

## Simulating Thermal Sheet Cutting of Figured Parts

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**Abstract:** This paper considers the problem of modelling the thermal cutting process of sheet material, which occurs when cutting using equipment, such as laser, gas, etc. The aim of the study is to solve the problem of optimizing the toolpath while considering the thermal effects that occur in the material being cut. A problem statement is given in this paper. An approach to modelling the change in temperature of the material during cutting is proposed, based on a discrete representation of information. The results of the computational experiment are also given.

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**Keywords:** Tool path problem, CNC sheet cutting machines, Thermal deformations, Constraints, TSP, Discrete representation.

### 1. INTRODUCTION

One of the important and promising areas of modelling is the objects and processes of the industrial production of a particular product. The process of creating any product begins with the manufacture of its elementary structural components – parts. Parts represent the bulk of objects in any industrial plant. In the production cycle of creating products, the manufacturing stage is one of the most time-consuming and complex. In addition, many enterprises are currently operating in single and small-scale production. Due to the large range of parts in the manufacture of blanks, problems arise in organizing the technological design of cutting and the procurement operations, see Wäscher et al. (2007).

In the process of cutting sheet materials into figured blanks, one of the most important stages is the construction of the path of the cutting tool. For the manufacture of blanks and parts from sheet materials, figured cutting machines with numerical control (CNC) are used. Laser cutting has gained popularity, which uses a focused laser beam that heats the surface at a specified point to the evaporation temperature of the material, Dewil et al. (2016). By moving the laser beam along a given route, the desired shape is cut out of the material. Optimization of the path of the cutting tool can reduce the cost of cutting and improve the quality of the resulting parts, see Yang et al. (2010); Tavaeva et al. (2019a,b).

Typically, path optimization comes down to minimizing tool-free travel and reducing plunge points. However, when forming such a route, compliance with the temperature regime of the material is not considered. Depending on the order of cutting out the figures, the temperature of the material being cut can vary greatly in different local areas, cause overheating of the material with its subsequent deformation and lead to a deterioration in the quality of the resulting parts, see Petunin (2019); Petunin et al. (2016); Chentsov et al. (2018), Sonawane et al. (2020).

In this regard, it becomes necessary to consider the thermal factor, which makes it possible to improve the quality of the

obtained workpieces in comparison with the usual minimization of the idle path. To do this, two approaches are currently used: 1) formalization of heuristic rules developed by experienced technologists for interactive tool routing and 2) application of CAE systems to simulate temperature fields in the material that occur during thermal cutting. The first approach includes the “part stiffness” rule, which limits the choice of permissible pierce points for the next part to cut, and the “sheet stiffness” rule, which, in turn, imposes restrictions on the selection of the next part to be cut when forming the route, see Petunin and Stylios (2016), Petunin and Chentsov (2020). The second approach is implemented, for example, in the works of Mejia et al. (2018); Petunin et al. (2019); Verkhoturov et al. (2021).

Of other works that consider thermal material deformations, which occur to some extent when modelling the cutting route, we note Lagerkvist et al. (2013); Hajad et al. (2019); Balamurali et al. (2019). In Mejia et al. (2018) more accurate and faster thermal estimation methods have been developed. Although this direction of research is encouraging, a more detailed study of the relationship between material temperature and acceptable route options is required. It is important to note that Dewil et al. (2015), Petunin et al. (2019) and Levichev et al. (2020) show the practical possibility of applying the heuristic approaches of the GTSP/megacities theoretical model to the problem of modelling the tool path for the thermal cutting machine, while simultaneously considering the temperature of the material. At the same time, the given calculation results in all works, which consider the thermal aspects of the tool routing of a CNC thermal cutting machine, do not yet look very convincing so far as real-time and cost optimization of the cutting process is concerned. The main reason for this is that the proposed methods for reducing the problems associated with the thermal deformation of metal, during cutting, are mainly of a qualitative nature. It can be firmly asserted that, to date, no exact numerical data have been obtained on the magnitude of geometric distortions of parts, when choosing one or another cutting route, depending on the degree of implementation of the heuristic rules of “rigidity”,

or depending on the distribution of temperature fields during thermal cutting. The value of thermal deformations is also significantly affected by the brand, the thickness of the material, and the features of the equipment. Research in this area, in fact, has not yet been carried out. Therefore, the mathematical formalization of dynamic constraints in instrument routing problems causes obvious difficulties.

On the other hand, if we talk about modelling as close to reality as possible, then “synchronization” with the cutting process under consideration is necessary, and, first, with the real temperature of a certain part of a particular material being cut. Below we will consider this approach when solving the problem of tool routing for the case of fixed pierce points for each boundary contour of the part to be cut. This problem is equivalent to the TSP (traveling salesman problem) with additional restrictions.

## 2. PROBLEM STATEMENT

Let:

$L(axb)$  – rectangular area to be cut (see Figs. 1-2).

$\{S_i\}$  – parts to cut, where  $i = 1 \div n$  – part number.

$\{C_{ij}\}$  – parts’ contours, where  $i$  – part number,

$j$  is the number of the part  $S_i$  contour,  $j = 1 \div m_i$  ( $m_i \geq 1$  is the number of external and internal contours of the part  $S_i$ );

$\{P_{ij}\}$  – pierce points onto contours, where  $i$  is the number of the part,  $j$  is the number of the contour of the part  $S_i$ .

$P_{start}$  – the initial position of the cutting tool.

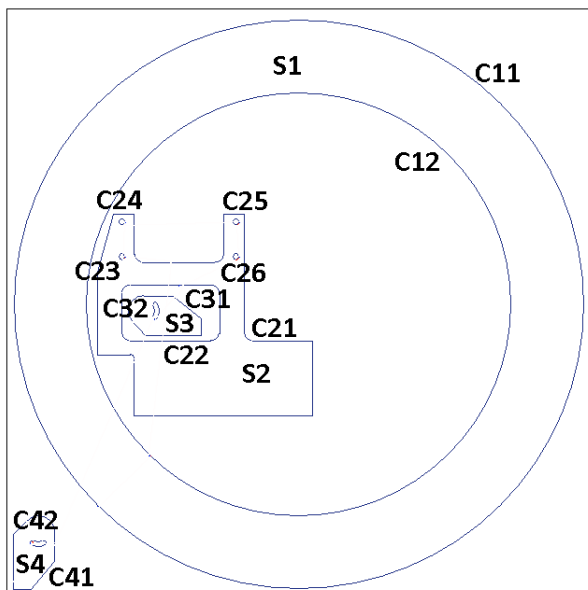


Figure 1. Nesting plan (parts  $S_i$  & their contours  $C_{ij}$ )

Find:

Such  $R^*$  that

$$T(Tr(R^*), L) \leq t_{max}, \text{ where:}$$

$R = (P_{start}, \dots, P_{ij}, \dots, P_{start})$  is a sequence of contour inset points, where  $i = 1 \div n, j = 1 \div m_i$ ;

$Tr(R)$  is the path of the cutting tool when moving along the sequence of points  $R$ .

$T(Tr(\cdot), L)$  is a function that determines the maximum temperature of the point  $(x, y)$  ( $0 \leq x \leq a, 0 \leq y \leq b$ ) of the sheet  $L$  being cut during cutting along the path  $Tr(\cdot)$ .

It should be noted that the problem may not have a solution for certain values of  $t_{max}$  less than a certain value  $t_{MAX}$ , because when cutting, the metal is heated to its melting temperature and this temperature spreads over the entire area of the sheet.

Accordingly, when the cutting tool moves at a given speed over all parts, a situation may arise in which there will be no areas of the sheet with a temperature less than  $(t_{max} - \text{delta})$ . Therefore, if you start cutting a part located in such a zone, the temperature will rise more than the value of  $t_{max}$ .

In practice, this problem can be solved only by suspending the cutting process for some time until certain areas of the sheet are cooled to an acceptable temperature. However, in practice, this approach is not applied.

In this context, it is worth talking about minimizing the number of instances of overheating, and not avoiding exceeding the value of  $t_{max}$ , which is further described in the paper.

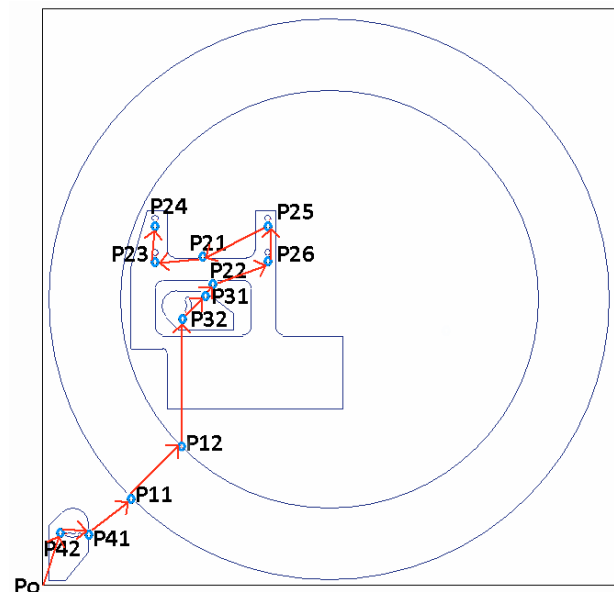


Figure 2. Nesting plan  
(toolpath through pierce points  $P_{ij}$  into contours  $C_{ij}$ ;  
 $P_0$  – starting point)

Such an approach, when constructing the path of the cutting tool, which does not consider the nesting of the internal contours of parts in its external contours, as well as the possibility of placing parts in the internal contours of other ones, can lead to the following problems:

1. Parts/contours that are not connected with the sheet after cutting can be displaced/deformed due to thermal effects and the presence of internal stresses that have been present in the sheet since manufacturing, respectively;

parts/contours that are inside the cut contours/parts, in this case, will be cut out also with an offset, i.e., incorrect.

- Overheating of this part/contour and contours/parts inside it is possible in the process of the subsequent cutting of contours/parts located inside the one under consideration, again since there is no connection with the “basic” material, which would be a heat sink.

When solving the problem under consideration, it is necessary to consider **additional constraints** on the “connectivity” of parts/contours located inside other contours/parts with the “main” part of the sheet (uncut contours/parts should not remain inside the cut blanks/contours).

Let  $Q_{ij}$  be the serial number of cutting the contour  $C_{ij}$ , ( $Q_{ij} > 0$ ,  $Q_{ij} \in Z$ ).

When passing from the contour  $C_{ij}$  to the contour  $C_{kl}$ :  $Q_{kl} - Q_{ij} = 1$ .

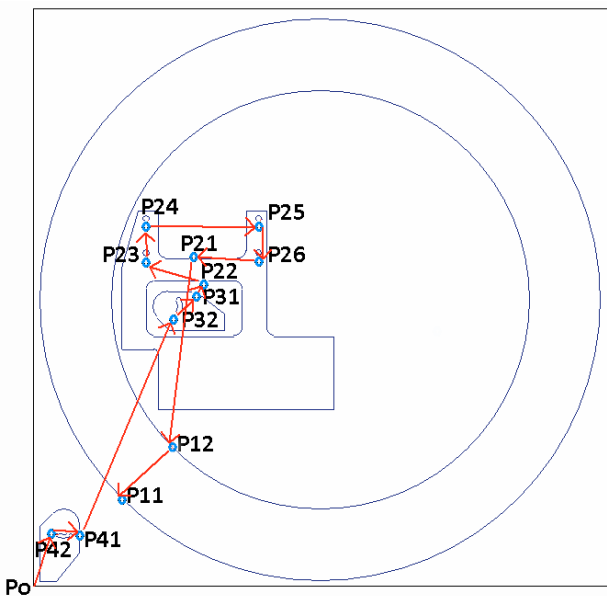


Figure 3. Nesting plan and tool path through pierce points, considering connectivity constraints

**Restriction of the “internal – external” connectivity:** When constructing the path of the cutting tool, you must first cut out all the internal contours of the part, and then process its external contour:

$$\forall C_{kj}, C_{k1} : Q_{k1} - Q_{kj} = 1, j > 1$$

The following condition must be met:

$$\forall C_{kb} : b > 1 \exists Q_{kb} : Q_{kb} \leq Q_{kj}, 0 < Q_{k1} - Q_{kb} < m_k$$

**Restriction of connection “external – internal”:** Let  $IN_{C_{il}} = D_k$  be the set of all parts located inside the inner contour  $C_{il}$  of the part  $S_i$  at the first nesting level. Before you start cutting the contour  $C_{il}$ , you need to cut out all the parts that are in the set  $IN_{C_{il}}$

$$\forall C_{k1} : D_k \in IN_{C_{il}}, l \in (1; m_i] \exists Q_{k1} : Q_{k1} < \min\{Q_{il}\}_{l=2}^{m_i}$$

An example of the path of the toolpath for the nesting plan above, considering “connectivity” restrictions, is shown in Fig. 3.

### 3. SOLUTION APPROACH

In this formulation, the problem is reduced to one of the most well-known discrete optimization problems – the travelling salesman problem (TSP; see Gutin and Punnen (2006)) and belongs to the class of NP-hard problems. The main problem in its solution lies in the difficulty of determining the temperature of any point of the sheet in the process of cutting it along a particular path. It is not possible to solve this problem analytically.

In this regard, an approach was developed based on the discrete representation of information, which was tested and gave good results in solving problems of two-dimensional and three-dimensional placement of objects of complex geometric shapes, see Verkhoturov et al. (2016).

The main idea of this approach is the “direct” modelling of parts placed on a sheet in computer memory, carried out based on the discrete-logical structure of random-access memory. In our case, this is a representation of memory in the form of an n-dimensional matrix, each element of which is such a section of it that corresponds to the concept of a point of the allocation area. In the simplest case, the matrix of points is two-dimensional (n=2), and for more accurate modelling of sheet heating and temperature propagation over it, a three-dimensional matrix (n=3) can be used, and the size of the third coordinate Z depends on the thickness of the material.

Let us consider the two-dimensional case.

In the process of modelling, it is necessary to solve two main tasks:

- Simulate the heating of the points of the cutting area during cutting (for example, by a laser beam).
- Simulate the spread of temperature over the sheet, considering the thermal conductivity of the sheet material from points located on the cutting path of parts to cut, as well as heat transfer to the environment. At this stage, it is also necessary to provide that, after cutting the material, the corresponding areas/points of the sheet are melted and filled, in general, with air, which has a different, usually much lower, thermal conductivity than the material being cut (metal, for instance).

Let us consider each stage in more detail.

#### Heating of the cutting area during cutting

When the cutting tool moves along the path  $Tr(\cdot)$ , those points of the cutting area (sheet L), through which it passes during piercing and actual cutting of the contour  $C_{ij}$ , are heated to the melting temperature of the corresponding material.

#### Temperature spread

The following principle of temperature distribution in discrete space is proposed (Fig. 4):

1) For each area of 9 points (with 8-connectivity), point P with the highest temperature is selected (Fig. 4a).

2) Then the new temperature of the selected point P is calculated depending on:

T is the point temperature.

$\Delta T$  is the amount of heat transferred to each neighbouring point.

Count – the number of neighbouring points.

Kconductivity – coefficient of heat distribution ( $0 \leq K_{\text{conductivity}} \leq 1$ ).

Kloss – coefficient of heat transfer to the environment ( $0 \leq K_{\text{loss}} \leq 1$ );

$\Delta T = P.T * K_{\text{conductivity}}$

$P.T = (P.T - \Delta T * \text{count}) * K_{\text{loss}}$ .

3) For each of the neighbouring points S (Fig. 4b). the temperature is calculated considering the increment  $\Delta T$  depending on the coefficient of thermal conductivity Kconductivity and heat loss to the external environment Kloss (Fig. 4c):

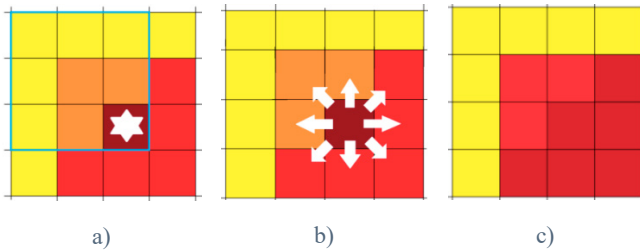


Figure 4. 2D model of heat distribution

Following is the pseudocode of the algorithm to implement “Additional Constraints”.

```

def Main
begin
  Generate_set_of_cutting_contours_W()
  while  $W \neq \emptyset$ 
    Select_contour_from_W_to_cut()
    Cut_selected_path_and_update_set_W()
  end while
end
def Generate_set_of_cutting_contours_W()
begin
   $W = \emptyset$ 
  for  $i := 1$  to  $n$ 
    for  $j := 1$  to  $m_i$ 

```

```

      if  $j = 1$  then
        if  $IND_i \setminus C_{ij} = \emptyset$  then  $W = W \cup C_{ij}$ 
      else
        if  $INC_{ij} = \emptyset$  then  $W = W \cup C_{ij}$ 
      end if
    end for
  end for
end
def Cut_selected_path_and_update_set_W
begin
   $W = W \setminus C_{kz}$ 
   $IND_k = IND_k \setminus C_{kz}$ 
  if  $z = 1$  then
     $INC_{0l} = INC_{0l} \setminus D_k$ 
    for  $i := 1$  to  $n$ 
      if  $D_i \in INC_{0l}$  then
        for  $j := 2$  to  $m_i$ 
          if  $C_{ij} \in IND_i$  then  $D_k \in INC_{ij}$ 
          begin
             $INC_{ij} = INC_{ij} \setminus D_k$ 
            if  $INC_{ij} = \emptyset$  then  $W = W \cup C_{ij}$ 
          end
          end for
        end if
      end for
    end
  end if
end

```

#### 4. COMPUTATIONAL EXPERIMENT

To test the developed methods and algorithms, a computational experiment was carried out based on an example from Verkhoturov (2007).

The number of local overheating in the material was chosen as an indicator in modelling the cutting process, considering thermal effects.

Four algorithms were compared: “Shortest path”, “Minimization of overheating”, “Random transitions” and

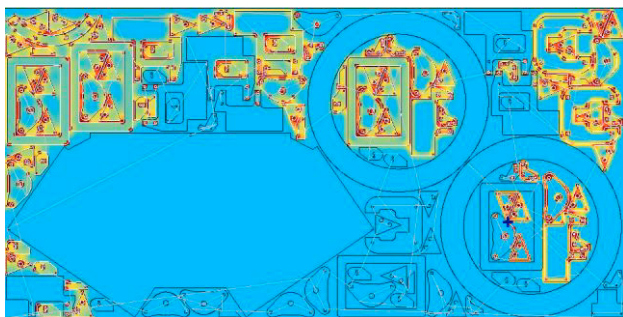
“Minimization of the path and overheating considering real-time temperature”, developed in this work, and based on real-time temperature estimations.

The results of the experiments are presented in Table 1.

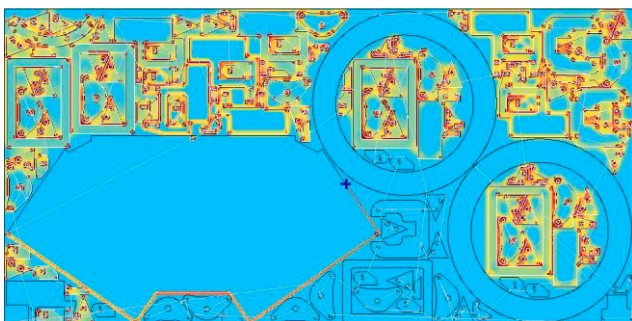
Figure 5 shows an example of a cutting considering “Additional restrictions”. The red colour shows areas with increased temperature or in the process of cutting or “local overheating”, in the process of cooling down with decreasing temperature, the corresponding areas are shown in yellow.

Table 1. Experimental results

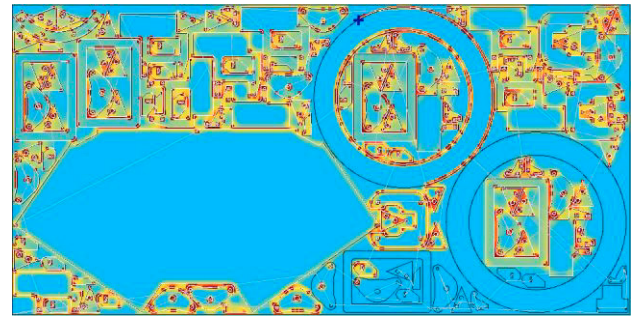
Algorithm	Air move, cm	Overheating count
Shortest path	2788	518
Overheating minimization	33787	460
Random transitions	45952	451
Minimize travel and overheating with real-time temperature	11176	456



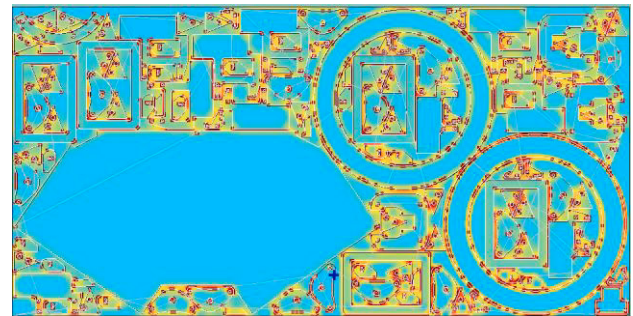
a)



b)



c)



d)

Figure 5. Nesting plan, tool path considering the “Additional restrictions” and the change in the sheet temperature during the cutting process (a – d)

## 5. CONCLUSIONS

The paper considered an approach to solving the problem of modelling the process of thermal cutting of flat material, considering thermal effects, based on a discrete representation of information, including a mathematical model, methods, algorithms, and software. According to the results of the experiment, the algorithm developed by the authors showed a 26% higher efficiency than the “Shortest Path” algorithm. The length of the idling path, when using the developed algorithm, increased by 2.4 times more compared to the “Shortest Path” algorithm.

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