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A methodology to assess energy efficiency of conventional lathes

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Abstract Conventional machine tools are still widely used for a large group of small machining companies, mainly in countries with emerging economies. There is a wide variety of high-efficiency electric motors for machine tools in machining; however, most conventional machine tools are driven by three-phase squirrel-cage induction motors (SCIM). This type of machines in small companies deserves a systematic study on energy efficiency. Therefore, the main purpose of this work is to propose a methodology to assess the energy efficiency of conventional lathes with three-phase squirrel-cage induction motors. A case study was conducted with the proposed methodology that demonstrated that the energy efficiency can be depicted by constructing characteristic curves for each machine tool. The control of depth of cut (a_p) is a sufficient condition for the construction of the characteristic curves of a conventional lathe. As a result, it was concluded that at the shop floor environment, the final user could install a digital wattmeter to read the electric power and analyze, from the characteristic curves, whether the machining operation is running on an efficient mode. The machine tool manufacturer can also incorporate a wattmeter into conventional lathes with squirrel-cage induction motors to measure and report the efficiency status during the machining operation.

Keywords Energy efficiency · Energy consumption · Machining · Conventional lathes

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Introduction

Energy consumption and energy efficiency are interdependent issues which have received a lot of attention in the machining field in recent decades. Nowadays, energy efficiency is a mandatory concern in the shop floor (Fysikopoulos et al., 2013; Hae-Sung et al., 2015; Yingjie, 2014; Zhou et al., 2016).

The study of energy consumption in machining focuses on the energy flow understanding along the entire process chain in a production system. Although a systemic view should be a necessary condition to assess energy efficiency (Duflou et al., 2012), the current literature approach is based on three layers: machine tool design, cutting process, and scheduling (Yufeng et al., 2014).

At the machine tool design layer, the main concern is loss reduction. The design of lightweight structures (Bustillo et al., 2014; Kroll et al., 2011), optimization of hydraulic systems (Ramesh et al., 2018; Vukovic & Murrenhoff, 2015), and the use of more efficient spindles (Abele et al., 2011; JingXiang et al., 2017) and high-efficiency motors (Almeida et al., 2014) are some examples of the current approaches to more efficient machine tools generation.

At the cutting process layer, the main concern is force reduction. The concept of specific cutting energy (SCE) is fundamental to set conditions in order to reduce the cutting force without reducing the material removal rate (MRR). The relationship between SCE and energy efficiency has been studied by several researchers (Gutowski et al., 2006; Li & Kara, 2011; Sarwar et al., 2009; Warsi et al., 2018). For example, higher feed values can reduce energy consumption on milling and the use of cutting fluid can reduce energy consumption on turning process of medium carbon steel (Balogun et al., 2019). On the other hand, tool wear could significantly increase the SCE value. An alternative to reduce the cutting force for low machinability materials is the workpiece heating on the cutting area (b; Shang et al., 2019a).

At the scheduling layer, the main concern is the idle time reduction. Idle time happens in the following situations: at the start-up/shut-down, at the set-up; during the load/unload operations and when the machine is waiting for a preceding bottleneck operation. In order to overcome those problems, energy consumption has been incorporated into the traditional scheduling methods (Liu et al., 2013; Zeng et al., 2009; Zhang et al., 2016).

The energy consumed by a conventional lathe performing a turning process consists of not only the energy required by the tool tip for material removal but also the energy used for auxiliary functions (Li & Kara, 2011). The power demand can be assigned to operation machining states, as can be seen in Fig. 1 (Schudeleit et al., 2016). The standby state requires electrical energy for the machine tool resource and its auxiliary functions at zero load. The ready state requires energy for all transitional movements just before the cut. The processing state requires energy for material removing operation.

Although the whole energy consumption varies significantly with the changes of cutting parameters, the main share of energy consumption for tool

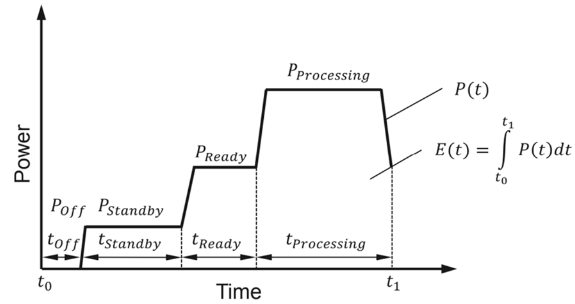

Fig. 1 Schematic power profile by machine state (Schudeleit et al., 2016)

machining processes remains attributed to electrical energy consumption (Newman et al., 2012). An average three-quarters of the total energy is consumed by the machine on the ready and processing states (Balogun et al., 2019).

According to Almeida et al. (2013), about 35–40% of the generated electrical energy worldwide is consumed by electrical motors in industrial applications. Furthermore, today, high-efficiency motors as permanent-magnet synchronous motors (PMSM) and synchronous reluctance motors (SynRM) can lead to significant reductions in energy consumption. But, in spite of the wide sort of electric motors available in the market, three-phase squirrel-cage induction motors (SCIM) represent, by far, the vast majority of the market of electric motors.

The concept of energy efficiency has been proposed to guide the machine tool selection and set up the cutting conditions. Although there is a good understanding of energy consumption, the definition of energy efficiency of machining is neither straightforward nor objective (Schudeleit et al., 2016; Zein, 2012).

Energy efficiency (η) is the ratio between the machining energy (U_M) and the input energy (U_E), as shown in Eq. 1.

$$\eta = \frac{U_M}{U_E} \tag{1}$$

Machine tools consume a significant amount of input energy (U_E) for machining tasks that may be classified into three categories: constant, variable, and cutting power (b; Li et al., 2014a). The measuring of the input energy (U_E) should be carried out along the entire device chain that supports the cutting processes (Gontarz et al., 2015; Hacksteiner et al., 2017). In this case, conventional power meters can be used to measure the active power (P_E), and the input energy can be obtained from the integration of P_E over time.

On the other hand, the machining energy (U_M) can be assessed by measuring the cutting velocity (V_c) and the cutting force (F_C) (Al-Sulaiman et al., 2004; Zhong et al., 2016). The cutting power (P_C) is determined by the product of V_c and F_C. Consequently, the integration of P_C over time results in the machining energy.

Most of the research on energy efficiency is based on computer numerical control (CNC) machines (Dambhare et al., 2015). There is still a lack of comprehensive analyses of energy efficiency on conventional machines with squirrel-cage induction motors. Therefore, a simple and universally acceptable method to compare energy efficiency of similar machine tools has not been proposed yet.

Despite the flexibility provided by CNC machines and their worldwide dissemination, the conventional machines are still in use (Gao & Wang, 2017). Their use is more significant in small manufacturing companies (SMC), particularly in countries of emerging economies (Chen, 2014; Kumar, 2003).

For example, the number of purchased conventional lathes in Brazil (Brazil, 2019) has been greater than CNC lathes from 2007 to 2018, except in the 2016 as can be seen in Fig. 2.

Considering that scenario, the main objective of this work is to propose a methodology to assess the energy efficiency of conventional lathes with three-phase squirrel-cage induction motors. This methodology is based on the construction of the characteristic curves for conventional lathes.

Methodology

A conventional lathe can be considered a very simple machine tool. Generally, it is composed of just two electrical squirrel-cage induction motors. The main electric motor named spindle motor must be able to perform cutting velocity and feed rate in machining movements. The secondary electric motor named coolant pump motor must be able to flood coolant at the tool edge during machining.

The energy flow that occurs during material removal can be considered as shown in Fig. 3. Just a portion of the input electrical energy is converted to machining energy. A very significant amount is converted into heat, noise, and other power losses that occur in the electric motor itself, belts, gearing, slides, and bearing.

Coolant pump motor pumps the cutting fluid with a constant flow rate. Therefore, its energy requirements remain constant during the operation time. On the other hand, the spindle motor converts the input electrical energy into useful work according to the

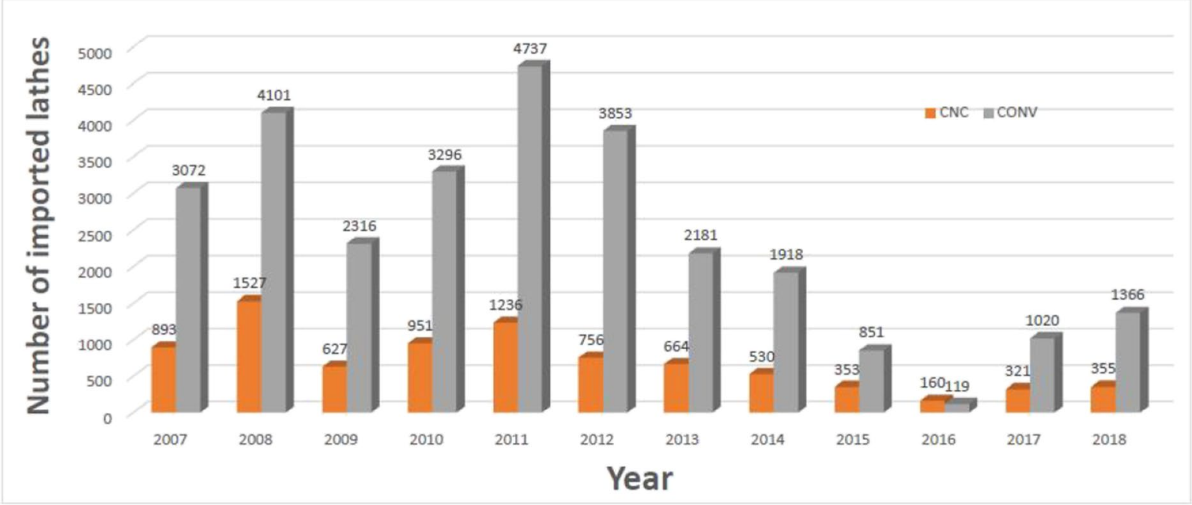

Fig. 2 Foreign trade lathe statistics (Brazil, 2019)

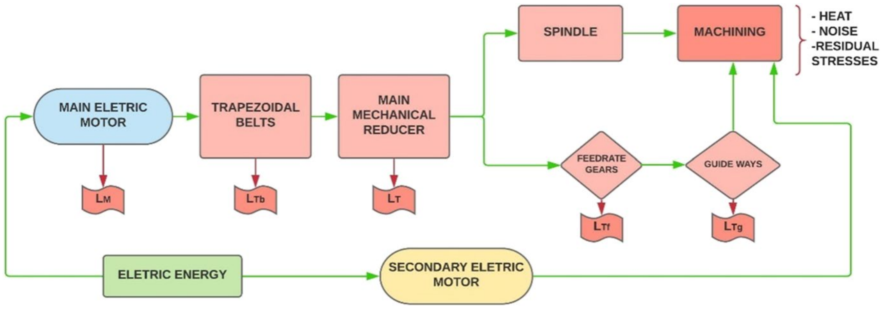

Fig. 3 Energy flow in a conventional machine

selected cutting parameters, workpiece material, and tool conditions. In other words, this energy does not remain constant, but changes as the cutting conditions change as well.

The power loss (L_M)—Eq. 2—occurring in the electric motor can be separated into the loss due the Joule effect at stator and rotor (L_{Mj}), the iron loss (L_{Mi}), the mechanical loss (L_{Mm}) occurring in the bearings and fan, and, finally, the stray loss (L_{Ms}). The first loss (L_{Mj}) has a quadratic current dependency and, consequently, it will increase as the cutting power increases (Auinger, 2001).

$$L_M = L_{Mj} + L_{Mi} + L_{Mm} + L_{Ms} \quad (2)$$

Power losses in electrical motors are not easy to be determined at service since it requires special methods. Generally, the motor manufacturer provides efficiency curves or data to build them. However, these characteristic curves give the motor efficiency as a function of the motor relative load. This relative load remains unknown to the user during the machining process.

In a typical horizontal lathe, the spindle motor is mounted close to the ground floor, which demands a pulley-belt drive to transmit power to the main spindle. The energy loss due the transmission drives occurring in this pulley-belt drive (L_{Tb}) is caused by frictional sliding, belt hysteresis, and belt engagement/disengagement (Bertini et al., 2014). The whole loss depends on the belt type, on the belt wear condition, and on belt-pulley alignment (Balta et al., 2015). In general, this loss is estimated at around 2 to 5% of the whole transmitted energy (Stockman et al., 2015).

In this kind of machine, there are no variable speed drivers. Two or three gearboxes are used in the lathe design. The main gearbox—also named headstock—contains all the necessary gears to set the spindle speed in a discrete way. The power losses (L_{Th}) at the headstock occur mainly due to two causes. The first one is related to friction among gear teeth, bearing, and seals. The other one is credited to the oil shaking caused by the movement of the gears, called churning loss (L_{Tc}).

Power loss in the headstock is the most significant portion of energy dissipation that occurs in a conventional lathe transmission.

Other gearboxes are built to control the feed rate and thread pitch selection. In that case, the energy loss (L_{Tf}) is also caused by friction. Generally, the loads at these gearboxes are very low, when compared to the headstock. Consequently, the power consumption is also low. Energy loss also takes place in the bearings and in the machine guides (L_{Tg}).

Total loss due the transmission drives (L_T)—Eq. 3—is a summation of the preceding losses and will increase as the load becomes greater, similarly to what occur in the electric motor. However, in this case, the loss/load relationship tends to be linear instead of being quadratic, but its quantification is not provided by the machine tool manufacturer (Magalhaes et al., 2010).

$$L_T = L_{Tb} + L_{Th} + L_{Tc} + L_{Tf} + L_{Tg} \quad (3)$$

Machine tool efficiency assessment is a hard task. The global loss (L_G), which is the summation of L_M and L_T as described by Eq. 4, is not informed by the machine tool supplier, and both L_M and L_T change during the operation.

$$L_G = L_M + L_T \quad (4)$$

There are two main methods to assess machine tool efficiency according to the current literature (b, b; Li et al., 2014a; Shang et al., 2019a).

The first one, as defined by Eq. 1, is the ratio between the energy necessary to cut the workpiece (U_M) and the input electrical energy (U_E). On the other hand, efficiency can be also assessed by measuring power instantly instead of energy. Therefore, Eq. 1 can be rewritten as shown in Eq. 5, where P_E is the electric active power measured before the motor, and P_M is the machining power, which is the sum of the cutting power (P_C) and the feeding power (P_F).

$$\eta_1 = \frac{P_M}{P_E} \tag{5}$$

However, in a regular machining process, the feed rate (*f*) is very low when compared to the cutting velocity (V_c). Accordingly, Eq. 5 can be arranged as defined by Eq. 6, where F_C is the cutting force.

$$\eta_1 = \frac{P_C}{P_E} = \frac{F_c V_c}{P_E} \tag{6}$$

The problem with Eq. 6 is the technical difficulty in measuring the cutting force and the high relative cost of instrumentation (b; Shang et al., 2019a). This is the direct mode.

A second way of estimating efficiency by considering the global loss (L_G) is the measuring of the idle loss power (L_{Gz}), i.e., the global power before the cutting operation (Li & Kara, 2011), as summarized in Eq. 7. By this method, both L_{Gz} and P_E can be precisely and easily measured using a simple wattmeter. This is the indirect mode.

$$\eta_2 = \frac{P_E - L_{Gz}}{P_E} \tag{7}$$

However, L_{Gz} is a poor estimation of L_G. During the cutting, the losses increase in both the electric motor and transmission as the load increases, and this waste of additional energy cannot be separated from the instantaneous measurement of active power. Consequently, Eq. 7 is not as accurate as Eq. 6.

An alternative to overcome the cost and the difficulty to measure the cutting force in the shop floor and the inaccuracy of adopting L_{Gz} as an estimation of L_G is the development of the characteristic curves for all available gear combinations in the headstock for every particular model of conventional lathe. Those characteristic curves should be built by the machine tool manufacturer and made available to the final user at the shop floor. Figure 4 contains a flow chart of the proposed methodology.

Data acquisition demands an investment in the following resources: a precise digital wattmeter, a piezoelectric dynamometer, a digital photo tachometer, workpiece materials, and cutting tools for straight turning operations.

The relationship between depth of cut (a_p) and cutting force (F_c) is set in order to avoid the motor overloading beyond its service factor, which is assumed here to be 15% of the nominal power (P_N).

The depth of cut (a_p) is proposed here as a sufficient and independent parameter to build the characteristic curves. Depth of cut is easy to set and control. In addition, according to the classical literature in the machining field, there is a linear relationship between depth of cut (a_p) and cutting force (F_c) (Shaw, 2005) (Wright & Trent, 2000).

For every selected spindle speed, the lathe should run with no load before the test until the measured active power converges to a steady state. This warm-up stage is necessary to allow the reduction of oil viscosity in the headstock. The efficiency curves can be plotted on the lathe handbook or approximated by cubic splines and presented as a set of coefficients to allow for further interpolations.

In this way, energy efficiency could be depicted in the characteristic curves as a function of the active power measured at the electrical panel of the machine tool for all speeds of the headstock. This is the main objective of this work, to propose a methodology to assess energy efficiency of conventional machines with squirrel-cage induction motors.

Case study: materials and instrumentation

The proposed methodology was carried out on a conventional lathe equipped with two three-phase squirrel-cage induction motors. The main motor (60 Hz–220 V–4 kW) powers the spindle and the carriage assembly. It is connected at 220 V delta winding for asynchronous speed of 1750 rpm. It is coupled to the headstock by means of a belt-pulley drive (3 V-belts). The secondary electric motor (60 Hz–220 V–92 W) is employed to power

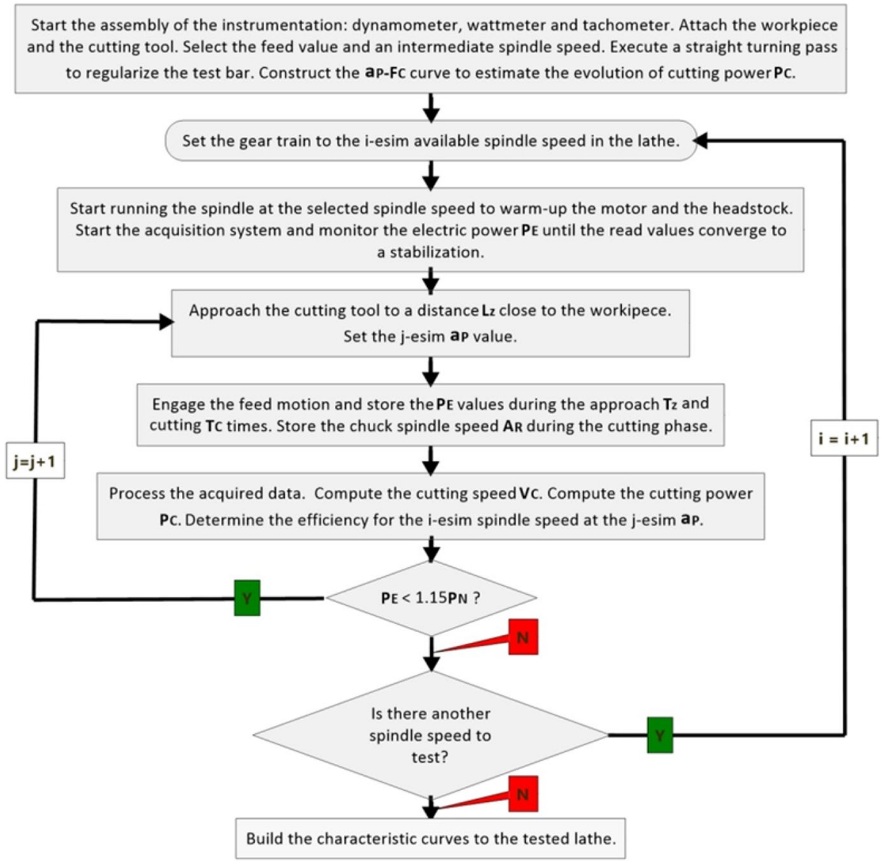

Fig. 4 Methodology to assess energy efficiency of a conventional machine

the coolant system, but was turned off throughout experimentation. Figure 5 contains a schematization of the experimental procedure.

The headstock assembly is composed of 27 spur gears, 8 axels, 18 bearings, 10 seals, and lubricating oil. The gears are arranged in three trains (R1, R2, and R3) as schematized in Fig. 5. The combination of R1 and R2 provides 12 different speeds distributed in low, medium, and high ranges. The R3 gear train provides two speed ranges (low and high) to drive a Norton type gearbox.

Only a set of five spindle speeds, considered the most representative of the operational scope for this specific lathe, was selected to test the proposed methodology. These nominal speeds were 315, 515, 612, 900, and 1239 rpm.

Two desktop computers were assigned to data acquisition via serial port (RS232). The choice of two units is due the independent development of two dedicated software for processing force and power data.

The selected cutting tool was a coated carbide insert (Iscar, WNMG 060,404 – TF 8250) mounted on a MWLNR 2020 K06 tool holder. Machining conditions and workpiece materials can be found in Table 1.

All tests were straight turnings in dry cutting conditions with a constant feed rate of 0.25 mm/rev. The cutting forces were measured using a three-component piezoelectric dynamometer (Kistler, 9129A). Only the cutting force (F_C) was recorded from the data readings. The spindle speed was evaluated by using a photo tachometer (Minipa, MDT-2238b). The active power (P_E) was measured at the main electric motor with a multifunction meter (Kron, Multi K-120). The acquired data are transmitted to the computer through a serial (RS485) network based on Modbus® protocol.

Besides the measurements of cutting velocity, force, and power, which compose the necessary data to run the proposed methodology, the lubricating oil temperature was estimated using an infrared thermometer

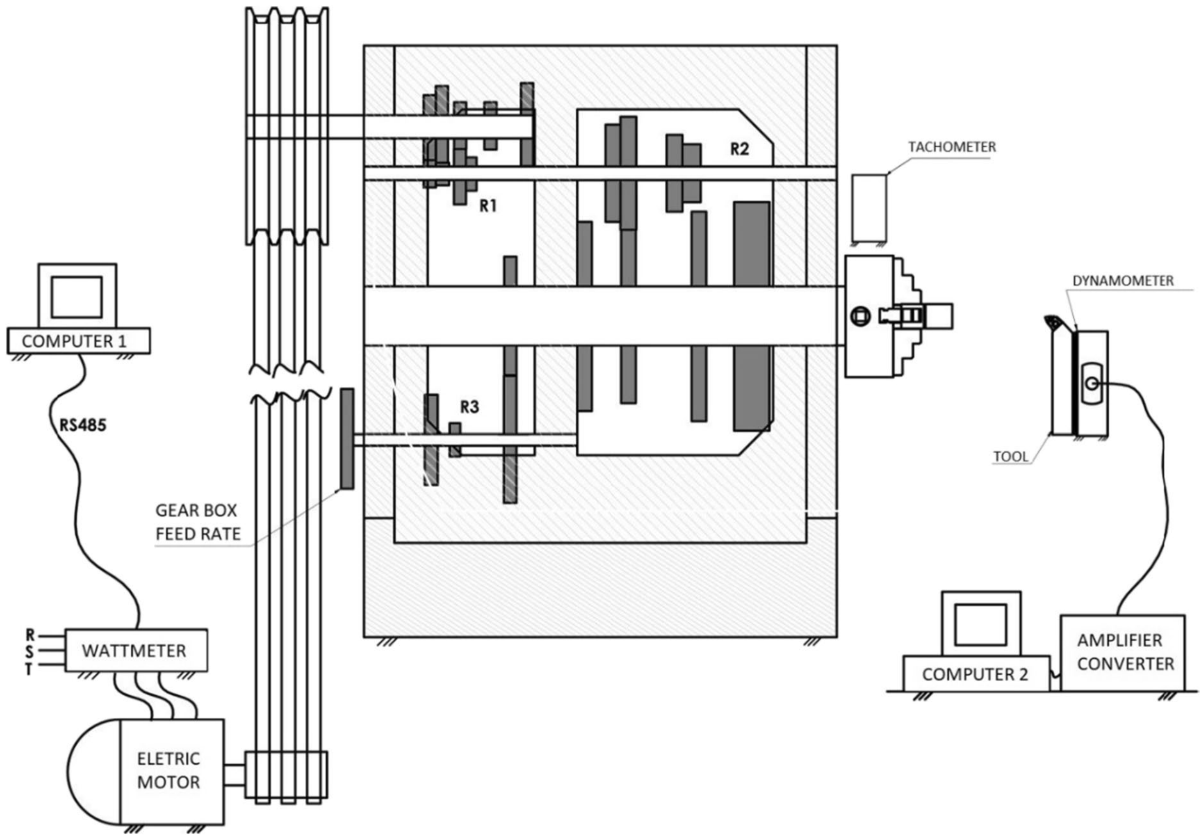

Fig. 5 Schematization of the experimental procedure

Table 1 Machining conditions

Nominal speed, $\boldsymbol{N}$ (rpm)	Initial diameter, $\boldsymbol{d}_{\mathrm{i}}$ (mm)	Cutting depth, $\boldsymbol{a}_{\mathrm{p}}$ (mm), min/max values	Material
375	177	0.125/1.75	Forged steel bar–AISI 1045
515	100	0.125/1.5	Hot-rolled mechanical tube DIN-ST52
612	88	0.125/1.75	
900	87	0.125/1.25	
1239	60	0.125/1.0	Hot-rolled steel bar–AISI 1045

(Raytek, ST20) close to the headstock cap in two different nominal speeds (515 and 900 rpm). The measurement of temperature was intended to verify the influence of oil temperature on the stabilization of power readings.

Results and discussion

There are three charts related to time, active power, and temperature stabilization in Fig. 6. During the first 60 min, the temperature increases sharply

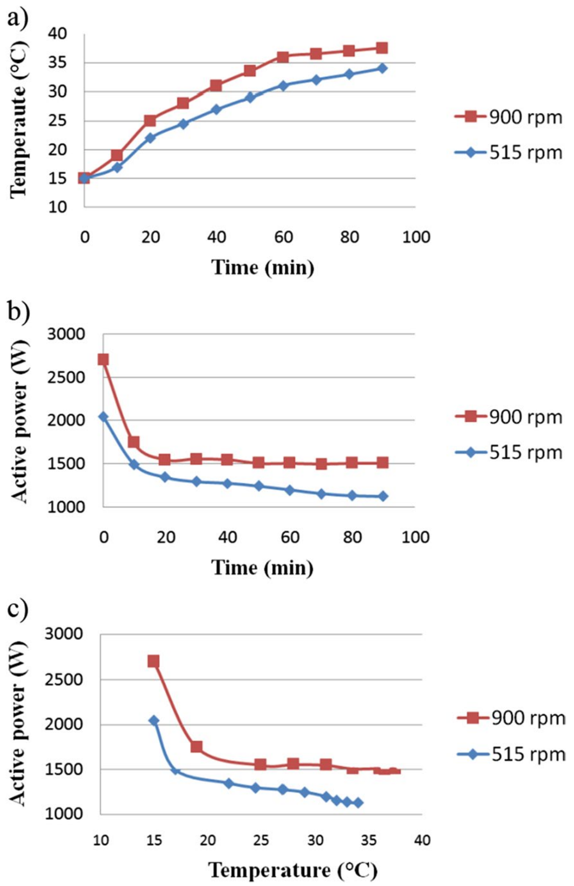

Fig. 6 Temperature and active power during the time

(Fig. 6a). Conversely, the active power goes down drastically during the first 20 min (Fig. 6b). From the temperature-power chart (Fig. 6c), it can be observed that the electric power decreases as the temperature increases. That behavior can be credited to the reduction of the churning loss, which tends to decrease with the increase of oil temperature (Hu et al., 2019).

In short, it can be said that the temperature at the headstock affects the accuracy of the energy efficiency assessment. Accordingly, a warm-up time is necessary to provide the temperature stabilization, and this can be checked by active power stabilization.

Table 2 contains the registered measurements for the five nominal speeds (N) subjected to the variation of depth of cut (a_p). The actual speed (A_s) is the mean value of the readings taken with the photo tachometer during the cutting time. The cutting velocity (V_c) is the ratio between A_s and the average workpiece diameter (d_m), by taking into account the selected a_p value. The cutting force (F_c) is the average of measuring values and the cutting power (P_c) is the product of F_c by V_c.

The idle loss (L_{GZ}) is the active power measuring during the approaching time. It can be taken as the dissipated energy in the electric motor with the whole mechanical transmission with no cutting. The electric cutting power (P_{EC}) is the difference between the total active power (P_E) and (L_{GZ}).

Based on the (L_{GZ}) values, it can be inferred that the energy consumption in the analyzed lathe model can be credited, mostly, to the losses occurring in the electric motor and in the transmission.

Two efficiencies—η_1 and η_2—were estimated according to Eq. 6 and Eq. 7, respectively. To a_p beyond 0.125 mm, the efficiency estimated by the indirect method (η_2) is greater than the direct method (η_1). This behavior was expected since the power loss—particularly that in the stator/rotor of the electric motor (L_M)—increases during the cutting time.

It can be seen from Table 2 that the actual speed (A_s) decreases as the cutting power (P_c) increases. This can be explained by the slip phenomenon, typical of induction motors.

The curves shown in Fig. 7 were built after applying a linear regression to the pair of data (a_p, F_c) shown in Table 2. Subsequently, the F_c values were interpolated for an evenly spaced a_p set, from 0.125 to 1 mm. For each of the nominal speeds (N), the R^2 of regression was greater than 0.99.

From the curves shown in Fig. 7, it can be seen that depth of cut (a_p) linearly affects the evolution of cutting force (F_c). This behavior is important for two reasons. First, the variation of cutting velocity (V_c)—as shown in Table 2—apparently does not significantly affect the relationship a_p-F_c for the same nominal speed (N). Second, since the feed rate was kept constant, the control of a_p is a sufficient condition for the construction of the efficiency curves of a conventional lathe, as stated in the proposed methodology.

Figure 8a and b contain two characteristic curves. For simplification, only the data for $\boldsymbol{N} = 900$ rpm were considered, but the same behavior was observed in the other speeds, as registered in Table 2. In both figures, the curves in blue (◆) were determined by the direct method (η_1), as defined by Eq. 6. Curves in red (■) were computed from the indirect method (η_2), as defined by Eq. 7. The difference between Fig. 8a and b resides on the parameters adopted in the abscissa. In

Table 2 Mean values of the measured parameters in the five nominal speeds (N) for the present case study

N (rpm)	a_p (mm)	d_m (mm)	A_r (rpm)	V_c (m/s)	F_c (N)	P_c (W)	L_Z (W)	P_e (W)	$P_{e\text{-}c}$ (W)	η_1	η_2
375	0.125	175.9	385	3.54	79	281	1272	1557	285	0.18	0.18
	0.5	176.5	382	3.53	267	940	1239	2267	1027	0.41	0.45
	1	174.8	375	3.43	534	1830	1304	3352	2049	0.55	0.61
	1.5	172.3	373	3.36	709	2385	1320	4045	2726	0.59	0.67
	1.75	168.8	371	3.28	835	2739	1252	4463	3210	0.61	0.72
515	0.125	100.8	559	2.95	72	212	1473	1690	216	0.13	0.13
	0.275	100.3	557	2.92	159	465	1464	1961	497	0.24	0.25
	0.75	99.2	551	2.86	404	1156	1504	2774	1271	0.42	0.46
	1	97.5	549	2.80	510	1431	1484	3070	1586	0.47	0.52
	1.5	93.6	542	2.65	821	2178	1529	3995	2466	0.55	0.62
612	0.125	89.4	663	3.10	66	206	1532	1743	211	0.12	0.12
	0.25	88.6	660	3.06	154	473	1640	2146	506	0.22	0.24
	0.5	87.5	657	3.01	261	784	1645	2507	862	0.31	0.34
	0.7	88.1	655	3.02	357	1079	1519	2713	1194	0.40	0.44
	1	86.0	650	2.93	505	1479	1658	3321	1663	0.45	0.50
	1.25	86.1	649	2.93	600	1755	1504	3491	1987	0.50	0.57
	1.5	83.5	644	2.82	746	2101	1592	4033	2440	0.52	0.61
	1.75	81.7	642	2.75	857	2352	1549	4286	2737	0.55	0.64
900	0.125	87.4	957	4.38	84	367	1746	2138	391	0.17	0.18
	0.25	87.0	954	4.34	148	643	1777	2477	700	0.26	0.28
	0.525	86.3	944	4.26	274	1168	1756	3079	1322	0.38	0.43
	0.75	84.8	939	4.17	381	1587	1809	3604	1795	0.44	0.50
	1.025	84.0	935	4.11	483	1987	1765	4049	2284	0.49	0.56
	1.25	81.7	929	3.97	581	2307	1766	4435	2668	0.52	0.60
1239	0.125	54.6	1329	3.80	82	311	2246	2576	330	0.12	0.13
	0.25	54.5	1325	3.78	145	540	2232	2811	579	0.19	0.21
	0.425	50.8	1321	3.52	233	819	2159	3059	901	0.27	0.29
	0.5	58.7	1314	4.04	276	1115	2196	3462	1266	0.32	0.37
	0.75	54.7	1309	3.75	388	1453	2200	3873	1673	0.38	0.43
	1	54.7	1300	3.72	497	1851	2169	4368	2198	0.42	0.50

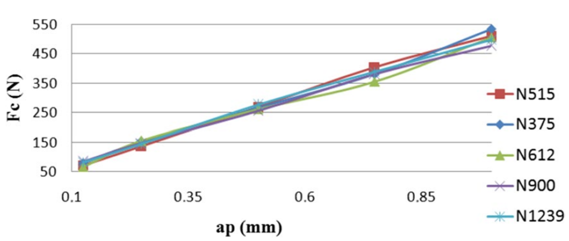

Fig. 7 Cutting force × depth of cut

Fig. 8a, the efficiencies were plotted as functions of the total active power (P_E). On the other hand, the electric cutting power (P_{EC}) was used in the chart displayed in Fig. 8b. At first sight, both charts—Fig. 8a and b—provide the same information, since the idle loss (L_Z) remains constant during the approaching time.

However, during the warm-up, the P_E-η curves will result in an overestimation of the machine tool efficiency, which can be corroborated by the chart (T-P_C) depicted in Fig. 6b. Thus, the P_{EC}-η curves can provide a better estimate.

The problem with the P_{EC}-η curves is their dependency on sophisticated and expensive instrumentation. The computing of P_{EC} values demands on the reading and storing of the idle power loss (L_{GZ}), which must be done during the approaching time. The same procedure should be executed in the cutting phase to

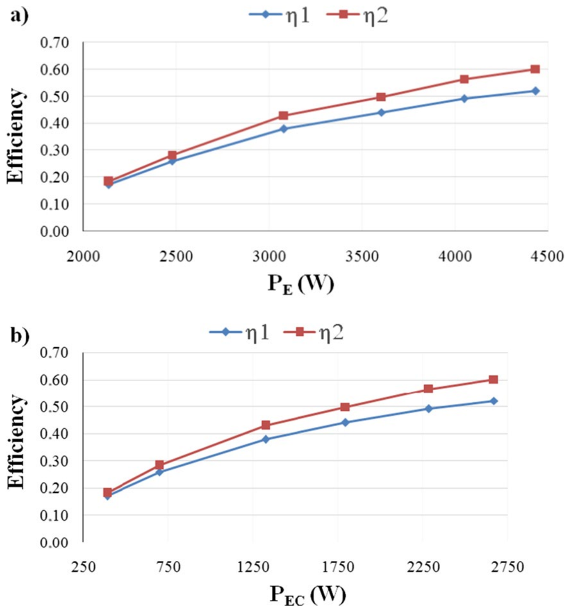

Fig. 8 Characteristic curves

store the values corresponding to the total power (P_E). At last, L_{GZ} should be subtracted from P_E in order to find the P_{EC}. In that case, the wattmeter used in this work cannot fulfill that procedure. Consequently, a personal computer is mandatory although resulting in a more costly technique.

Another problem related to both approaches (P_{EC}-η and P_E-η) lies in the fact that the machining efficiency is load-dependent information but not directly correlated to the material removal rate. In that sense, machining with a worn tool, since the cutting force increases, will be more efficient than cutting with a fresh cutting edge. Consequently, a better supervising system is demanded to indicate that. If the cutting conditions are not changed, a significant increase in the electric power could be related to a deterioration of the cutting tool.

The indirect method (Eq. 7) is significantly less accurate when compared to the direct method (Eq. 6). On the other hand, it is cheaper and less intrusive, which qualifies it as a more appropriated technique to be adopted at the shop floor environment. In short, the direct method could be adopted by the machine tool developer to generate the characteristic curves of each particular lathe model. This information can be useful to the final user.

At the shop floor environment, the final user could install a digital wattmeter to read the electric power and analyze, from the characteristic curves, if the machining operation is running on an efficient mode. The machine tool manufacturer can also incorporate a wattmeter to conventional lathes with squirrel-cage induction motors to measure and report the efficiency status during the machining operation.

Conclusions

In the present work, it is argued that a significant number of conventional lathes with squirrel-cage induction motors (SCIM) are still in use, particularly in emerging economies. In addition, it is also advocated that the efficiency control on this kind of machine tool still remains an open issue.

It was demonstrated that the methodology for construction of characteristic curves for conventional machine tools with squirrel-cage induction motors is useful and feasible. Furthermore, the energy efficiency assessment based on the cutting force and speed measurements can be easily carried out and incorporated in the machine tool by its manufacturer.

The characteristic curves by themselves do not provide information enough to compare the lathe efficiency running on different speeds and different cutting parameters since they are based on instantaneous power measuring instead of the whole process energy.

The characteristic curves could provide information enough for the final user to compare different conventional lathes running on similar conditions, i.e., the same cutting velocity and feed rate. For these cases, the adjustment on depth of cut can enhance the machining efficiency. After the construction of the characteristic curves for a given set of machines, energy efficiency can be assessed and the potential for energy savings for this type of machine can be estimated. For that, another experimental round that will be the next stage of this research will be necessary.

Declarations

Conflict of interest The authors declare no competing interests.

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