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Energy metrics for product assembly equipment and processes

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A B S T R A C T

A key factor deciding the capacity to increase the sustainability of final products is the energy efficiency. The energy embodied in a product is an aggregation of all of the energy embodied in the products' components and subsystems, expended through its manufacturing processes and logistical activities. Currently, accurate estimation of this energy metric is hindered due to the unavailability of energy use data traceable to individual processes and equipment associated with the product's assembly. In this paper, we propose using minimally-required energy to compute energy efficiency of a product assembly process. Based on the proposed approach, efficiency metrics established on the process, product, material and equipment characteristics have been presented at the assembly activity and equipment level. A case study has been presented for a hybrid laser welding process to demonstrate the computational methods used to arrive at these efficiency metrics. Major contributions of this paper are the metrics development and exemplifying the metrics through an actual assembly process (hybrid laser welding) case study. We will explain how these metrics can provide industries with a capability to identify opportunities to improve their sustainability performance across their assembly processes.

1. Introduction

The number of manufacturing companies that are making fundamental changes towards sustainability is increasing around the world (Jovane et al., 2008; Haanaes et al., 2011; Goldstein et al., 2011). Energy is a crucial component of sustainability. High levels of energy efficiency are an essential part of a dynamic productive economy with a high quality of life even though the different viewpoints on the energy efficiency do exist (Herring, 2006). Energy efficiency is one of the important drivers for sustainability in regard to manufacturing industry, since it is known as one of the greatest energy consumers and carbon emitters in the world. The manufacturing sector is responsible for about 33% of the primary energy use and for 38% of the CO_2 emissions globally (IEA, 2008; EIA, 2010). Many global automotive manufacturers have research efforts focused on improving energy efficiency in assembly processes (Comoglio and Botta, 2012). These companies recognize that challenges in energy improvement include i) performing reliable energy assessment of part assemblies and ii) evaluating energy efficiency before, during, and after an assembly process. However, there is a major technical problem: measuring energy consumption is rarely traceable to individual processes and equipment. Because of this, the reported energy usually has large uncertainty due to subjective allocation. The uncertainty hinders sound analyses of energy performance in assembly processes, and reporting energy performance to the public and stakeholders. Industry needs an equitable energy metric for analysis and verification of energy use in product assembly processes.

An assembly process (Kalpakjian and Schmid, 2010) is conceptually an aggregation of part delivery, workpiece handling, fixturing, joining, and other auxiliary operations. Major joining processes include welding, brazing, soldering, bonding, riveting, and fastening. Most research on assembly processes are primarily focused on process technologies, capabilities, and product design for assembly processes (Whitney, 2004; Sudarsan et al., 2006; Murshed et al., 2009). Kellens et al. (2012) developed a methodology for systematically characterizing unit manufacturing processes and called for co-operative research effort to improve the existing inventory of life cycle data for manufacturing processes. However their methodology advocates the use historical base line energy data which hampers the traceability of energy metrics. Little research is focused on measurement science for assessing energy efficiency and energy performance of assembly processes based on the theoretically minimum required energy. As types of assembly processes are numerous and complex, we established the scope of this paper on energy transformation, focusing on joining. Joining is the method to assemble separate parts into one piece without

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relative movement, e.g., mounting chips to the printed circuit board by soldering. Subcategories of joining include adhesive bonding, welding, and mechanical fastening. Welding can be further classified as fusion, brazing or soldering, and solid state joining. Fusion breaks down even further into electric welding and chemical welding.

This paper provides a detailed analysis of energy performance-related metrics, methods for the computation of energy efficiency, and a case study of welding. Section 2 explains metrics used for computing energy transformation in product assembly processes. Section 3 has an example of energy analysis based on the metric. Section 4 concludes the paper.

2. Metrics for energy in assembly processes

Energy is transformed while performing tasks in assembly processes. Measuring to quantify energy efficiency and then reducing energy consumption in product assemblies are steps towards improving the energy performance of an assembled product. This section describes energy metrics, an energy transformation model for assembly equipment, activity, and process.

2.1. Definition of metric

Metric is defined as a standard measure of a single parameter of a system. A metric has the following characteristics: measurable, relevant, understandable, reliable, usable, data accessible, timely, and long term-oriented (Sustainable Measures, 2009). Metrics enable companies to quantify the energy performance of their manufacturing processes, including energy efficiency. Quantifiable performance can lead to performance improvement.

Our work is focused on energy efficiency as a metric for assembly processes. Determining energy efficiency involves quantifying energy consumption, loss, and minimally required energy. A product is assembled in a predefined sequence of assembly activities defined by the assembly process plan of the product. Additionally, energy metrics can be modularly composed to support many production scenarios without redefinition in the energy efficiency analysis.

Energy may be consumed by multiple pieces of equipment to support multiple processes within an assembly activity. Energy consumption is another metric for an assembly activity. Modeling energy transformation of an assembly activity involves quantification of energy consumed by both equipment and processes. The rest of this section describes the energy transformation model and energy efficiency metrics starting from equipment to processes.

2.2. Measuring energy efficiency at the equipment level

Energy consumed by assembly processes is primarily consumed by powered equipment (eQuipment or Q). Major functions of powered assembly equipment are material handling, thermal joining, powered fastening, fixturing, and adhesive bonding. For characterizing energy transformation in equipment, we define a new concept: *Unit eQuipment* (UQ). UQ is a piece of equipment that has a specific function, such as welding or material handling, and a defined boundary. The boundary is the interface between the equipment and its surroundings. Energy flows in and out of the equipment boundary. Unit equipment has energy input and can have energy or work as output. Pieces of unit equipment can be combined into *Complex Equipment* (CQ). Complex equipment consists of two or more pieces of unit equipment and hence can have one or more energy inputs. Each unit equipment piece in the complex equipment has its own energy input. For example, an automated arc-welding machine consists of a robot and a welder. The robot and the welder have their own energy inputs.

The energy consumed by the equipment (machine, work cell, or assembly line) is defined as *Energy Input* (E_Q^I). Examples of the energy input source are electricity, fuel, and natural gas. The energy from the equipment actually available to the workpiece is defined as *Energy output* (E_Q^O) and is considered as useful energy, i.e., exergy. Exergy is the maximum useful heat or work brought by the equipment into the workpiece(s) in a process. One example of exergy is heat generated by the welding electrode to weld two pieces of metal parts. Another example is mechanical work done during a robot motion to move the welder along the seam. While efficiently utilizing exergy to maximize sustainable efficiencies during the assembly process, quantifying exergy is outside the scope of this paper.

Energy input is greater than energy output from the assembly equipment. The difference between the energy input and the energy output is defined as *Energy Lost*. Energy lost is due to many reasons. Examples are irreversible processes (such as energy conversion losses, vibration, and friction) and heat exhausted from the equipment to the ambient environment. The *Energy Efficiency* (η_Q) of equipment is defined as the ratio of useful energy from the energy input. Eq. (1) is the efficiency of a piece of equipment.

$$\eta_Q = \frac{E_Q^O}{E_Q^I} \tag{1}$$

For complex equipment, the efficiency (η_{CQ}) is the energy output from the complex equipment divided by the energy input to the complex equipment. The energy input and output of a piece of complex equipment is the sum of energy input/output of unit equipment pieces. Note that the energy units of all the energy inputs and outputs have to be consistent. Eq. (2) is the efficiency of a piece of complex equipment, where n is the total number of unit equipment pieces in the complex equipment piece and i is an index from 1 to n.

$$\eta_{CQ} = \frac{\sum_1^n E_{UQ_i}^O}{\sum_1^n E_{UQ_i}^I} \tag{2}$$

Furthermore, equipment is classified into assembly and auxiliary equipment. Assembly eQuipment (AQ) delivers energy directly to the assembly process. Auxiliary eQuipment (auxQ) delivers energy directly to auxiliary processes, not directly to the assembly process. An auxiliary process is necessary for the assembly process to complete. For example, in welding, heat energy for the process is contributed by the arc welding equipment whereas the motion controllers and fume hood are considered auxiliary equipment. The assembly process and auxiliary processes concurrently take place during an assembly activity to complete an assembly task, such as welding a seam or placing chips to a Printed Circuit Board (PCB) in a reflow soldering process.

When measuring energy input or output of a piece of equipment, such as a welding machine, the first step is to describe what parameters of the equipment should be measured and how they are measured. Some fundamental elements for measuring the parameters include operations, measurement instrument to be used, measurement setup, instrument calibration certificates, instrument and equipment interface, and documentation of any models and simulations employed. Measurement methods may also include virtual measurements using computational models and simulations.

The second step is to document the measurement results which provide transparency and traceability. A measurement result