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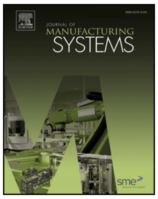

Smart optimization of a friction-drilling process based on boosting ensembles

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ABSTRACT

Form and friction drilling techniques are now promising alternatives in light and medium boilermaking that will very probably supersede conventional drilling techniques, as rapid and economic solutions for producing nutless bolted joints. Nonetheless, given the number of cutting parameters involved, optimization of the process requires calibration of the main input parameters in relation to the desired output values. Among these values, the gap between plates determines the service life of the joint. In this paper, a suitable smart manufacturing strategy for real industrial conditions is proposed, where it is necessary to identify the most accurate machine-learning technique to process experimental datasets of a small size. The strategy is first to generate a small-size dataset under real industrial conditions, then the gap is discretized taking into account the specific industrial needs of this quality indicator for each product. Finally, the different machine learning models are tested and fine-tuned to ascertain the most accurate model at the lowest cost. The strategy is validated with a 48 condition-dataset where only feed-rate and rotation speed are used as inputs and the gap as the output. The results on this dataset showed that the Adaboost ensembles provided the highest accuracy and were more easily optimized than artificial neural networks.

1. Introduction

The boilermaker industry especially in light and medium boilermaking, is leading calls for new techniques that can be used to join metals such as steel and aluminum at very different melting points [1]. Thermal welding is impossible with traditional welding techniques, because the temperature at which steel melts is high enough to boil aluminum alloys. In some cases, a structure needs high-temperature resistance in one area and good corrosion resistance in another, or toughness or wear resistance is required at one point at the same time as high strength at another point. However, the joint of a stiff, high-strength metal such as steel and light alloys containing aluminum can be a good solution; for example, in the manufacture of steel skeletons to which aluminum (of the 5xxx group) skin sheets and cover plates are attached [2]. Other examples, such as aluminum and copper for electrical terminals could also be considered. This branch of joining techniques is referred to as Dissimilar Material Joining (DMJ). These techniques are now in use, because they produce metal flow without melting, forming the basis of several techniques such as friction welding (rotational and linear), friction stir welding (FSW), flow or friction drilling and form taping.

DMJ research has been associated with metallic alloys including carbon and low-alloy steels, stainless steel, nickel, copper, and aluminum alloys. In the 1990s, there were research works involving titanium alloys, ceramics, polymers, and composite materials. More recently, techniques to join metal and plastic in automotive applications have become a key research area. Several factors have to be considered when joining metallic alloys: differences in melting temperature, thermal expansion-contraction mismatch during joining and in service, the effects of fixtures and constraints on joining stresses, formation of brittle inter-metallic compounds during joining that may lead to brittle joints, potential for galvanic coupling and corrosion in service, and heating and cooling rate effects on the microstructure of the joint. All these factors may affect the heat input intensity and its precision control.

Joining processes may be grouped into different categories: brazing and soldering, adhesive bonding, fusion arc-welding processes (shielded metal arc welding, gas tungsten arc welding, gas metal arc

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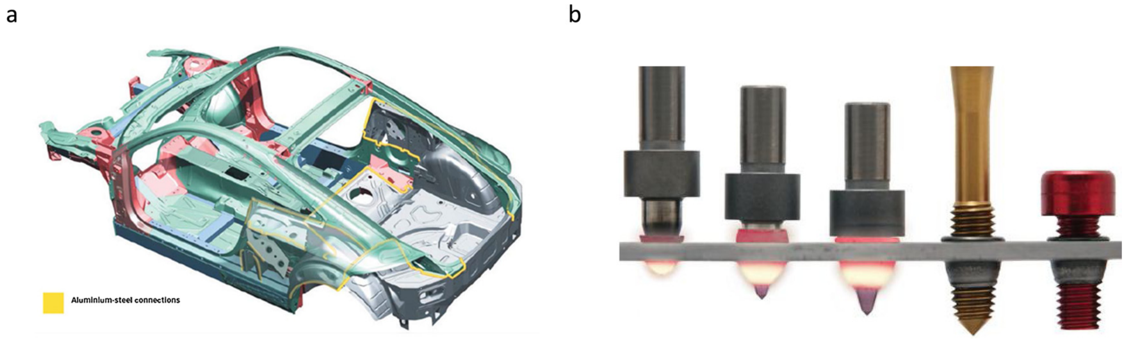

Fig. 1. a. Connection between steel-aluminum (AudiTT©); **b.** Threaded holes in only one sheet of metal (Form drilling©).

welding, and plasma arc welding), solid-state joining processes (friction stir welding, ultrasonic welding, friction and inertia welding, diffusion bonding, explosive bonding, and roll cladding), and mechanical joints including rivets, bolts and fasteners. The last two categories apply to dismantlable structures and are studied in the following section.

Mass reduction of automotive body structures is an issue for automotive builders. For instance, Audi© uses the Flow Drill Screwing FDS® (from Swedish company EJOT) process in addition to Metal Inert Gas (MIG) welding and punch riveting for high strength sheet metal joints (AudiTT©, see Fig. 1a). FSW of aluminum and steel has also been used in the manufacture of some vehicle components by Mazda© and Honda© [3,4]. Despite their promise, these techniques offer several limitations, namely: tool wear and the difficulty of creating a reliable bond between the pair of materials. These techniques lead to other similar alternatives for joining materials. Nishihara et al. [5] and Lazarevic et al. [6] proposed and studied the Friction Stir-Forming (FSF) process. In this case, a modified FSW tool is sharply plunged into the top workpiece creating frictional heat, stirring, and forming the work material into a new shape. The main process parameters were identified and optimized and the joint structure was characterized, by identifying two failure modes, aluminum-sheet peeling and bonding delamination. The same friction-based technology that is used to join dissimilar materials also has a number of industrial applications in the boilermaking industry, domestic appliances, solar industry (solar trackers), etc.

The concern of the scientific community to promote green manufacturing in almost all fields of engineering is gathering pace. In application to drilling operations, minimum quantity lubrication (MQL) techniques are worth mentioning as environmentally friendly machining alternatives [7,8]. In this paper, a lesser known process is proposed and studied that may surpass the limitations of conventional drilling. The friction (form) drilling process is a non-conventional process of generating holes in sheets. It is based on material removal by friction and heat generated by a rotary tool with no cutting edge [9]. The tool has two different sections: a conical surface that opens the aperture and softens the sheet material, and a cylindrical one that determines the final aperture diameter. One drawback is significant burring on exiting the hole.

The process has many advantages over traditional processes. First, there is no need for cooling. In conventional drilling processes, lubricant reduces friction and heat facilitates chip evacuation, unlike the friction-drilling technique, which is therefore defined as a clean process. Moreover, the burr can even be used to thread holes in complex and inaccessible tubular geometries. Most of the workpiece material in contact with the tool becomes part of the burr that is generated (see Fig. 1b) at the bottom of the part and a small portion of the material generates burrs on top. Kerkhofs et al. [10] compared the performance of (Ti, Al)N coated friction-drilling tools with uncoated drills in opening a large number of holes in austenitic stainless AISI 304. Tool wear and workpiece material deposition were examined by scanning electron microscopy and X-rays. Miller et al. [11–13] investigated the thermomechanical behavior of the workpiece and used the 3D finite-element method (FEM) to study work deformation in friction drilling. Bilgin et al. [14] proposed a finite element-based model using deform-3D software. This approach predicted some key parameters such as torque, axial power and process temperature and compared them with experimental values. After drilling the hole, the form tapping process takes place. Threading processes are widespread in many mechanical applications, as screwable joints represent the most extensively used methods in the assembly of mechanical components. In accordance with the manufacturing process, two methods are used to generate an inner thread: either by forming or by cutting. Thread may be produced by cold forming, which involves the deformation of the raw material under cold working conditions, while in the case of cut tapping, the thread is obtained as in many other machining processes by chip removal [15]. Urbikain et al. [16] demonstrated the feasibility of successively applying form drilling and tapping, in order to achieve a good joint of similar strength to conventional drilling, but simultaneously avoiding the use of nuts (and even screws) in some cases. The combination of drilling and tapping can be easily automated (approx. 10,000 threads without supervision), and it is therefore highly recommendable in applications where high productivity rates are required, as in the case of automotive applications [16].

Besides the analytical [11–14] and experimental [16] models for friction drilling presented above, the models of this industrial task have been tested with various Artificial Intelligence (AI) techniques. The necessary information to build an accurate physical model is unavailable in machining processes under industrial conditions, hence the use of data-driven techniques. The reasons are twofold. First, the machining processes usually depend on many inputs of different nature [15] and machines on the factory floor are not equipped with sensors to provide direct measurements of many of these inputs. Second, these machines have to fulfil demanding schedules, due to high productivity rates, and the process engineers have neither the time nor the authorization to perform the experiments that would define the physical models correctly. Nevertheless, data-driven models may function better than physics-based models under industrial conditions, as they are able to maximize the information extraction from real datasets. Following this strategy, El-Bahloul et al. [17] optimized the friction-drilling process on AISI 304 steel using both Taguchi experimental design and fuzzy-logic techniques, considering the resultant axial and radial forces as inputs and the following as outputs: aperture diameter dimensional error, roundness error, and bushing length. Pantawane and Ahuja [18] optimized the friction-drilling process on AISI 1015 steel using Taguchi experimental design once again but, in their case, with regression models that processed data inputs on tool diameter ratios, spindle speeds and the feed rates, and data outputs on maximum thrust force, the maximum torque during the friction-drilling cycle, and the surface roughness of the friction drilled holes. Ku et al. [19] optimized the friction-drilling process on SUS 304 steel, once again by applying Taguchi experimental design and, interestingly, grey relational analysis,