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Experimental investigation of energy saving opportunities in tube bending machines

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Abstract

In the scenario of containing the global warming, devising energy savings strategies in industry has become a proper and urgent matter. Since manufacturing is one of the most energy demanding sectors, research and the linked industries started tackling this issue proposing new eco solutions. In this paper, an experimental investigation of the energy saving opportunities in tube bending machines is performed and critically discussed. The analysis is carried out comparing an electrical tube bender and a hydraulic machine of comparable size. The experimental measured are also used to fit energy models that are used to extend the comparison considering different working conditions of the tube-bending machines. The results show that relevant energy savings can be achieved introducing the electrical drives.

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Keywords: Tube bending machines, Eco-solutions, Energy efficiency;

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1. Introduction

Mechanical manufacturing is a demanding sector for energy consumption in industrial countries. The increasing demand for machinery and production systems to be more energy-efficient is a relatively new challenge for machine designers. An important technical reference which has been used as the framework for the current analysis is the standard ISO 14955, part I, titled “Machine tools -- Environmental evaluation of machine tools -- Part 1: Design methodology for energy-efficient machine tools”. This standard identifies six different phases of the life of a machine tool as: raw material, production, transport, set-up, use, recycling; the standard clearly indicates the “raw material” and the “use” phases as the two major sources of environmental impact and energy consumption. The study presented here focuses only the energy consumed in use. Most studies in the literature are focused on assessment and improvement of energy efficiency of machine tools for material removal (Diaz et al. [3]). Energy savings in machine tools can be achieved by a proper energy-oriented machine tool components design or by a better machine usage, both in terms of machining strategy and process parameter selection, [2]. Not many previous studies are available in the field of metal forming machines, such as press brakes, forging presses, hammers, powder forming presses, stamping and blanking machines and tube bending machines. As an example, a method for a full Life Cycle Analysis is proposed by Santos et al. [1], where an LCA of an all-hydraulic press-brake was conducted. It revealed similar and significant contributions of energy spent while building the machine tool structure (40%) and electricity consumption during use (46%) to the global environmental impact of the equipment. According to the authors, this is due to the discrete loading character of the sheet bending process. Other relevant works in the metal forming area focus on the energy expenditure of the forming process alone and neglect the important role which is played by the machine in its different operating conditions (processing, stand-by, etc.). In the metal forming industry, traditional machines are either hydraulic or mechanic. In both cases, so-called servo-presses and CNC actuated machines are increasingly used for many purposes and especially in the bending industry, both for tubes and sheets, the machine axes are numerically controlled. In large forming presses, an important role in the overall assessment of the energetic impact is played by the design of the mechanical structure [4]. On the contrary, when forming

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forces are relatively small (as in tube bending machines), the importance of the control system increases. In the metal bending industry, there is a clear trend, especially for low tonnage applications, towards replacement of hydraulic CNC machines with so-called "electric" machines, i.e. machine with electro-mechanical rather than hydraulic actuation of movements. There is a common opinion that full electric machines are more controllable and less energy demanding than traditional hydraulic ones. While this opinion is most likely correct, there is a lack of clear, quantitative and rigorous assessments of the actual differences, in terms of energy consumption, between the two solutions. Furthermore, the already mentioned standard ISO 14955 suggests a list of possible improvements that can be investigated in the design of hydraulic machines. Some of the suggested enhancements are already industrial state of the art. As an example, considerable energy saving opportunities (up to 40%) may rise by developing specific control strategies of hydraulic machines, as demonstrated in [5]. The purpose of this paper is to present a compared assessment of energy consumption of two CNC rotary-draw bending machines, one hydraulically controlled and one with electro-mechanical control. The assessment methodology has been carried out according to the Machine Tool Energy assessment standard (ISO 14955, [6]). The same workpiece has been produced with both machines, a round tube with seven consecutive bends in different planes and with different bending radii. Exploiting experimental energy measurements, an energy model has been devised that is used to compare the machines in different working conditions. The presented paper is structured as follows. In Section 2, the machines and the experimental setup is described. In Section 3, a modelling approach for both the bending machines is proposed and used to perform some specific analysis. The achieved results are presented and discussed in section 4. As a conclusion (Section 5) the results will be critically considered in an attempt of generalization.

Nomenclature

P active power [W]
v_1, v_2, v_3 : three phases voltages [V]
i_1, i_2, i_3; three phases currents [A]
f_s: sampling frequency [Hz]
$\overline{\Delta t}$: moving average time interval [s]
E_{cum} cumulated global energy [kWh]
$E_{stand\text{-}by\ cum}$ cumulated stand-by energy [kWh]
$E_{working\ cum}$ cumulated energy linked to tube processing [kWh]
$E_{process}$ energy required for bending the tube[kWh]
$E_{movement}$ energy required to move all the machine axes [kWh]
$E_{control}$ energy required to power the active units [kWh]
ΔT tube processing time [s]
$P_{g\ m}$ average global power for producing one tube [W]
$P_{sb\ m}$ average stand-by power for producing one tube [W]
$P_{w\ m}$ average working power for producing one tube [W]
P_i average "i" power as a function of throughput (1/Δt) [W]
P_{i0}: constant term of Pi [W]
K_i: sensitivity to the machine throughput [W/(tube/s)]
MRR: Material Removal Rate
$T_{working}$: available time for production [h]
$T_{warm\text{-}up}$: duration of the machine heating cycle [h]
$\Delta t_{t\text{-}handling}$: time required for the tube handling (load-unlaod) [s]
E_{total}: total energy used in a shift [kWh]
E_{tubes}: energy used for processing the tubes[kWh] in a shift
$E_{warm\text{-}up}$: energy used to heat the machine [kWh] at the beginning of the shift
$E_{t\text{-}handling}$: energy used during the shift regime to load/unload the tube [kWh]
$E_{1\text{-}tube}$: specific energy required for processing one tube [kWh/tube]
$\Delta E_{1\text{-}tube}$: specific energy saved changing technology (Hydraulic into Electric) [kWh/tube]

2. Methods and experiments

2.1. Tube bending machines under study

Two tube-bending machines were analyzed and critically compared, focusing on their energy consumption. The first machine is a traditional hydraulic CNC rotary draw tube bending machine that is equipped with some servo electric axes (the booster and the boost clamp). All the other units are hydraulic. Fig. 1 shows the analyzed electro-hydraulic machine. The main units and the axes are also shown in Fig.1. The working pressure set for the test was equal to 120 bar. The second machine is a fully electric CNC rotary draw tube bending machine. It is equipped with servo motors that are piloted by drives and a CNC controller. In this case all the machine units are driven by electrical axes. Focusing on the bending performance, the analyzed machines are comparable. Indeed, for both the machines, the maximum bending capacity consists of being able to bend a 80 mm diameter tube with a maximum thickness equal to 2 mm.

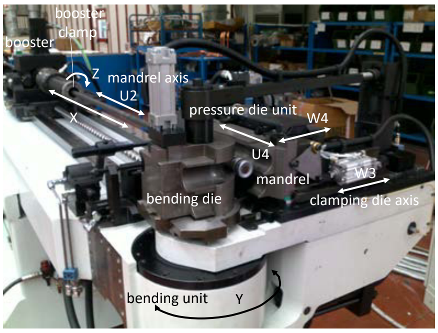

Fig. 1 electric-hydraulic tube-bending machine with the main units and axes

2.2. Energy assessment methodology

As suggested by the standard ISO 14955 [6], the environmental assessment of machines (machine tools and presses) can be brought back to the analysis of the electrical energy absorbed during its entire life. In this case, the energy assessment was performed considering different machine operating states: "Machine off", "machine warm-up", "ready for operations" and "working". Moreover, as suggested by the

ISO 14955, a shift regime that considers a reasonable combination of the identified states: 16hours machine off, 0.5 hour machine in warm-up state and 7.5 hours for processing. In this specific case, the defined shift regime corresponds to a working day. The “processing” state is composed of a working phase in which a bent tube is produced and a phase in which the processed tube is discharged and a new tube is loaded for being bent. During the handling of the tube, the machine is in the “ready for operation” state. For the working phase of the shift regime, the tube reported in Fig. 2 was assumed a meaningful benchmark for the analysis that will be further performed. As can be easily observed, the tube has 7 bends along its length, in different planes, with different bending angles and with different radii. It requires all the most typical movements generally required for operating these rotary draw bending machines and all the driving units are involved in this cycle. For each bend, the following steps are required: the booster (X axis) feeds the tube to the die, the tube is clamped by the clamping die unit and the bending unit performs the bend with the support of the pressure die unit that moves both along W4 and U4. The bending unit is retracted as well as the pressure die unit. The tube is then rotated (Z) and axially fed along X in order to be prepare for the subsequent bend.

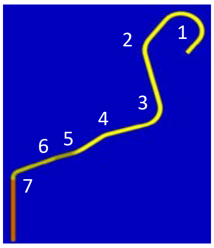

Fig. 2: reference tube used for the experimental assessment

2.2.1. Measurement of the machine electrical consumption

For each tube-bending machine, several absorbed power measurements were performed. The power measurements were done in the above reported states. Moreover, in order to characterize the power of the main energy demanding units, specific measurements were performed insulating the contribution of some subcomponents. For instance, this was achieved progressively switching on the main machine modules or performing differential power measurements.

Active power P(t) computation (Eq.1) is performed after having measured at high sampling rate (sampling frequency, fs=30kHz) the three-phases voltages (v_1, v_2, v_3) and the corresponding currents (i_1, i_2, i_3). The phase currents were measured using three LEM units.

$$P(t) = v_1(t) \cdot i_1(t) + v_2(t) \cdot i_2(t) + v_3(t) \cdot i_3(t) \qquad (1)$$

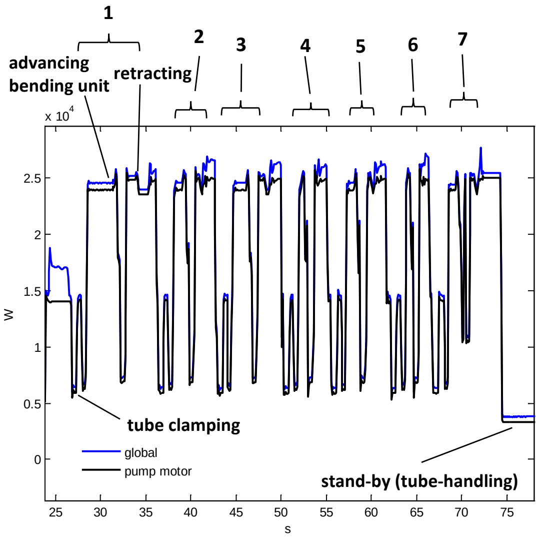

Fig. 3: powers revealed on the electric/hydraulic machine – tube processing

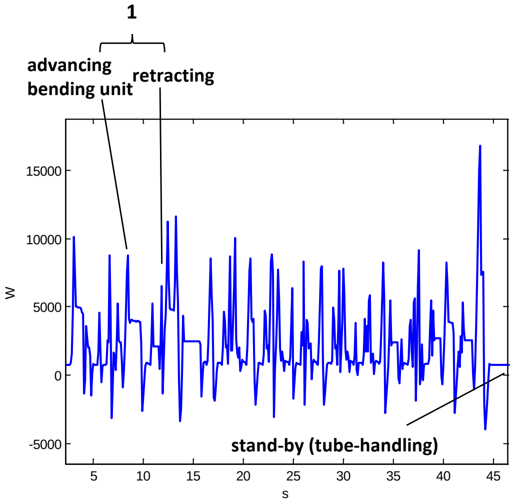

Fig. 4: power measurements- fully electric machine – tube processing

A moving average computation was also performed in order to remove the high frequency noise components included in the measurements. A time interval $\Delta t = 0.1s$ was considered for the moving average processing. As examples, in Fig. 3 and Fig. 4, the global power measurements performed during the tube processing are reported. Fig. 3 refers to the electric-hydraulic machine while Fig. 4 refers to the fully electric-machine. For instance, focusing first on the power measurements reported in Fig. 3, different phases (7 bends) of the working cycle are clearly visible. Moreover, for each single bend the advancing and the retracting of the bending unit can be observed. As can be noted in Fig. 3, both the global power and the power absorbed by the main pump motor were acquired during the tube bending cycle. Just before performing detailed analysis, it must be noted that the motor pump power represents the most relevant power contribution to the global power.

The already described phases are also recognizable in the power measurements performed on the fully electric machine, Fig. 4 even if in this case a different power profile is appreciable for the same operation.

2.2.2. Ready for operations analysis

As anticipated, the first energy analysis was performed focusing on the “ready for operations” state.

In the following tables the stand-by power linked to the ready for operation mode was decomposed into the main contributions and functions. It is clearly visible that the hydraulic machine shows an increasingly higher stand-by power. This is only the first hint that makes the hydraulic machine be considered very energy demanding.

Tab. 1: Electric-Hydraulic Bending Machine (stand-by power)

component	Value [kW]	function
PLC+24V units	0.26	base power supply+diagnostic
Drives	0.077	control
Pump Motor	3.89	main unit
SUM	4.22	

Tab. 2: fully electric bending Machine (stand-by power)

component	Value [kW]	function
PLC+24V units+fan	0.363	base power supply+diagnostic
Drives	0.222	control
Drives (IGBT)	0.215	drives power
SUM	0.8	

3. Energy modelling – shift regime

In order to generalize the energy assessment it is necessary to extend the analysis to the shift regime since also the tube processing is involved. In order to arrange a more robust energy comparison (for instance considering different working conditions) of the machines, a suitable energy model must be identified. For many kinds of machine the Gutowski [7] model can be appropriate:

$$P_i(MRR) = P_{i0} + \mathrm{K}_i \cdot MRR \qquad (2)$$

The model considers that the absorbed power depends linearly on the process rate. For instance, in machine tools, if the MRR is increased the absorbed power increases too. This can be connected to the material removal but also to other aspects (i.e. friction of the axes that increases with the feed velocity). In order to adapt the model to a different type of machine (bending machines), in this paper we assume as process rate the tube-bending machine throughput (1/Δt), where Δt is the time for processing the single tube.

$$P_i(1/\Delta T) = P_{i0} + \mathrm{K}_i \cdot (1/\Delta T) \qquad (3)$$

In order to verify the suitability of the model and for identifying the unknown coefficients, experimental tests (tube processing) were performing at different process rates with both the machines. Since the selected model deals with the absorbed power, the average powers were computed from the experimental tests. In particular the average global power $\mathrm{P}_{\mathrm{g\,m}}$, the average stand-by power $\mathrm{P}_{\mathrm{sb\;m}}$ and the average working power $\mathrm{P}_{\mathrm{w\,m}}$ can be determined as follows:

$$\begin{aligned}
&E_{cum} = \int_{t_1}^{t_2} P_{global}(t)dt;\\
&E_{\text{stand-by cum}} = \int_{t_1}^{t_2} P_{\text{stand-by}}(t)dt; \qquad (4)\\
&E_{\text{working cum}} = E_{\text{process}} + E_{\text{movement}} + E_{\text{control}} =\\
&= \int_{t_1}^{t_2} \left(P_{global}(t) - P_{\text{stand-by}}(t)\right)dt;
\end{aligned}$$

Where ΔT is the duration of the tube processing

$$\Delta T = t_2 - t_1 \qquad (5)$$

Thus, the following average powers can be computed

$$P_{g\,m} = E_{cum} / \Delta T \,;\; \mathrm{P}_{\mathrm{sb\,m}} = E_{\text{stand-by cum}} / \Delta T \,; \qquad (6)$$
$$\mathrm{P}_{\mathrm{w\,m}} = E_{\text{working cum}} / \Delta T$$

An example of the cumulated energy computation is graphically shown in Fig. 5, for the hydraulic machine.

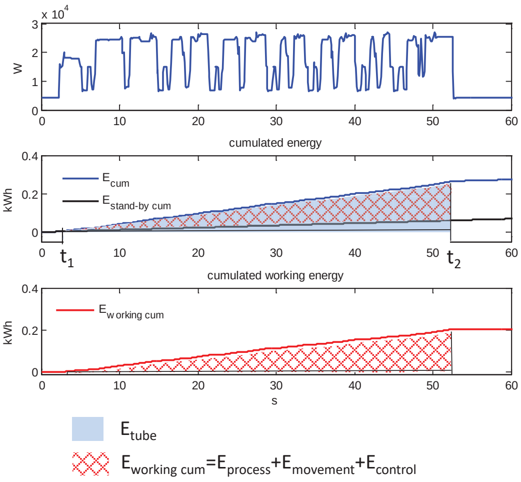

Fig. 5: Cumulated energy (stand-by and process energy)

It is thus possible to fit the experimental data with equation (3) where “i” can be “global”, “sb” or “w”. In the following subsections, the results of the model parameter identification will be reported.

3.1. Hydraulic Bending Machine – power modelling

After having performed the model parameters identification using a LSR (Least Square Regression) approach, in Fig. 6 both the experimental data and the linear models are reported. The identified model parameters are reported in Tab. 4.

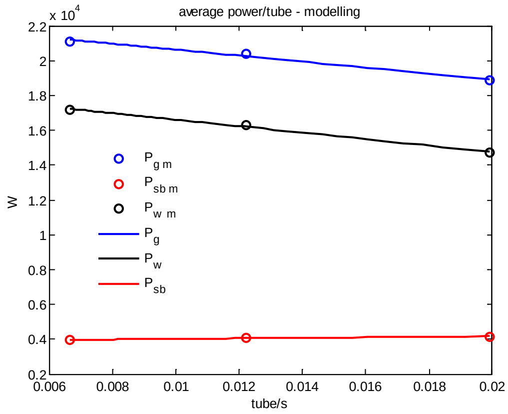

Fig. 6: effect on tube processing time on average powers (hydraulic) – identified models

Tab. 3: model parameters identification – hydraulic machine

Parameter [unit]	value
Pg0 [W]	22330
Psb0 [W]	3863.3
Pw0 [W]	18467
Kg [W/(tube/s)]	-170472
Ksb [W/(tube/s)]	15504
Kw [W/(tube/s)]	-185976

The model exhibits quite high (close to 1) coefficients of determination ($R_g^2 = 0.988;\ R_{sb}^2 = 0.994; R_{sb}^2 = 0.94$). It can be observed a negative slope both for the working average power and for the global average power (it means that increasing the throughput decreases the average power used for each single tube). It is not common for machine tools, [7]. Moreover, the stand-by average power shows a positive slope. It means that increasing the bending feed rate, a moderate increment of the stand-by power can be observed. This could be linked to the pump motor: increasing the feed the effect of oil viscosity could be higher.

3.2. Fully Electric Bending Machine – power modelling

The same approach was also used for the fully electric machine. The identified parameters are reported in Tab. 4.

It can be noted that the k_g is positive, it means that average global power increases with the increment of the process rate (throughput), that is the typically expected behavior.

Tab. 4: model parameters identification – fully electric

Parameter [unit]	value
Pg0 [W]	341.56
Psb0 [W]	793.37
Pw0 [W]	-451.81
Kg [W/(tube/s)]	87245
Ksb [W/(tube/s)]	-70.353
Kw [W/(tube/s)]	87315

4. Results and discussion

After having determined the parameters of the proposed modelling approach, it is possible to perform an energy assessment for both the machines considering the defined shift regime. The energy consumed for processing a single tube ($E_{1\text{-tube}}$) will be used as a key performance indicator. In order to compute that indicator is necessary to calculate the global energy absorbed in the shift and the number of processed tubes N. For this purpose, the following equations can be used:

$$T_{working} = 7.5h;\ \ T_{warm-up} = 0.5h;\ \ \Delta t_{\text{t-handling}} = 20s \tag{7}$$

$$T_{working} = T_{working\ \text{active}} + T_{handling} = \Delta T \cdot N + \Delta t_{t-handling} \cdot N \tag{8}$$

Energy computation referring to the analyzed shift:

$$\begin{aligned} &E_{total}(1/\Delta T) = E_{tubes}(1/\Delta T) + E_{t-handling}(1/\Delta T) + E_{warm-up} = \\ &= N \cdot \Delta T \cdot P_g(1/\Delta T) + \\ &+ T_{handling} \cdot P_{sb}(1/\Delta T) + P_{warm-up} \cdot T_{warm-up} \end{aligned} \tag{9}$$

The specific energy for processing a single tube can be computed using eq. 10:

$$E_{1-tube}(1/\Delta T) = E_{total}(1/\Delta T)/N \tag{10}$$

In the following pictures both the energy used for processing a single tube $E_{1\text{-tube}}$ and the global energy E_{total} (also splitted considering different contributions) as a function of the bending machines throughput were reported for the analyzed machines. It can be observed that in both the cases the $E_{1\text{-tube}}$ is decreasing with the throughput increment.

If we focus on E_{total} we can note a different behavior. If the E_{total} is increasing with the throughput for the electric machine this is not true for the hydraulic machine.

This explains how hydraulics cannot be efficient due to the need of powering the unit with pressurized oil even if the machine is not performing an active part of the cycle. In Fig. 9, the savings that the electric technology would provide are also reported in terms of energy for processing the single tube as a function of the throughput that means as a function of the working condition of the machine.

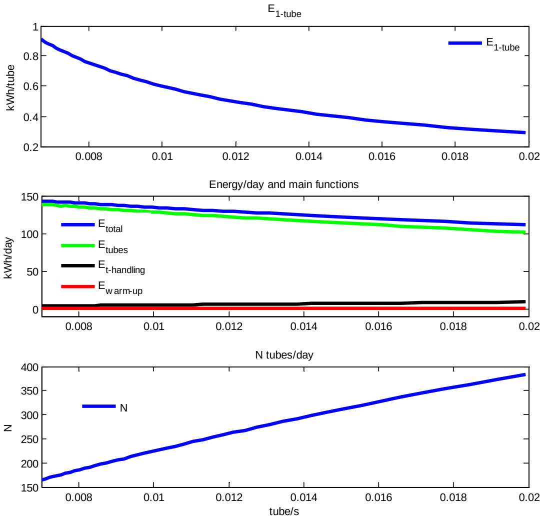

Fig. 7: shift regime analysis – working day production – Electric-hydraulic

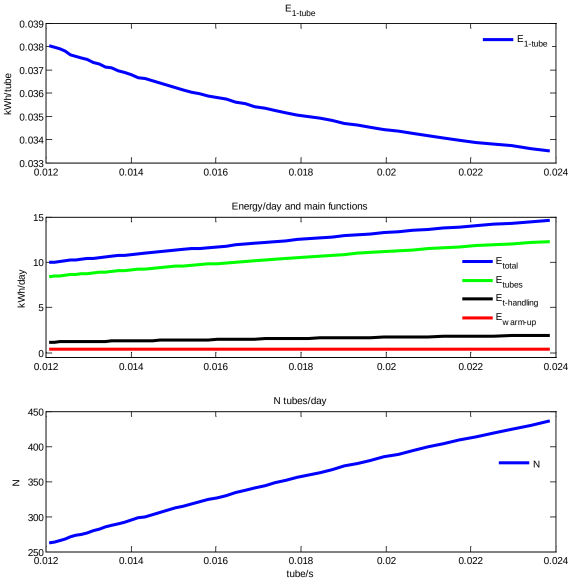

Fig. 8: shift regime analysis – working day production – Fully Electric

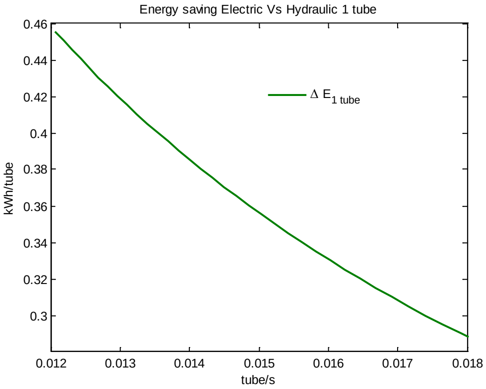

Fig. 9:energy/tube (hydraulic vs electric) as a function of the bending machine throughput.

5. Conclusions

In this paper a methodology for performing an energy assessment of two different tube-bending machines is proposed. The methodology is based on the experimental approach suggested by the ISO 14955 but also propose a modelling strategy that allows extending the energy assessment comparison for the whole working range of the machines. The analysis shows that full electric bending machine allows saving a relevant quantity of energy. This advantage decreases as the production rate increases.

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