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Experimental optimization of tab and slot plug welding method suitable for unique lightweight frame structures

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ABSTRACT

The tab and slot plug welding method applied to frame construction represents an interesting and low-cost construction system. Regarding the materials used, it is possible to create both unique lightweight aluminium frames, applied to service robots or effectors, as well as conventional steel frames for machines and peripherals. This article firstly summarizes the technologies and general aspects of the frame structure, and then it presents the characteristics of the tab and slot plug welding method, followed by a brief theoretical analysis. Furthermore, experimental and numerical simulations are performed based on the comparison of the given method with the common construction system of extruded profiles. The main focus is on optimizing the tab and slot system based on extensive laboratory experiments, where emphasis is placed on the dimensions of the joints in relation to used materials. This is followed by numerical simulation of the stress fields in joints. In the conclusion, recommendations are made for frames of different materials produced by the presented method; Work also includes selected real examples of structural applications of the given system.

1. Introduction to frame design

Frames represent the basic supporting element of most machinery and peripherals, means of transport, but also many buildings. In all cases, the basic criteria are low or acceptable production costs [1] and adherence to proportional design parameters [2]. The most advanced developments in light and ultralight structures can be seen in astronautics [3–5], and subsequently in avionics [6–8] from drones onwards [9,10]. Another important area that develops the application of such technologies and systems for mass use is the automotive industry [11–13]. In all of these areas, the application of lightweight frames has a direct impact on performance, both in terms of performance parameters and cost savings [1,14,15]. However, it is necessary to bear in mind that special structures are often connected with a high purchase price, both in terms of the materials and production technologies used. In standard industrial practice using frame structures, it is necessary to seek a compromise between the cost of production and the resulting parameters of the fabricated structure [16]. Frequent parameters of common structures include, in particular, the requirement for high rigidity, often in relation to lowest possible weight, and, in the case of moving parts, low inertia. Another equally important requirement is the overall level of development of the design task, from both a technical as well as aesthetic point of view.

The development of frame structures generally includes the areas of construction materials, modern methods for dividing and processing the materials and, last but not least, the frame connection technology. These areas are closely intertwined and advancements in one of them often influences and expands the possibilities in other areas. Examples include modern methods of material separation and processing, which provide many new ways of acquiring the desired design [16,17].

Modern cutting technologies include CNC cutting machines based on a laser or water jet, or even plasma, which can favourably reduce costs. This method falls into the promising area of digital fabrication, where the use of metal plates as the input intermediate product enables easy and above all space-saving transport of the resulting fragments to the place of assembly or to the customer. The use of a wide range of plate thicknesses also expands the variability of the resulting assembly. An alternative is the use of 3D printing [9,18,19], which represents an unconventional modern technology in the engineering industry with a wide range of applications, which provides, among other things, a high potential for new types of construction. One of the main advantages is not only

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the shape variability of the products, but also the possibility to use a wide range of materials and their combinations, from plastics and ceramics to metals.

In general, the most promising materials are composites, which have excellent mechanical properties in relation to low weight. For structural purposes, carbon fibre composites are the most suitable for ultra-light rigid frames [20,21]. However, the purchase price is very high, so in the vast majority of cases they are only used in aviation applications or in luxury cars, etc. Furthermore, the price is also not favourable in terms of production costs, including subsequent machining, because the composites are very hard and abrasive [22,23]. For conventional applications, it is more economical to use conventional materials such as steels, materials based on aluminium alloys, and also titanium or plastics [24–26]. Titanium alloys have the best ratio between maximum strength and minimum weight but their cost is very high and in most cases their use for structural applications would be unprofitable. Conversely, plastics are not widely used as conventional frame structures because of their low rigidity. Steel materials can be divided into conventional and stainless steel in this context. In terms of mechanical properties, conventional structural steels have a relatively high rigidity and a low weight if the rigidity is proportional to the shape relief. The cost of conventional structural steels is relatively low, but the emphasis has to be on the surface treatment. Stainless steels have considerably higher intermediate product costs, which can be partly offset by eliminating surface treatment. Aluminium alloys are best suited for less stressed structures, where emphasis is primarily placed on low weight. Acquisition costs are lower for aluminium alloys than they are for stainless steel, but they are relatively comparable with conventional steel in terms of material density. The products costs depend on the geometrical complexity of the parts in the case of machining, which is closely related to the choice of the machining technology used. By using unconventional cutting methods, the price depends on the dimensional size and usually only marginally from the flat shape complexity.

In addition to the materials and methods of cutting and machining, the formation of non-monolithic frame constructions is closely related to the connection system [27–29], which includes several factors – joining method, locating and holding. Joining can be achieved by adhesion, mechanical components or welding. In the case of the use of mechanical elements, except for self-tapping screws, a hole must be made in both joints to achieve, in addition to the rigid connection, positioning of the part in the correct position relative to the assembly. Positioning can be accomplished by external means, i.e. positioning devices [30], or within the assembly itself, with the help of internal or external (pins) shape elements. Specific positioning devices are particularly suitable for mass production. In the case of single-piece production, universal positioning devices are often used. Positioning systems using external shaped elements in the form of pins or centring cavities etc., carry greater demands on the workpiece, i.e. the production of holes and grooves. In relation to modern cutting technologies, where the complexity of the plate shape is not an essential item in the cost of fabrication, positioning elements may be used as an integral part of the finished product. This is generally referred to as the tab and slot method.

2. Tab and slot method

The tab and slot system is a well-known design system [16,31,32] with a wide range of applications. Perhaps the best known is the use of tabs and slots for the positioning of parts in welded structures (Fig. 1b) [33], thus reducing or even eliminating the requirements for positioning devices. Another structural area utilizing the tab and slot system is the joining of plates, which occurs by means of bending or other deformation of the overhang tabs (Fig. 1d) [34,35]. In a broader sense, a specific manufacturing process called origami [36] can be included in the field. Also, the system is widely used in small workshops, in the construction of frames without welding, where the inserted tabs are deformed in the slot, for example by a punch, or screws are used as fasteners and nuts are inserted into the slot (Fig. 1e).

A less-known yet very promising method is the tab and slot welded construction system, where welding is only performed in the area of the tab and slot joints (Fig. 1c). This is a method with high potential application for producing frames, representing an alternative to conventional welded frames from profiled bars but at similar or even lower production costs. A great advantage of the system is the easy application of relief, while maintaining a comparable or even higher frame rigidity. The main advantage of the tab and slot plug welding system is the shape precision of the resulting welded structure where, unlike the application of continuous or intermittent fillet welds [37–39], there is no thermal deformation of the frame. Another advantage is the ability to create relatively interesting industrial designs of exposed frame structures. By grinding the area of the welds, it is possible to achieve an aesthetically interesting frame without any visible connection. The presented method is able to produce both cheap steel structural frames of equipment and peripheries, as well as lightweight aluminium alloy frames, usable in avionics, effectors and conventional devices requiring a lower weight.

Metal sheets cut by laser, water or plasma cutting centres can be used as intermediate products. The thickness of usable plates is limited, in particular, by the production limits of the cutting centres in relation to the selected material [40–42]. The method is particularly suitable as a replacement for frames of thin-walled profiles, where the thickness of the wall is normally in the range of several millimetres (typically 2 or 3–6 mm). For sheet cutting, any shape relief can be realized, which, when properly designed, results in weight saving of the resulting frame while maintaining its strength and stability. They can also be used for easy access to the internal area of the final frame, for example for electrical wiring, pneumatics or hydraulics.

In order to obtain the optimal strength and appearance parameters of the resulting construction system, including production and cost optimization, it is necessary to observe the basic application procedures. These are mainly given by the optimal shape and dimensions of the tabs and slots, which are dependent on the applied structural material and the thickness of the used plates. To create tabs and slots, there are principles that need to be met for the production technology.

The shape of the tabs and slots is given by the following rules (Fig. 2). In the case of tabs, the width (a) is determined by the thickness of the selected sheet metal. The optimum length of the tabs (b) is assumed in the basic theory of the given technology to be similar to the width, i.e. the base of the tabs is formed by a square or pseudo-square profile, which is derived from the weld plug. Of course, it is also possible to apply a rectangular base profile, which is also the subject of presented optimization, see Chapter 5. The height of the tabs (c) is given by the thickness of the used plate (d) counter piece with the slot, with the specific value being derived from the material used based on the practical knowledge of the local welding technology ($c = f(d)$). The tabs also include recesses to facilitate contact with the surfaces. In addition, the slots must be fitted with characteristic grooves, whose orientation in relation to the mounting must be parallel to the thickness of the opposite plate due to its flatness. The groves are desirable not only in relation to the production technology but also in terms of reducing the local stress in the corners of the elements. The profile of the slot ($g \times h$) is defined by the tab dimensions ($a \times b$), which is increased by approximately 0.2 mm ($g = a + 0.2$ mm, $h = b + 0.2$ mm).