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Tube bending machine modelling for assessing the energy savings of electric drives technology

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ABSTRACT

The aim of the work is to carry out a comprehensive analysis of the energy saving opportunities offered by the introduction of electric drives in the rotary-draw tube bending technology. Although there is a clear industrial trend towards the replacement, especially for low tonnage forming machines, of the traditionally adopted hydraulic drives, there is a lack of scientific research that has studied its implications on energy consumption.

For this purpose, an energy model for tube bending machines was developed. The parameters of the model were identified exploiting experimental power measurements performed on both a hybrid hydraulic-electric and a fully electric machine.

The energy saving analysis was carried out through the updated energy models. For sake of generality, the analysis was extended considering various tube material-diameter combinations and different machine working conditions.

The results showed that relevant energy savings can be obtained and that the improvements are affected by the machine throughput. It was also observed that the minimum achievable energy saving is significantly higher (at least three times) than the energy share for processing the tube.

An efficiency analysis of both types of machines was also reported. The introduction of the electric drives allows increasing the machine efficiency up to 50 percentage points. This achievement slightly decreases with the increment of the rotary-draw bending machine throughput.

1. Introduction

Discrete part manufacturing is an energy demanding industrial sector, that craves for more-efficient machines and production systems. This represents a stimulating challenge for machine tool designers that typically do not consider the energy consumption during the conceptual design and the full development of their machines.

For this purpose, a working group of the International Organization for Standardization (ISO) released a useful technical reference on the methodologies for designing energy-efficient machine tools, ISO 14955 (2014).

ISO 14955 reports that the energy consumed by the machine during its usage phase is typically much higher than the energy spent for the other phases of the machine life (i.e. machine production, transport, set-up and recycling). This is also confirmed by the available scientific literature, Avram and Xirouchakis (2011). The ISO standard also includes a list of suggestions that can be considered for the eco-machine tool design. The standard is mostly focused on machine tools for metal cutting, but it considers also machines for metal forming technology. In the metal forming industry, as well, environmental issues can be addressed by acting either on the manufactured product design, on the process and on the machines, Duflou et al. (2011).

Many studies on energy efficiency in machine tools can be found in the scientific literature. Unfortunately, most of them are focused on metal cutting machines. As reported in Diaz et al. (2010), energy savings can be fulfilled adopting specifically eco-designed subcomponents or implementing strategies oriented to a better machine use. The latter approach can involve both the machining strategy optimization (Yingjie (2014)) and a suitable technological parameters choice, Albertelli et al. (2016).

In metal forming, most of the researches are traditionally focused on process modelling and on the estimation of the required machine load. Very few research works are available in the

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literature, that deal with the eco-design of metal forming machines (i.e. press brakes, forging presses, powder forming presses, blanking machines, tube bending machines, etc.). As one of the very few published works, Santos et al. (2011) proposed a methodology for the Life Cycle Analysis LCA of hydraulic press-brakes. They demonstrated that the energy spent during the machine building phase is comparable to the energy spent during its use. This is mainly due to the discrete loading character of the sheet bending process. Devoldere et al. (2007) also developed a test case around a press brake, they underlined that a major part of the total energy consumption of the machine does not depend on the production rate, and suggested some initial design improvements.

In tube and sheet metal bending (Pulzer, 1998; Stange, 1997), machines are typically equipped with Numerical Controls NC, i.e. they are so-called servo-presses. Three different kinds of drive controls can be found:

- mechanical servo-presses, also called electric machines, Osakada et al. (2011) and Du and Guo (2003)
- hydraulic servo-presses, Zhao et al. (2015)
- hybrid machines, which combine hydraulic and mechanical servo-drives, Altan (1998) and Li and Tso (2008)

High tonnage presses are hydraulically driven, because other types of drives would be economically inefficient. In big hydraulic presses, the energy consumption is strongly affected by the mechanical structure design, as demonstrated in Strano et al. (2013). In forming presses with high tonnage, some energy savings can also be expected with better designed hydraulic systems and improved control. To this aim, Zhao et al. (2015) have developed an energy assessment model of large and medium sized hydraulic presses.

In presses and machines built for lower forming loads (e.g. tube bending machines), the efficient use of energy depends mainly on the type of drive mechanisms and on the control strategies. Servo-presses are generally considered less energy demanding than hydraulic machines, but no scientific literature is available with experimental evidence. However, even for hydraulic tube benders, relevant energy savings (up to 40%) can be achieved if developing specific control strategies, as demonstrated by Lin and Renn (2014). Industrially, there is a clear tendency in low tonnage metal bending applications for replacing the hydraulic units with electric modules. This transformation from hydraulic or hybrid to full-electric is mainly pushed by a common belief that fully electric machines are more precisely controlled. At the same time, the full-electric conversion is thought to reduce, as a positive side effect, the energy consumption. While this general opinion is likely correct, there is a lack of clear, quantitative and rigorous assessments (either numerical or based on experiments) of the actual differences, in terms of energy consumption, between the two solutions.

The goal of this research is to bridge the gap of the scientific community on this specific aspect. For this purpose, two NC rotary-draw bending machines were studied: one hybrid machine, equipped with hydraulic units in addition to some electro-mechanical drives; the other one only controlled by electro-mechanical drives. In order to make the energy assessment as much generalized as possible, a combined experimental-analytical approach was adopted. The experimental session was performed first. Power measurements were carried out on both types of machines during the process of bending a representative tube geometry. All phases of the process cycle were characterized registering the power absorptions of the machine and its main sub-modules. In order generalize the analysis, the two machines were experimentally characterized setting different machine velocities, i.e. different machine throughput. This allowed to describe if and how the throughput affects the power consumption.

An energy model suitable for both tube bending machines was proposed. The model parameters were identified exploiting the experimental measurements. The identified models were used for performing a general energy assessment of the machines. The performed analysis points out the achievable energy savings and their relevance in comparison with the energy required for forming the tube. For sake of generality, a sensitive analysis considering different test cases for the processed tube was also accomplished.

The paper is structured as follows. In Section 2 the methodology for performing the energy assessment and the studied rotary draw tube bending machines are thoroughly described. In Section 3 the tube bending model development is described. In Section 4 the main achieved results in terms of energy savings and machine efficiency (considering also the energy share of different meaningful test cases) are reported. Conclusions and future works are described in section 5.

2. Materials and methods

Two comparable tube-bending machines were critically analyzed from the energy consumption perspective. The energy savings potentials linked to the rotary draw tube bending machine electrification are mainly connected with replacing the hydraulic system (including the pump), that typically consumes energy even when the machine is not performing active phases of the bending process. Due to their high level of programmability, controllability, speed, accuracy and repeatability, electrical drives are a preferred drive technology when high production and quality performances is required. Moreover, these performances were easily assessed in the production environment by checking the quality of the bent tube and measuring the production cycle. On the contrary, since energy consumption can depend on the way the bending machine is used, a comprehensive and exhaustive energy assessment needs a more structured approach.

Before proceeding with a detailed description of the studied machines, the conceived methodology for performing the energy assessment was explained. One of the most important issues is the possibility to generalize the results of the energy analysis. For this purpose, it was decided to separate the energy expenditure of the working phase into two different components or shares: one which is tube dependent and one which is machine dependent. This approach was inherited by Diaz et al., 2009 that dealt with machine tools for metal cutting. The tube dependent share is made of the internal deformation energy of the tube itself (which obviously depends on the tube material and wall thickness). It can be easily estimated by means of empirical models or by means of relatively simple FEM (Finite Element Method) simulations, Kobayashi et al., 1989. The machine dependent components are the energy required for winning the inertial and frictional resistance of the machine itself and for keeping the clamps closed. The machine-dependent shares can hardly be predicted by a simple and reliable model. So far, only a specific research on hydraulic tube bending machines modelling has been found in the scientific literature, Lin and Renn (2014). The model was developed for evaluating innovative control strategies. Only numerical simulations are reported. Much attention was put in modelling the hydraulic cylinder, but the capabilities of predicting the energy absorbed by the whole machine was not experimentally verified. For this reason, in the present research, an empirical-analytical energy model for rotary draw bending machines was developed. This choice was also supported by a detailed literature review. Indeed, it was found that the empirical-analytical modelling methodology assures, at the same time, a high level of accuracy in terms of consumed energy estimation and the possibility of analyzing different scenarios of use for the considered machine, Balogun and Mativenga, 2013. Moreover, in the present