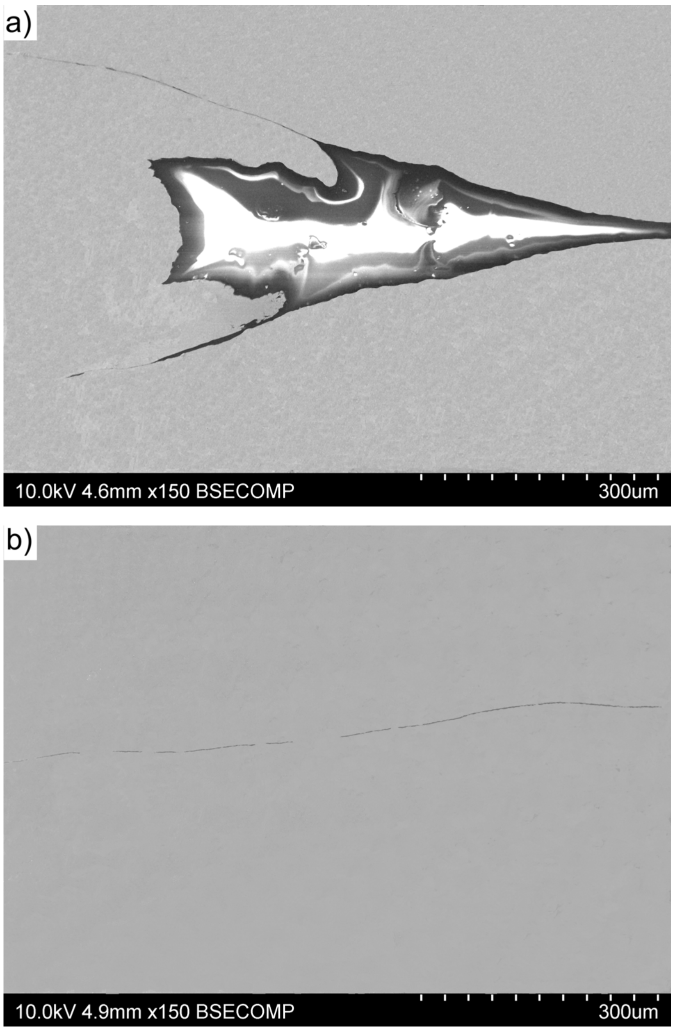

Fig. 2. Microstructure of weld in case of: a) hole edge area; b) internal area

(Fig. 2a), while the internal area was free of them (Fig. 2b). During the hot rolling process, materials of outer layers filled holes in the perforated sheet and were subsequently welded to themselves. However, the edges of the holes were obstacles to the material's flow, hence the lack of full filling.

3.2. Mechanical properties

Table 2 shows average values of mechanical properties of three-layer material depending on the type of perforation and orientation of the inner layer. An increase in the open area value resulted in a decrease of tensile strength (Fig. 3) due to the decrease of the inner-layer sheet's strength. Outer layers did not provide sufficient strength to withstand applied load. Moreover, it was found that the holes present in the inner-layer sheet were the main source of cracks in the sample during the tensile test.

TABLE 2

Mechanical properties of three-layer materials depending on the type of perforation and inner layer orientation

Type of perforation (open area value)	**Orientation of inner layer**	**Yield strength $R_{p0.2}$, MPa**	**Tensile strength R_m, MPa**	**Ultimate elongation A_{50mm}, %**
Po2s3 (34.89%)	0°	92	95	1.5
	45°	95	97	1.3
Po2s4 (19.63%)	0°	99	103	1.6
	45°	105	107	1.6
Po2s10 (3.14%)	0°	103	108	2.5
	45°	110	113	2.1
Po2s30 (0.35%)	0°	105	111	2.6
	45°	115	120	2.4

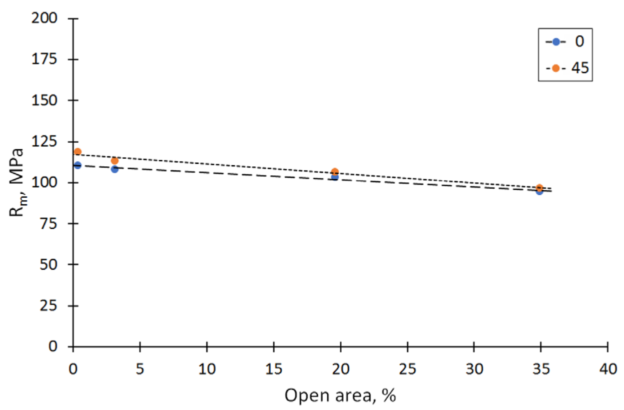

Fig. 3. Effect of open area value and orientation of inner layer on the strength of three-layer sheet

As shown on the graph, the orientation of the inner-layer sheet significantly affects the strength of the three-layer material, especially in the case of a lower range of the open area value (Fig. 3). For P = 35%, tensile strength was similar for both orientations. The cut-out direction of perforated sheet also affects the distribution of material properties. In both cases, anisotropy of properties was found (Fig. 4). However, in the case of 0° inner layer orientation, the lowest value of tensile strength was observed for the three-layer sheet plane direction of 45°, especially for a lower range of open area values (Fig. 4a). On the other hand, for the cut-out direction equal to 45°, the lowest strength of material was observed for the 0° direction (Fig. 4b).

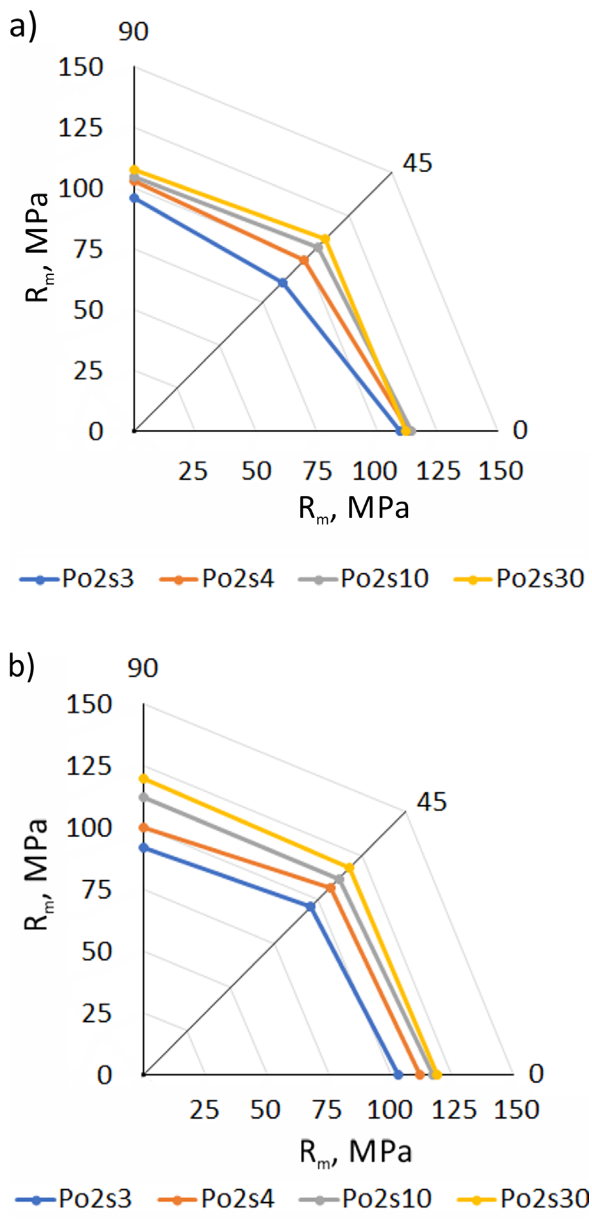

Fig. 4. Distribution of tensile strength R_m for inner layer orientation equal to: a) 0; b) 45

One of the features of multilayered materials is the possibility of controlling their properties by selecting the type of material for particular layers. It was found that usage of perforated sheet made of material with higher mechanical properties resulted in a significant increase of the strength of three-layer sheet (Table 3). The value of tensile strength was about 80% that of solid sheet made of 5754 aluminium alloy (for P = 3.14%) and 140% that of Al1050 solid sheet. On the other hand, the effect of the outer layer's thickness was smaller than expected (Fig. 5).

TABLE 3

Mechanical properties of three-layer materials depending on the type of inner layer material and outer layer thickness

Material of inner layer	Type of perforation	Thickness of outer layer	Yield strength $R_{p0.2}$, MPa	Tensile strength R_m, MPa	Ultimate elongation A_{50mm}, %
Al1050	Po2s10	0.25	81	91	1.7
		0.50	92	100	2.3
		1.00	103	108	2.5
	Po2s30	0.25	98	109	2.1
		0.50	98	109	2.4
		1.00	105	111	2.6
Al5754	Po2s10	0.25	130	148	1.6
		0.50	140	153	1.9
		1.00	149	158	2.0
	Po2s30	0.25	145	177	1.8
		0.50	156	182	2.1
		1.00	166	186	2.3

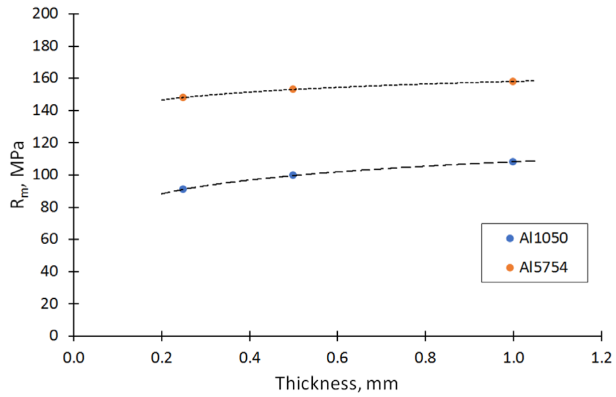

Fig. 5. Influence of outer layer thickness on the strength of multilayer sheet for inner layer with Po2s10 perforation

3.3. Drawability

Drawability of three-layer material was examined by four tests: Erichsen, Engelhardt-Gross, Fukui and cup drawing test. The indexes for all four tests were determined. Table 4 shows values of drawability indexes as a dependency of open area value and inner layer orientation. In the case of the latter, all tests showed little effect of this parameter. On the other hand, the value of open area had a significant effect on the drawabil-

TABLE 4

Drawability of multilayer sheets depending on the type of perforation and inner layer orientation

Type of perforation (open area value)	Orientation of inner layer	Erichsen index *IE*, mm	Engelhard-Gross index *T*, %	Fukui index η_F	Limiting drawing ratio *K*
Po2s3 (34.89%)	0°	4.0	4.6	0.924	1.52
	45°	4.1	7.1	0.913	1.60
Po2s4 (19.63%)	0°	4.2	13.9	0.925	1.73
	45°	4.5	15.2	0.916	1.79
Po2s10 (3.14%)	0°	6.5	51.3	0.884	1.82
	45°	6.8	54.3	0.874	1.87
Po2s30 (0.35%)	0°	8.1	56.9	0.855	1.88
	45°	8.3	58.3	0.851	1.90

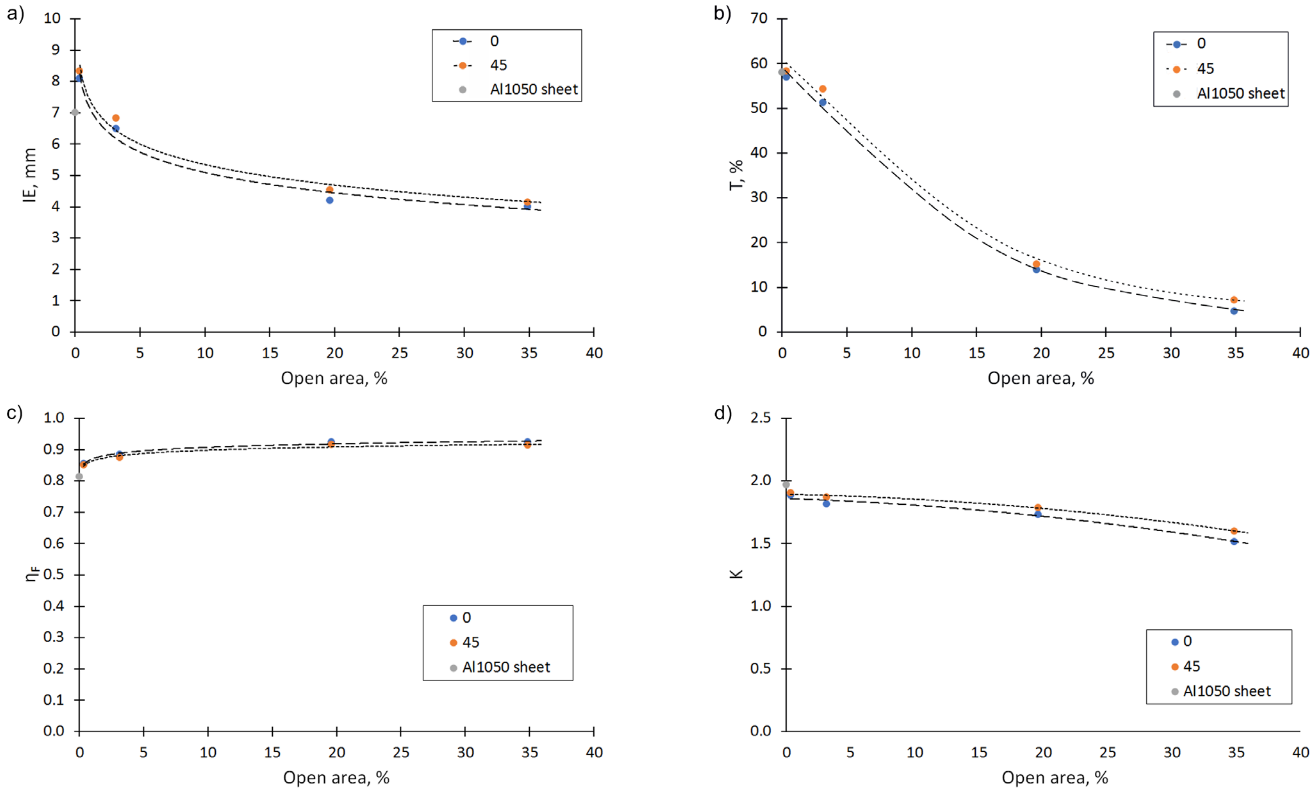

Fig. 6. Influence of open area value P of inner layer sheet on drawability of three-layer material: a) Erichsen index; b) Engelhardt-Gross index; c) Fukui index; d) limiting drawing ratio

ity of multilayer sheets (Fig. 6). Generally, drawability of the examined material decreased with the increase of *P* value. The most significant change of determined indexes was observed in the case of a lower range of open area value (from 0.35 to 3.14%). Their values are comparable with the values of indexes obtained for solid Al1050 sheet.

Based on the appearance of the workpiece in the Erichsen test, the structure of sheet can be qualitatively evaluated. It was determined that the surface of the drawpieces was rough, and the shape of the cracks was irregular (Fig. 7). This means that the material's structure was coarse-grained. In the case of higher open area values, cracks began to appear mainly at the location of holes in the inner sheet and were responsible for irregularity of crack shape.

Fig. 7. Appearance of draw area after Erichsen test

Similarly as in the case of the tensile test, drawability of multilayer sheets depended on the type of inner-layer sheet (Table 5). Better drawability was determined in the case of the inner layer made of Al1050 perforated sheet, which corresponds to higher plasticity of technically pure aluminium than of 5754 aluminium alloy. This is particularly evident in the case of the Engelhardt-Gross test, which takes into account the stress state in the workpiece during the deep drawing process (Table 5, Fig. 8b). Values obtained for three-layer material with Al1050 sheet as the inner layer were about 5 times higher than for 5754 aluminium

TABLE 5

Effect of outer layer thickness and material of inner layer on drawability of multilayer sheets

Material of inner layer	**Type of perforation**	**Thickness of outer layer**	**Erichsen index *IE*, mm**	**Engelhard-Gross index *T*, %**	**Fukui index η_F**	**Limiting drawing ratio *K***
Al1050	Po2s10	0.25	4.9	45.6	0.915	1.59
		0.50	5.4	49.9	0.894	1.72
		1.00	6.5	51.3	0.884	1.82
	Po2s30	0.25	7.7	45.7	0.865	1.62
		0.50	8.0	50.6	0.859	1.76
		1.00	8.1	56.9	0.855	1.88
Al5754	Po2s10	0.25	3.4	12.1	0.970	1.40
		0.50	4.5	16.3	0.924	1.57
		1.00	5.8	19.7	0.895	1.71
	Po2s30	0.25	6.5	23.5	0.867	1.41
		0.50	6.8	29.2	0.862	1.60
		1.00	7.0	33.8	0.857	1.84

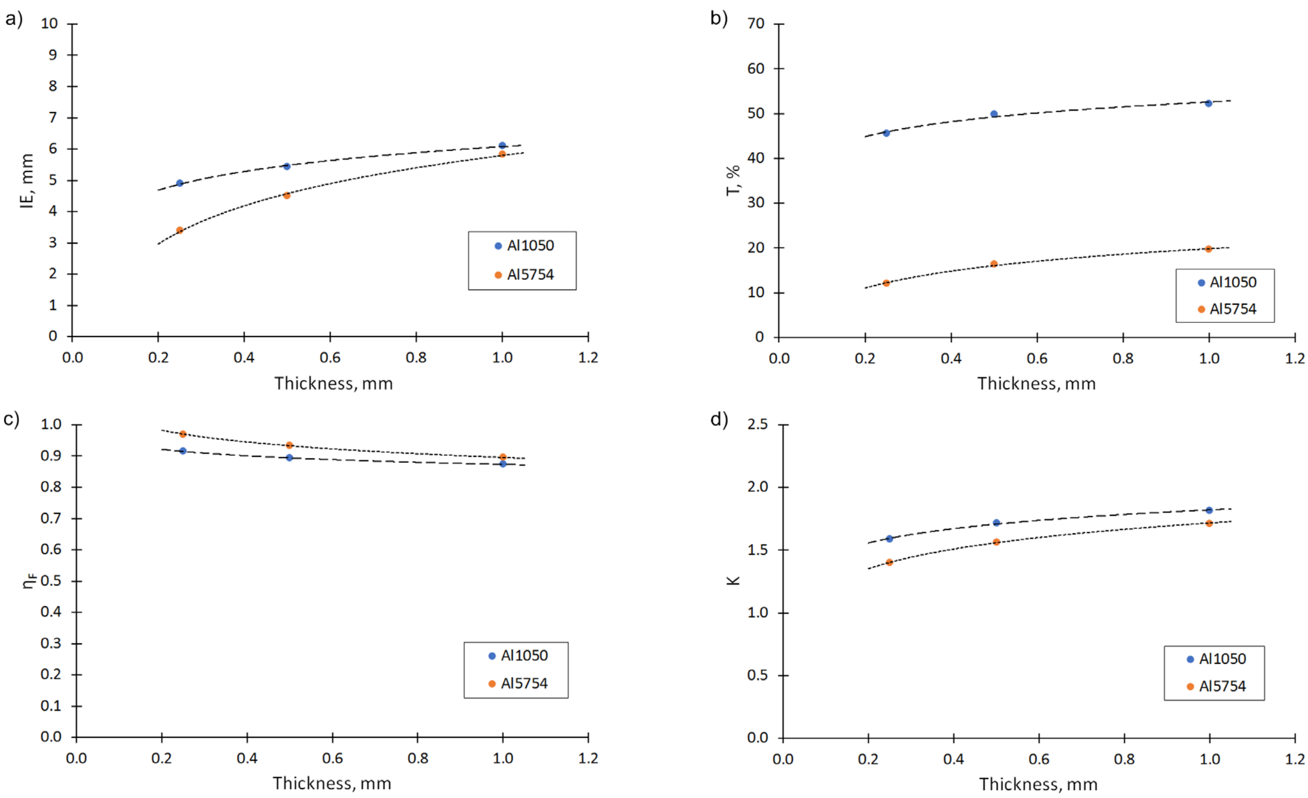

Fig. 8. Effect of inner layer material and outer layer thickness on drawability of three-layer sheet: a) Erichsen index; b) Engelhardt-Gross index; c) Fukui index; d) limiting drawing ratio

alloy. For both cases of inner-layer material, it was found that the thickness of the outer layer affects the drawability of sheets (Fig. 8). In the case of Po2s10 perforation, it was shown that, for both materials, values of indexes increase as the thickness of the outer layers increases. However, for 5754 aluminium alloy, the dependence on outer layer thickness is higher than in the case of Al1050. This is particularly evident in the case of the Erichsen test, where plane stress occurs. This means that it is necessary to have a sufficient amount of plastic material as the outer layers to be able to obtain good quality cups.

4. Conclusion

The mechanical properties and drawability of multilayer sheet with perforated sheet as the inner layer were investigated. Both in the case of drawability tests and tensile tests, multilayer materials with lower open area values of the inner-layer sheet were characterized by better parameters determined in these tests. The thickness of the external layers was an important factor influencing the strength, drawability and plasticity of the examined materials. In the case of thinner sheets, these materials were characterized by worse drawability indexes and lower mechanical properties. The type of material of the inner layer turned out to be an important factor. The three-layer material with perforated sheet made of EN AW-5754 alloy had higher strength properties. At the same time, it was characterized by lower ductility and worse drawability.

Proper selection of the type of perforation, thickness and type of material for individual layers of the composite makes it possible to control the properties of this type of multilayer material from the perspective of using it as a construction material and a preform for further plastic processing, especially deep drawing.

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REFERENCES

[1] D.R. Lesuer, C.K. Syn, O.D. Sherby, J. Wadsworth, J.J. Lewandowski, W.H. Hunt, Int. Mater. Rev. **41**, 169-197 (1996).
[2] J. Inoue, S. Nambu, Y. Ishimoto, T. Koseki, Scripta Mater. **59**, 1055-1058 (2008).
[3] M.H. Serror, J. Adv. Res. **4**, 83-92 (2013).
[4] T. Kubina, J. Nachazel, Mater. Tehnol. **51** (4), 557-561 (2017).
[5] C.M. Cepeda-Jimenez, P. Hidalgo, M. Pozuelo, O.A. Ruano, F. Carreno, Metall. Trans. A **41** (1), 61-72 (2010).
[6] W. Muzykiewicz, M. Wieczorek, M. Mroczkowski, P. Palka, L. Kuczek, Met. Form. **27** (4), 283-300 (2016).
[7] L. Kuczek, W. Muzykiewicz, M. Wieczorek, M. Mroczkowski, P. Palka, D. Zieba, PLASTMET2018: Integrated studies of foundations of plastic deformation of metals, November 27-30, 2018 Lancut.
[8] W. Muzykiewicz, The formability of perforated metal sheets, Publishing House "AKAPIT", Krakow 2013.
[9] S.C. Baik, H.N. Han, S.H. Lee, K.H. Oh, D.N. Lee, Int. J. Mech. Sci. **39** (7), 781-793 (1997).