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Optimization Models of Tool Path Problem for CNC Sheet Metal Cutting Machines

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Abstract: The problem of tool path optimization for CNC sheet metal cutting equipment is considered. Sheet metal cutting equipment includes laser/plasma/gas/water-jet machines and some others. Users of CAD/CAM systems develop numerical control programs for the cutting equipment after nesting of parts onto the sheet. The control programs contain information about tool path. The tool path is a routing of cutter head used for cutting of sheet material. Classification and the correspondent mathematical models of tool path problem are considered. The tasks of cost/time minimization for various types of cutting techniques are formalized. Mathematical formalization of technological constraints for these tasks is also described. Unlike the known analogs this formalization allows to consider constraints of thermal cutting. In some cases the optimization tasks can be interpreted as discrete optimization problem (generalized travel salesman problem with additional constraints, GTSP). In paper also the developed exact algorithm and some heuristic algorithms of tool path optimization based on described models is reported. Results of computing experiments for some instances are given

Keywords: Tool path problem, CNC sheet metal cutting machines, control programs, technological constraints, thermal cutting, discrete optimization, GTSP

1. INTRODUCTION

In various industries many parts are produced from sheet materials by CNC equipment. Such kind of equipment includes, for instance, machines for laser, plasma, gas, and water-jet cutting. Special software (Computer-Aided Manufacturing, CAM systems) provides an automation of development of NC (numerical control) programs. Generating of NC programs is next step after nesting that is positioning parts onto sheet material. Optimization of sheet utilization reduces the cost of sheet material used for parts producing. The nesting problem was not considered in this study. The control programs contain information about tool path for CNC machine and some technological commands. Optimization of tool path reduces time and cost of cutting process. First classification of problem was conducted by Hoeft and Palekar (1997). Tool path problems are usually divided into 4 classes depending on cutting technique and its parameters (see, for Example, Dewil et al. (2015)):

1. *Continuous Cutting Problem (CCP).*
2. *Endpoint Cutting Problem (ECP).*
3. *Intermittent Cutting Problem (ICP).*
4. *Generalized Traveling Salesman Problem (GTSP).*

Petunin (2015) offered new classification of cutting techniques and described one more class of problem: *Segment Continuous Cutting Problem (SCCP).*

The tool path includes the following components (see Fig.1, Fig.2):

- pierce points (piercings);
- points of switching the tool off;
- tool trajectory from piercing upto point of switching the tool off;
- lead-in (tool trajectory from piercing upto the entry point on the equidistant contours);
- lead-out (tool trajectory from exit point on equidistant contour upto tool switching off point);
- Airtime motions (linear movement from tool switching off point upto the next piercing).

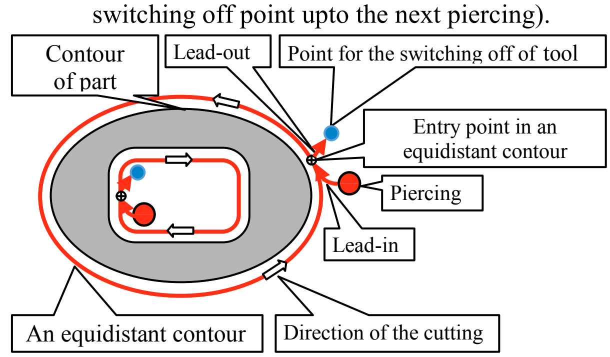

Figure 1. Scheme of the standard cutting technique

Fig. 2 shows an example of non-standard cutting techniques. In practice CAM systems users often use the various cutting technique interactively to get technologically admissible solutions. Trajectories of lead-in to the contour and lead-out (exit of contour) also can be different (along the straight line, along the arc, "in corner"

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and etc.). Decrease of the sheet material deformation is provided in particular by lead-in "in corner" of part (Fig.3).

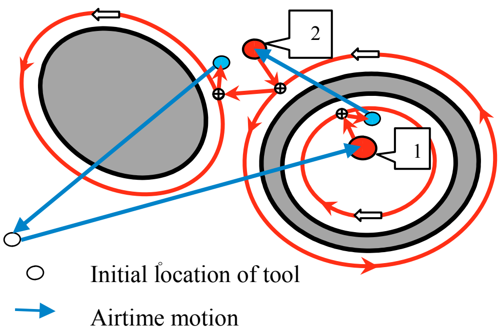

Figure 2. Example of cutting for two parts (three contours) by using technique "chain cutting"

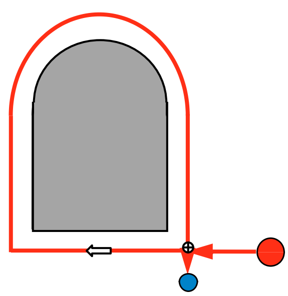

Figure 3. Example of lead-in "in corner"

Automatic methods are developed generally to discrete models (GTSP and ECP). Some heuristic algorithms are offered by Lee and Kwon (2006), Verhoturov and Tarasenko (2008), Xie and al. (2009), Yang et al. (2010), Dewil et al. (2011, 2015, 2015a), Jing and Zhige (2013), Helsgaun (2014). For GTSP class without technological constraints the effective approximate algorithms offered by Karapetyan and Gutin (2011, 2012) also can be used. For the same class of problems with precedence constraints Petunin and al. (2014, 2015a) described an exact algorithm based on method of dynamic programming.

The existing mathematical models and algorithms do not consider many technological constraints of the thermal cutting process in particular heuristic rules "part hardness rule" and "sheet metal hardness rule". The latter was described by Petunin (2009). In this paper we formalize this kind of constraints and describe a new formalization of the tool path problem concerning cutting technique we used. In certain cases we will interpret the considered optimizing tasks as problems of discrete optimization with additional constraints. In paper the results of computing experiments for some instances are also given

2. CLASSIFICATION OF THE CUTTING TECHNIQUES AND FORMAL DEFINITION OF TOOL PATH

Definition 1. Segment of cutting $S = MM^*B^S$ is a tool trajectory from piercing M upto point of switching the tool off M^*. $(S \subset \mathbb{R}^2; M = (x, y), M^* = (x^*, y^*) \in \mathbb{R}^2)$.

Definition 2. Basic segment B^S is a part of segment $S = MM^*$ without trajectory lead-in and trajectory lead-out.

Let's consider that unlike a cutting segment the corresponding basic segment has no direction of cutting, i.e. it contains only geometry information. In Fig. 4 (see also Fig.2) two basic segments are allocated with dashed lines of orange and yellow color.

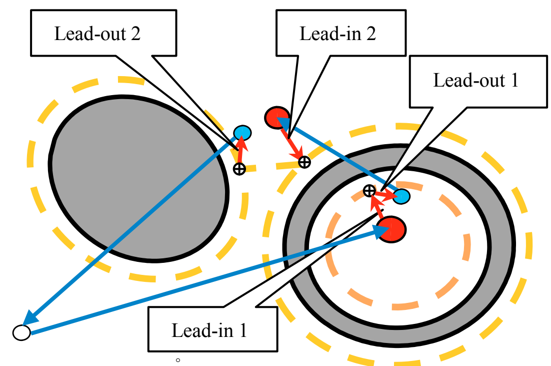

Figure 4. Illustration of term "basic segment" for example given in Fig.2

All the cutting techniques we divide into three classes:

1. Standard cutting.
2. Multi-contour cutting.
3. Multi-segment cutting.

Standard cutting technique assumes:

- Piercings number is equal to contours number and parts number;
- Cutter head runs each closed equidistant contour of part to cut exactly once from beginning to end.

At the same time the basic segment coincides with this closed contour.

The multi-contour cutting cuts several contours in one segment of cutting. External contours of parts are cut jointly with the only piercing without switching cutter head off.

The multi-contour cutting can be itself divided into 2 classes: "chain" cutting (see Fig.2), and multi-section cutting. The latter assumes that some contours can be cut piecemeal. Example of Multi-section cutting is in Fig.5.

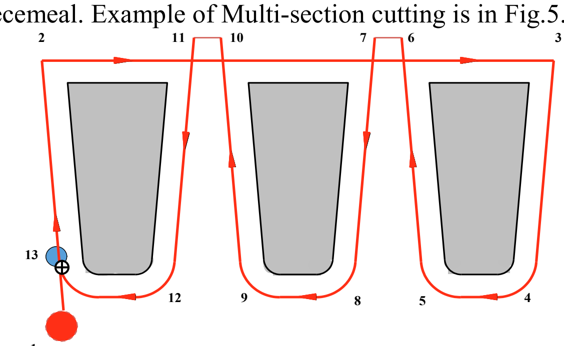

Figure 5. Multi-section cutting: "Snake" technique