GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

4.2 Energy consumption analysis of robot based SPIF

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Abstract

Production processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products, but are still poorly documented in terms of environmental impact. A thorough analysis of the causes affecting the environmental impact in metal forming processes is mandatory. The present study presents an energy consumption analysis, including a power study of Single Point Incremental Forming (SPIF) processes using a 6-axes robot platform. The present paper aims to investigate whether the fixed energy consumption is predominant or negligible in comparison to the actual forming operation. Power studies are performed in order to understand the contribution of each sub-unit towards the total energy demand. The influence of the most relevant process parameters, as well as the material being processed and the sheet positioning, with respect to the power demand are analysed.

Keywords:
SPIF, 6-axes Robot, Energy consumption, Sustainable manufacturing

1 INTRODUCTION

Production processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products. Nevertheless such processes, in particular non-conventional production processes, are still poorly documented in terms of environmental footprint. Thus, a thorough analysis on the causes affecting the environmental impact of these processes is a welcome contribution to increased knowledge in this domain.

Duflou et al. [1] provide a comprehensive overview of the state of the art in energy and resource efficiency improvement methods and techniques in the domain of discrete part manufacturing, with attention for the effectiveness of the available measures.

As far as metal processing technologies documented today are concerned, the reported studies predominantly focus on machining processes such as turning, milling and grinding, dealing with the influence of material removal and cutting fluids, in parallel with the electricity consumption [2,3,4]. Despite some exceptions [5,6,7], many other non-machining technologies, such as sheet metal forming processes, are still not well documented in terms of environmental impact. In this respect, the CO2PE!–Initiative [8] has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes and to provide guidelines to improve these. A methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) is provided by Kellens et al. [9]. The evaluation of the environmental performance of metal forming processes (bulk and sheet forming) is an urgent topic to be investigated since there is still a substantial lack of knowledge in terms of analysis and modeling of their environmental impact. Beside by substituting environmentally hazardous lubricants by new, less harmful ones [10]; the environmental impact reduction in cold sheet metal forming processes can be reached by minimizing the electrical energy usage and material waste .

The available literature on the environmental performance of sheet metal forming processes is typically limited to life cycle inventory analyses of air bending processes [11,12,13].In consequence a thorough analysis on the causes affecting the environmental impact in metal forming processes, especially the innovative but very energy intensive [14] (e.g. longer forming times, heat assisted processes, high pressure liquid, etc…) sheet metal forming technologies to form light-weight materials, is required. One of these technologies receiving increasing attention is certainly the category of incremental forming processes. In the simplest configuration (Single Point Incremental Forming, SPIF), the process setup consists of generic sheet clamping equipment and a hemispherical punch that incrementally forms the sheet toward a desired geometry by a proper trajectory on the sheet itself. Such incremental action allows avoiding the use of a rigid and dedicated clamping system. In consequence process costs and lead times are reduced. ISF (Incremental sheet Forming) processes also allow high formability compared to conventional stamping operations [15]. More recently, several researchers highlighted the ISF suitability for lightweight material processing: Duflou et al. [16] introduced a laser assisted local heating variant of the SPIF process, demonstrating that stress levels and springback effects could be reduced to obtain an improvement in terms of geometrical precision. In 2008, Ambrogio et al. [17] investigated warm incremental forming of magnesium alloy AZ31B, proving a formability enhancement by working magnesium in warm conditions. Other authors [18]investigated the hot incremental forming of titanium alloys by using electrical heating. As far as the environmental evaluation of such processes is

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

concerned, some first comparative environmental studies on incremental forming processes have been published by Ingarao et al. [19] and Dittrich et al. [20]. The latter paper presents an exergy analysis approach to compare - from an environmental point of view - incremental forming processes with conventional forming and hydro forming processes.

The authors of the present paper have recently developed an energy consumption analysis [21], including a power and time study, of Single Point Incremental Forming (SPIF) processes performed on a 3-axis milling machine. Principal conclusion of this study is that the first strategy to reduce the energy demand of SPIF processes is reducing the forming time by optimizing the tool path and working at the highest admissible feed rates. As the analyzed machine tools showed a very low machine tool efficiency, another strategy to improve the environmental performance of SPIF processes could be the redesign of the machine tool architecture in order to decrease the required power levels.

The present paper presents an energy consumption analysis, including a power study of Single Point Incremental Forming (SPIF) processing based on a 6-axes robot. The overall objective of the study is to identify the most energy efficient hardware solution for SPIF processing. Power studies have been performed in order to understand the contribution of each sub-unit towards the total energy demand. The influence of the most relevant process parameters (e.g. feed rate, step down), has been analyzed. Moreover also the effects of the material being processed and of the sheet positioning on the power/energy demand are analyzed.

2 CASE STUDY SPECIFICATION

The experimental study was aimed at manufacturing a truncated cone(shape commonly used to analyze SPIF processing) with a wall inclination angle of 45°, a maximum diameter of 120mm and a final depth of 40mm. A 6-axis Kuka KR210 robot was used during the tests. In order to form the AA-5754 aluminum alloy sheets with a thickness of 1.5mm, a hemispherically shaped punch with a diameter of 10mm was utilized and mineral oil was used as lubricant. The applied feed rates and step down values for the different tests are listed in Table 1. A free spindle rotation (the spindle was left idle and free to rotate, so that tangential friction would make the tool rotate) was used.

Table 1: Applied parameter settings for the developed tests and resulting forming time

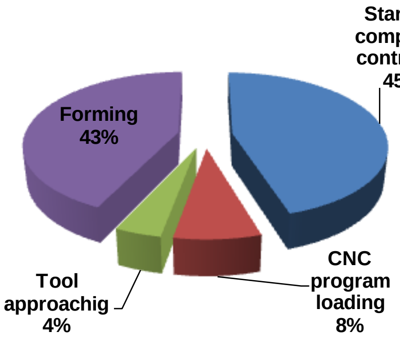
Test ID	Feed rate [mm/min]	Step down [mm]	Forming time [s]
1	2000	1.0	287
2	1000	0.5	1141
3	2000	0.5	575
4	1000	1.0	579

3 LIFE CYCLE INVENTORY (LCI) DATA COLLECTION

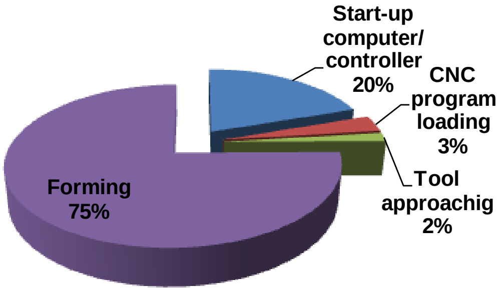
This section reports the results of the performed LCI data collection effort.

3.1 Working cycle time study

A time study was performed in order to identify the different production modes of the considered machine tool and their respective shares in the covered time span. For this purpose the machine tool was monitored during multiple working cycles. The identified production modes cover the machine tool start-up, use phase as well as shut-down operation. Figure 1 shows the averaged time share of the different production modes for two different parameter settings: the fastest process variant, Test 1 (Figure 1a), and the slowest one, labelled Test 2 (Figure 1b).



(a)



(b)

Figure 1: Time share for different production mode for Test 1 (a) and Test 2 (b)

As can be concluded from Figure 1, even for the fastest process parameter settings (Test 1), the time share of the productive mode (forming mode) is dominant. Comparable to machining processes, the productive time is substantial. Applying the process parameter settings of Test 2 (Table 1), results in a forming time share rise up to approximately 75%. It is necessary to underline that the shape taken into account in the present study is a very simple one; the forming time (and related share) for industrial products can be expected to be substantially higher, while the duration of the other modes is product shape independent.

3.2 Power/Energy study

The energy consumption is determined by the supplied average power multiplied by the duration of an operation. In order to estimate the energy usage in each phase, the consumed electrical power was measured for all the identified production modes. For each production mode, the total power demand as well as the power demand of all relevant sub-units were monitored by using electrical power meters with a sampling rate of 12.8 kHz (results logged and shown are for averaged values over 1 second intervals). The measurements were repeated for all tests listed in Table 1. Once the power and the time values were collected, the corresponding energy consumption was determined. Table 2 reports the times and the energy calculated for Test 1. To better illustrate the power demand over a full working cycle, Figure 2 reports the power profile registered for Test 1. From the power profile shown in Figure 2, three main power levels can be distinguished: the start up/computer controller power level of approximately 220W; the tool approaching phase, characterized by a peak corresponding to a fast positioning of the robot and a subsequent power level equal to 630 W; and the productive (forming) power level. The productive phase is characterized by a growing trend: such increasing trend, as will be better explained in Section 4.2, is due to the hardening phenomena of the material being formed.

Table 2: Energy consumption and related times for each production modes for Test 1

Production mode	Time [s]	Energy [kJ]
Start-up computer/controller	300	66
CNC program loading	50	11
Tool approaching	27	18
Forming	285	208
Total	662	303

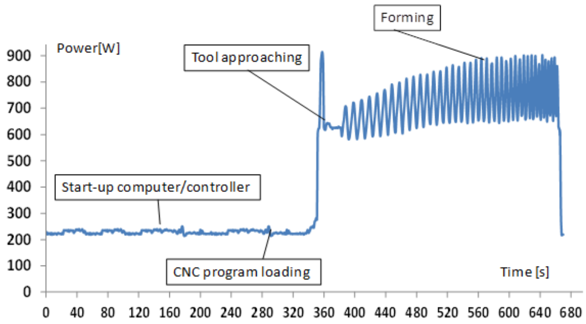
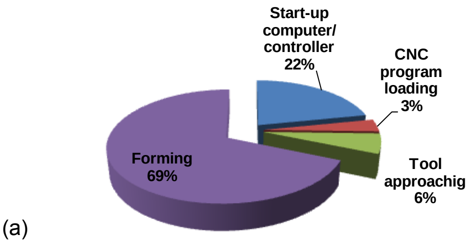


Figure 2: Power profile for Test 1

A cross analysis of Figures 2 and Table 2 allows to conclude that the power consumption in the productive forming mode is dominant, i.e. the energy demand during the forming step is much higher in comparison to the other production modes. Figure 3 shows the energy share of the different modes for both Test 1 (a) and Test 2 (b). For the faster operation the forming mode accounts for 69% of the total electrical energy consumption while for the parameters settings of Test 2 (the slower one) the energy share of the forming mode rises up to 89%.



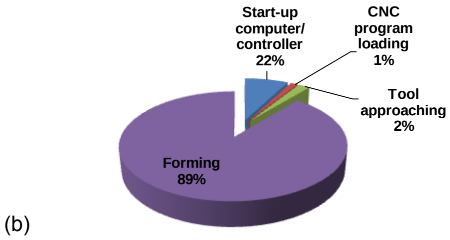


Figure 3: Energy share for Test 1 (a) and Test 2 (b)

3.3 Sub-unit breakdown analysis

The power demand of relevant sub-units was also measured for all production modes. This helps to understand the cause of the energy consumption and facilitates the identification of strategies to reduce the total energy demand and related environmental impact (e.g. by selectively switching off non-required sub-units). Since the dominance of the production mode was demonstrated in the previous section, the sub-unit breakdown analysis during the forming step was analyzed in detail. The used robot has three main sub-units: the drives, the 24V-circuit (for all low power electronics for the control cards including drives control) and the circuit for the ventilator. For each sub-unit, the power profile was measured and the energy consumption was determined. Figure 4 (a) shows the breakdown analysis. As can be observed, the drives and the 24V circuit play a relevant role, accounting for almost the total of the energy consumption. Actually the drives and the 24V circuit account for 44% and 48% respectively. In Figure 4(b) instead all the sub-unit power profiles registered for Test 1 are simultaneously plotted. It can be observed that the increasing trend of the total load curve is totally due to the power demand in the drives that, actually, move the tool to form the sheet, and as a consequence belong to the only sub-unit sensitive to the material hardening effect.

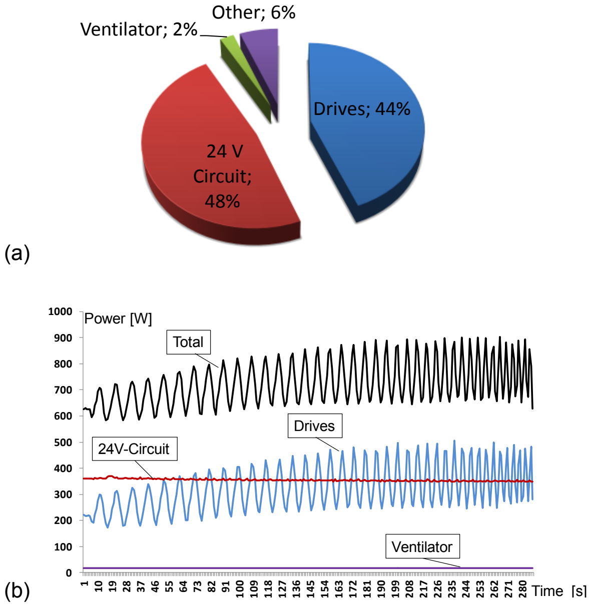


Figure 4 Sub-unit breakdown analysis (a) and sub-unit power profiles for Test 1(b)

4 ENERGY AND POWER INFLUENCING FACTORS

4.1 Influence of process parameters

In order to analyze the influence of the step down and of the feed rate on the power demand, the average power level and the energy demand during the forming phase have been measured for all the conducted experiments. The developed tests represent a complete two levels two factors array. In consequence it is possible to analyze the effect of each single parameter. The results are reported in the Table 3; as it can be seen by moving from the low level value to the high level value, the influence of a single parameter on the power level is limited to about 4 %, and even by changing both parameters simultaneously, the influence on the average power value is only about 6%. On the contrary, it is necessary to consider that by changing one of these parameters the forming time can double (compare forming times for Test 1 and 3 or Test 2 and 4 in Table 1). The measured small power variation due to these parameter settings (limited to 4%) can be neglected in every electrical energy oriented analysis. The conclusion is that the step down and the feed rate significantly influence the energy requirement only because these parameters strongly affect the forming time. Table 3 reports also the total energy measured for each test. Considering the fastest working cycle (Test 1) as reference base for the energy demand, the additional energy consumption for the other configurations is reported.

Table 3: Energy and power results for the developed tests

Test ID	Energy [kJ]	Average Power [W]	Additional Energy Consumption
1	208	724.9	/
2	781.6	685	276%
3	401.3	698	93%
4	407.7	704	96%

Figure 5 reports the energy demand for all the parameter settings (Tests 1-2-3-4) listed in Table 1. As expected, a decrease of the step down and/or feed rate results in a longer forming time. In consequence, the energy demand rises as well. The linear trend of the forming energy as a function of the forming time further proves the forming time dominance.

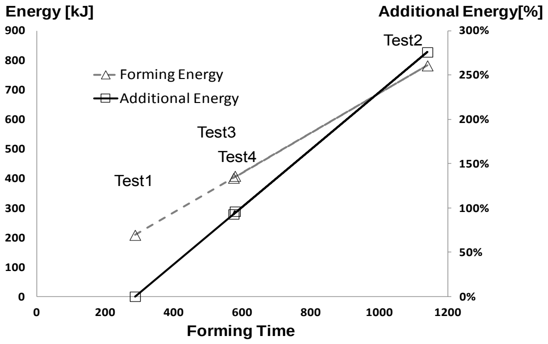


Figure 5: Energy demand and Additional energy for the developed tests

4.2 Material contribution to the power/energy demand.

In order to analyze and quantify the effect of the material contribution itself on the power demand, the power profile obtained while a material is being formed has been compared with the power profile obtained in air forming conditions (the air forming process was developed by keeping the same process parameters but without the presence of the material itself). In order to cover a quite wide material properties range, three different materials have been selected: a very soft aluminum alloy (AA-1050) characterized by very limited hardening, a high strength aluminum alloy, namely AlMg03 (AA-5754), and finally also DC01 steel was tested. Due to technical constraints in all the tests a feed rate equal to 2000 mm/min and a step down equal to 0.5 mm were used. For all three materials the sheet thickness was equal to 1.5 mm.

In Figure 6, the power profile related to the air forming conditions and the ones related to the AA-5754 aluminum alloy and to the DC01 steel are reported. For the soft AA-1050 material, only a slight increase in power demand was observed. In particular since the material is characterized by limited hardening, the related power curve is not characterized by an increasing trend, but, on the contrary, only a slight offset of the air forming power curve was observed. When considering the other materials, it can be noticed in Figure 6 that the power profile is characterized by an increasing trend. The stronger the material, the more noticeable is the growing trend. This phenomenon can be explained by the material hardening effect during the forming phase.

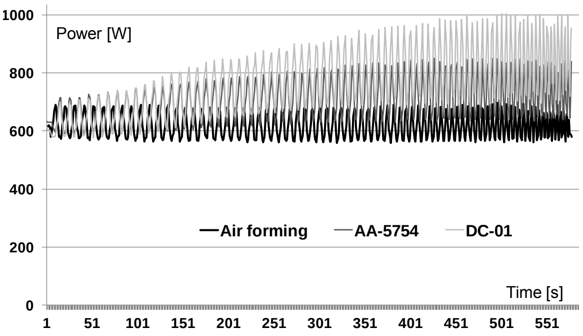


Figure 6: Power profiles comparison for varying material strength

The electrical energy, the average power level as well as the contribution of the material share on total power demand are reported in the Table 4..

Since the air forming energy is constant and equal for each test, at the increasing of the material strength the energy demand increases considerably and as a consequence, the material contribution share on the energy demand considerably increases as well. More in details the material being formed accounts for the 3% in the case of the softer material and account for up to the 22% for the DC-01 steel.

Table 4: Results of varying the material

Material	Energy [KJ]	Average Power [W]	Material contribution share
Air forming	358.6	619.4	/
AA-1050	368.8	636.9	3%
AA-5754	408.0	704.6	12%
DCO1	459.4	793.4	22%

4.3 Effect of the sheet positioning

The sheet positioning is another parameter to analyze from the energy demand point of view. Actually at the varying of the sheet position, the motors, driving the different axes, are used under different load conditions and the energy demand could be affected by such phenomenon. In particular, the sheet clamping equipment has been shifted over a distance of 600 mm, in the mounting rig shown in Figure 7. Such change has increased the lever of the mechanical moment the drives of the robot have to apply to form the material.

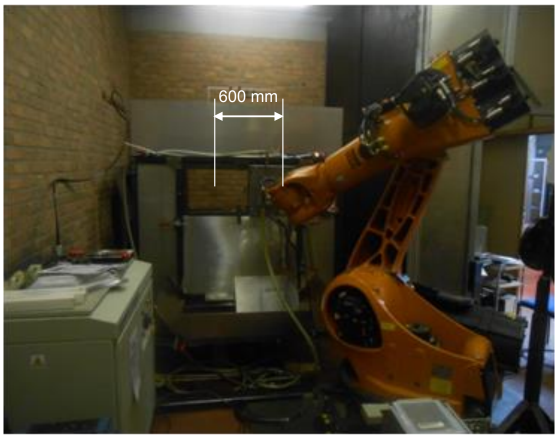


Figure 7: Setup for the analysis of the sheet position influence

It was expected that such mechanical moment increase could result in an increase of power level as well. In particular again the three mentioned tests with the three different materials were developed and also a power measurement for the air forming condition was performed. As could be expected, no relevant difference in power demand was observed between the air forming condition and the case of the soft AA-1050 forming process. On the contrary, as the strength of the formed material increases, the differences in terms of power level are relevant between the two different positions. In particular developing the experiment in the shifted position leads to a noticeable increase of the power demand. In Figure 8, the comparison between the power profiles obtained in the two different positions for the DC01 case are reported. As can be noticed from these results, even a relatively small sheet displacement results in a substantial power increase. In particular, the stronger the material the higher is the power increment.

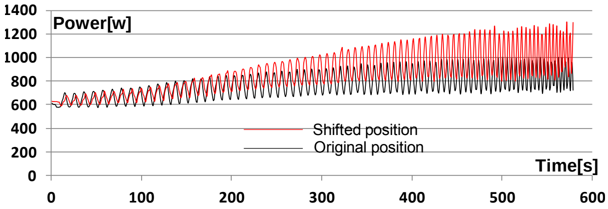


Figure 8: Effect of the sheet positioning on the power profile for the DC01 steel test

Table 5 reports the additional energy due to position changing. For DC01, the material tested with the highest tensile strength, the additional energy amounts to 9 %. As a consequence, the effect of the material on the power demand result is amplified compared to the influence the material had in the original position. Again in the case of the DC-01 steel the material contribution on the total energy thus rises up to 39%.

Table 5: Results obtained for the shifted position

Material	Energy [kJ]	Average power [W]	Material contribution share	Additional Energy due to position changing
Air forming	358.5	619		0%
AA-1050	370.7	640	3%	0.5%
AA-5754	434.4	750	21%	6%
DC-01	500.3	864	39%	9%

The results reported above lead to the conclusion that the positioning of the sheet plays a relevant role in terms of energy consumption, and in consequence such parameter has to be optimized from an energy efficiency point of view.

5 CONCLUSIONS

The present study reports an energy consumption analysis, including a power study of Single Point Incremental Forming processes developed on a 6-axes robot. The influence of the most relevant process parameters (e.g. feed rate, step down), the material being formed and the sheet positioning have been analyzed from energy demand point of view. Main conclusion of the first part of the research is that the forming time is the dominant factor in the energy demand of SPIF processes. Such conclusion was drawn by analyzing the production mode time share as well as the energy demand for four different parameter combinations.

These statements lead to the conclusion that the first strategy to reduce the energy demand of SPIF processes is reducing the forming time by optimizing the tool path and working at the highest admissible feed rates.

In order to better understand the parameters affecting the variable part of the energy demand, also the contribution of the material and the positioning of the sheet on the power demand have been analyzed. Three different materials, characterized by different strength grades, were formed by the SPIF process and the energy demand was analyzed. It was observed that at the increasing of the material strength the power/energy demands considerably increase, so the material contribution share on the total energy demand account for up to 22% for the strongest considered material.

The sheet positioning is another parameter which , significantly affects the power/energy demand. As matter of fact to form the strongest material in the considered shifted position an extra energy requirement of 9% was observed. Summing up, the material being formed has to be considered for an accurate energy prediction, and since the positioning of the sheet strongly affects the energy demand; such parameter should also be optimized to improve the energy efficiency of the process. Such assessments lead to the conclusion that the energy demand for robot supported SPIF processes is characterized by a constant amount and a variable one. The constant part concerns the air forming energy demand, the variable part instead is affected by the parameters determining the force necessary to form the sheet (material, drawing angle, thickness, etc.) and by the sheet positioning.

6 ACKNOWLEDGMENTS

The authors acknowledge the financial support from FWO (Research Foundation – Flanders), under the scheme of Pegasus/Marie Curie, as well as the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) through its PhD grant No. 091232 and the O&O EnHiPro project (Project No. 090999).

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