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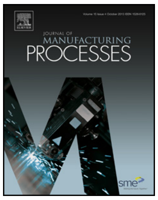

Energy based phenomenological model for optimizing the sheared edge in the trimming of steels

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ABSTRACT

Attributes related to the dimensional quality of hot rolled steels are very important in commercial sectors that make direct use of this product, because delay or equipment damage can be avoided when forming in downstream operations. In this research, the steel sheet edge trimming process and its relationship with the defect known as broken edge is experimental and numerically studied. The type of material, horizontal clearance between knives and the energy spent during the cutting process are analyzed in detail. A metal-mechanical study is carried out for obtaining a microstructural hardness and flow stress characterization. Consequently, the edge trimming process is FEM simulated and its results in relation to knife penetration and shear stress lead to determining the energy spent during the cutting process. A mathematical model is determined under the consideration that minimum energy gives the optimum cutting conditions. The model proposes a reliable value for the horizontal clearance ($\mathrm{H_c}$), between knives, taking as the principal factors: energy consumed during the edge trimming process, sheet thickness (T_h), carbon content (C) and/or its ultimate tensile strength, expressed as: $H_\mathrm{c} = \alpha + \beta T_\mathrm{h} - \gamma C$. A comparison of the recommended numerical results with the best practical conditions is carried out and a high coincidence is successfully found. This model is expected to be easily adopted as a tool where operators can adjust and control the parameters of process, and then, as a result, produce a sheet without edge trimming defects as well as a reduction in efficiency costs.

1. Introduction

The edge trimming process for sheet metal has been used to prepare steel coils for subsequent forming operations, from very light components to heavy appliances and machinery. As is already known, attributes related to the dimensional quality of rolled sheet have a significant importance in commercial sectors, such as the automotive and aeronautical industries, because they usually make direct use of this product. The dimensional quality of rolled sheet edge can be critical to avoid degradation, wastes, accidents and tardiness in subsequent production lines. Several studies have been carried out to try to understand the relationship of shearing with bulk and sheet metal forming processes in experimental work [1–11]. Deep drawing and forging processes are typically analyzed by finite element methods. However, there are very few studies addressing the trimming process and its relationship with operative parameters. Hilditch [12,13] carried out some trimming experiments on sheet metals, varying the knife-die clearance to obtain data as a function of clearance. He also prepared some trimmed samples to examine crack initiation, the generation of fracture surface profile and the mechanism of burr formation. Recently, Khelifa [14] and Yan [15] studied the sheet metal stamping process through computational simulation, predicting when and where the cracks could appear in the workpiece during the forming operation. Nevertheless, again, the trimming process study is deviated and is not clearly analyzed in terms of characterization, even though so far some patents related to the topic have been granted [16–18]. To date, there is no knowledge on the relationship between material properties and the features of the sheared edge in the trimming process. This lack of understanding makes it difficult to predict the trimming behavior of a new material introduced into the process [13]. On the other hand, Cortés[19,20] has formulated a numerical method based on plastic deformation energy in order to determine constitutive relations by using FEM simulations of

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metalworking processes considering microstructural transformations induced by strain. This technique brings to the present research a new idea for treating the relationship between the cutting process parameters and material characteristics.

Consequently, based on the minimum energy principle developed during shearing process, this research aims to develop a phenomenological model taking into account the relationship between the edge trimming process and material characteristics of rolled steels. The purpose of said model is to explain the edge trimming mechanism and, thus, to predict the final shape of the edge trimmed steel sheet. The model is compared with experimental results and the experience of shop floor workers at a leading steel company in the world, in order to be validated and to determine the confidence of the phenomenological model and the method used.

2. Methodology

The methodology carried out during this research comprises basically three study stages: I. Metal-mechanical characterization, II. FEM simulation of the cutting process and III. Mathematical modeling.

Metal-mechanical characterization. In this stage, microstructural analyses, hardness and tensile tests of each material are carried out in order to determine the elemental conditions of material during the edge trimming process, as well as to obtain the necessary information to be considered in the numerical processing and mathematical modeling. *FEM simulation of the cutting process*. In this stage, a computational simulation using the Rigid-Plastic Finite Element Method (FEM) is developed for reproducing the fundamental conditions that exist in the sheared edge during the trimming of steels. *Mathematical modeling*. In this stage, a physical analysis is carried out, in which the geometrical shape of the sheared edge is quantified in relation with the clearance between knives. Shear stresses are determined on the sheared edge at the moment when the knives penetrate the sheet by multiple simulation steps, taking into consideration different materials and clearances between knives. The area under the shear stress-penetration curve is taken as the energy consumed during the shearing of the material. The minimum energy evolved designates the optimal condition of the sheared edge in the trimming of each material. Thus, a mathematical correlation between the optimal clearance corresponding to each material monitored by sheet thickness and carbon content or UTS (due to the use of true stress/strain values) gives a general polynomial mathematical model. This mathematical expression, either clearance between knives as a function of carbon content or clearance between knives as a function of ultimate tensile strength, is compared with the value commonly used by experienced operators for its qualification.

3. Procedure

3.1. Metal-mechanical characterization

The chemical composition of four different types of low carbon steels is performed under ASTM E415-99$\underline{a}$ and E 1019-02 standards and by using an optical emission spectrometer Analytical Instruments 1201. Basically, specimens are taken at center and at 50 and 127 mm from edges. The metallographies are carried out according to the ASTM E-3, E-45 and E-112 standards. Nital as a chemical solution was used at 3 and 5 percent in volume for very low and low carbon steels respectively. The hardness tests are conducted under ASTM A-370, E-18 and E-140 standards with a Wilson Rockwell 2000 durometer with a 1/16-in. diameter steel ball and 100 kg of load. A series of tensile tests are performed according to the ASTM E-8 01 standard, with a universal machine Tinius-Olsen U-series for the very low carbon steels and with an Instron 5581 machine for the low carbon steels. Sampling is made at the edges and center of the sheet width and samples are taken from the edge trimming line. Some specimens have been chosen with broken edge defects, in order to analyze the edges and for quantifying the edge trimming pattern and rollover, nick, break and burr characteristics.

3.2. FEM simulation of cutting process

Finite element analyses, FEA, for simulating edge trimming are conducted using DEFORM 2D® commercial software. Tensile tests make it possible to obtain the stress–strain constitutive relationship of materials and consequently the exponent n and coefficient K of constitutive expression; $\sigma = K\varepsilon^n$ are found for each analyzed material. The friction between the sheet and the knives is considered to follow the Coulomb law. The friction values applied are 0.3 and 0.05 for the knives and material respectively. Heat transfer is considered constant, from 20 to 25 °C, and is not significant during the edge trimming process, i.e., it is considered an isothermal process since the maximum real temperature does not surpass 100 °C. Furthermore, the sheet hardness is considered constant. The cutting speed throughout the process can vary in a significant fashion, with speeds as high as 91.66 mm/s or as low as 2.77 mm/s at the beginning of the process. The speed that is taken into account for the model is the average speed, which is 41.67 mm/s. The sheet thickness varies from 1.9 to 2.6 mm for the low carbon steels, and to 4.86 mm for the very low carbon steels. The FEM discreteness is always the same. The mechanical property values used in the simulation are directly obtained from the tests. A negligible sheet speed and a constraint in the X movement for the opposite edge of the edge trimming operation as well as another constraint in the Y movement from the same edge until 20 mm are taken into account. Also, the knives' dimensions are represented only at the width of 39.1 mm and at the tip; due to the height of 419 mm, it is not important for the purposes of this study.

3.3. Mathematical modeling

Our hypothesis describes how a correct edge trimming process consumes only the minimum energy necessary. Thus, the shear stresses obtained during the computational simulation and managed by the software post-processor are all plotted as a function of the penetration of each steel; in that plot every stage of the edge trimming process is identified: *rollover-plastic strain*, *penetration-nick* and *fracture-break*. Then, the energy is calculated through the area under the plot, for different horizontal clearances between knives of different steels; this numeric integration is carried out with the Simpson method for each function and interval. Once the process energy from every kind of steel is obtained, then its value is plotted against the knives' horizontal clearance. The function in this graph is identified with the simplest possible function, such as a 2nd grade polynomial function, and that faithfully represents the plot behavior. This procedure is applied to each kind of steel. Then, in order to identify the minimal energy value and the knives' horizontal clearance for that energy value, it is necessary to obtain the function derivative and make it equal to zero. The last step to attain the mathematical model is to correlate the optimal horizontal clearances between knives for each tensile strength to different thicknesses or correlate the optimal horizontal clearances between knives for each carbon content to different thicknesses. This gives a mathematical function from the knives' horizontal clearance in terms of the sheet strength and thickness and a mathematical function from the knives' horizontal clearance in terms of the sheet carbon content and thickness. A confidence analysis indicates which model can be more reliable.