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Optimized design of press frames with respect to energy efficiency

Matteo Strano [a,*], Michele Monno [a], Andrea Rossi [b]

[a] Dipartimento di Meccanica, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy
[b] MUSP – Macchine Utensili e Sistemi di Produzione, Via Tirotti 9, 29122 Piacenza, Italy

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ABSTRACT

Large forming presses require great amounts of construction metal materials. Nevertheless, eco-design principles in the field of forming presses have seldom been confronted in the scientific literature. In this paper, an optimization model is proposed, suitable for designing press frames which are optimal in terms of energy efficiency. First, a framework is proposed for modular and functional description of a machine tool is described, in order to identify the largest energy consuming modules and functions. Then, a simple analytical model of loads, stresses and deformations is proposed for pre-stressed structures. Then, the equations of the analytical models are used as the constraints of a numerical global optimization algorithm, aimed at minimizing the amount of energy stored into the press frame and the extra-energy due to deformation of the columns in the usage lifetime of the press. The results clearly show that, only if the press frame structure is monolithic, it is possible to obtain a solution which is truly optimal. This conclusion is robust with respect to potential noise or uncertainty issues, which in this case are mainly related to the coefficient of the objective functions.

1. Introduction

Sustainable production in the forming industry can be addressed both acting on the manufactured product, on the manufacturing process and on the manufacturing system (Duflou et al., 2011). In the literature, the product/process has generally been addressed more than the machines. The increasing demand for machinery and production systems to be more energy-efficient poses new challenges for machine designers. The production of mechanical machinery employs about 13% of all the steel produced in the world (Allwood and Cullen, 2012) and a non-negligible amount of cast iron and aluminium. Lightweight design of machine tools is a relatively new concept, whose general influence on design approaches and criteria is starting to be considered, with respect to energy efficiency (Kroll et al., 2011). Some examples of design studies based on lightweight considerations are available, especially for machine tools for material removal (Jiao et al., 2012). The present paper discusses the quantitative consequences on energy consumption of designing forming presses with lightweight specifications. In fact, an important category of operating equipment is represented by forming machines, which are produced in large numbers worldwide, although the most important shares of machine tools in general and as a consequence of forming machines are concentrated in few countries (China, USA, Japan, Germany and Italy) (Gerczyński, June 2012). By elaborating data taken from different sources (the U.S. Census Bureau, the European CECIMO association and the Italian UCIMU association), it can be roughly estimated that the number of metalworking forming machines produced in year 2010 in the world was somewhere between 25,000 and 35,000 units, with an increase in turnover of about 18% over year 2009. More in detail, the world market estimations provided by CECIMO have been used to calculate the world total cost of new installations of machines (Gerczyński, June 2012). Data extracted from the "Schede prodotto" of UCIMU have been used to estimate the share of forming machines among the total machinery expenditure (Schede prodotto UCIMU). Data mined from the U.S. Census Bureau have been used evaluate the average cost of a forming machine (US Census Bureau).

Examples of metal forming machines are press brakes, forging presses, die casting machines, hammers, powder forming presses, stamping and blanking machines, etc. In addition to the metalworking industry, presses made of iron and steel frames are used also in the ceramic tiles industry for powder pressing (Shu et al., 2010) and in the plastics and rubber industry (compression and injection molding, thermoforming, etc.). Besides, the machinery sector is rapidly growing in a worldwide perspective. According to Eurostat, the machinery industry is currently the 6th fastest growing out of 29 main industrial sectors. This means that the

* Corresponding author. Tel.: +32 98325590.
E-mail addresses: strano.m@gmail.com, matteo.strano@polimi.it (M. Strano).

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number of installed presses per year will increase in the future and the environmental impact of their production and use will increase.

The main objective of the present paper is to develop and implement an FEM (Finite Element Method) based optimization model for designing a forming machine structure, able to minimize the total amount of energy consumed during its entire life, i.e. in a life cycle perspective. The proposed model, which is focused only on the structure of a machine tool, is meant as a technique ready to be incorporated into a more comprehensive and generalised approach for an energy efficient design.

The goal of "structural optimization" with energetic, rather than economic or safety criteria is innovative for the machine tool industry: no previous references can be found aiming at this particular target, to the authors' knowledge. General guidelines have been developed specifically for energy efficiency design tasks, but they are usually meant for end user products as in (Bonvoisin et al., 2010), not for production machinery. Furthermore, eco-design guidelines and rules are often qualitative and quantitative methods do still suffer from a lack of objectivity.

When dealing with machine tools, the scientific literature focuses on analysis, modelling or monitoring methods and techniques for energy consumption or environmental impact. These are very useful in a designer's perspective, but they do not directly lead to a clear and unique engineering decision. As an example, a method for a full Life Cycle Analysis is proposed in (Santos et al., 2011), 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 bending process. In Hu et al. (2012) the authors propose an approach for energy efficiency on-line monitoring of machining processes; in He et al. (2012) and Avram and Xirouchakis (2011), different methods for modelling the energy consumption are described. In the present paper the energy consumption is modelled, and the model is further enclosed in an optimization algorithm, in order to provide the designer with direct quantitative indications for designing the structure.

As another element of novelty of the proposed paper, it can be underlined that the optimization of forming press frames based on FEM simulations has been seldom investigated in the scientific literature (Lan et al., 2011). As one of the very few examples, in Duan and Wu (2010), topological optimization of the pre-stressed combined frame of a high speed hydraulic press was carried out in combination with generalized finite element modules, with the objective of increasing the value of the first natural vibration frequency, obtaining also an economic benefit by reducing the weight. In Strano et al. (2012) a quantitative comparison between conventional and pre-stressed solutions is carried out as an optimization problem, based on an analytical model.

2. Designing for energy efficiency

An important technical reference which has been used as the framework for the current analysis is the draft standard ISO/DIS 14955-1, titled "Machine tools – Environmental evaluation of machine tools – Part 1: Design methodology for energy-efficient machine tools". Although this standard only addresses energy efficiency during the use phase of machines, it still provides a valuable roadmap for identifying the sources of energy consumption in a machine tool throughout its entire life cycle. First of all, it identifies six different phases of the life of a machine tool as: raw material, production, transport, set-up, use, recycling (see left part of Fig. 1). The draft ISO standard clearly identifies the "raw material" and the "use" phases as the two major sources of environmental impact and energy consumption especially. The model presented in the following sections focuses only on these two energy consuming phases. The structure is significantly the most massive component of a machine tool, hence the share of energy consumed for its material is by far the largest. Forming presses, if

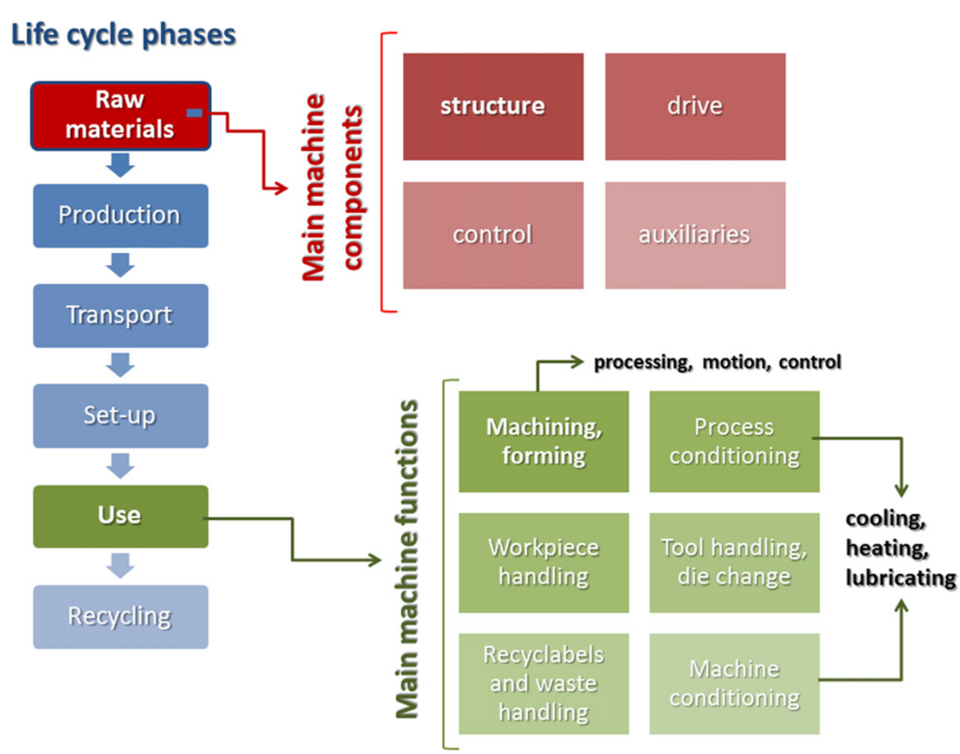

Fig. 1. Life cycle phases of a machine; main components and functions, relevant to energy consumption.