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Application of FEM and Vision-Based Methods to Analysis of Shearing Processes in the Aspect of Scrap Reduction

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1. Introduction

Metal cutting plays a very important role in mechanical manufacturing area, the nature of this process being concerned with many related subjects of technology and industry. Modern manufacturing cutting techniques are rife with problems related to ensuring the quality of manufactured products while minimising the cost of production and increasing process efficiency. In the 21stcentury, the production of new products must be subject to "*eco-design production*," which involves limiting negative impacts on the surrounding natural environment. The dominant components of this activity include the rational use of energy and environmental protection [4–8]. In this regard, it is important to correctly design and realise technological processes. In cutting process mechanism of material separation is often very hard to accomplish in the production cycle due to the difficulties encountered in precision process parameter settings [1–3]. As a result, such defects can appear after processing in workpiece (e.g., deformation, twisting, bowing, and defects of the sheared edge such as burrs and slivers). The accumulation of burrs and slivers on the knife, die and the work piece's sheared edge can result in an unacceptable surface finish and increases scrap (Fig. 1).

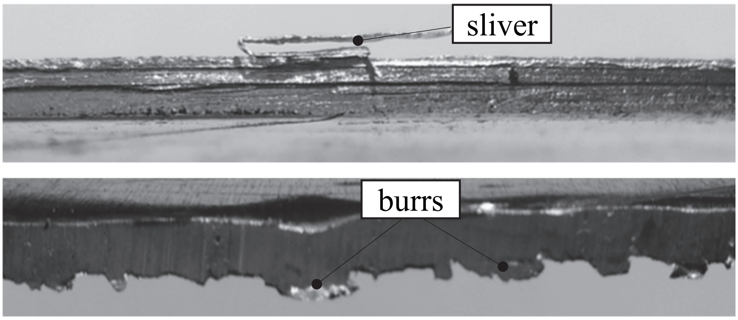

Fig. 1. A typical defects of the workpiece's sheared edge
Rys. 1. Typowe defekty napotykane na powierzchni przecięcia wyrobu

Finite element analysis (FEA) is a powerful and economical method that has been used widely for engineering design purpose [12–21, 23]. Whilst significant progress has been made in enhanced understanding of ductile fracture mechanisms in shearing process and developing advanced computational capabilities for detailed process simulation, application of FEM and vision-based methods is challenging [10, 11, 22]. A main difficulty in modelling of shearing process is that only a limited number of FEM models are currently capable of describing the complete shearing process, including the complete separation of the material parts through ductile fracturing. In experimental analysis a main problem is large and irregular deformations in tool - workpiece contact zone which is difficult to analysis [31]. For a long period of time, the method used for the analysis of displacements in contact zone was that of visioplasticity. Vision-based methods are ideally suited to the task of non-contact/non-intrusive deformation and strain measurement in cutting process. Using this methods an analysis of state of material displacements and deformation at any moment of process can be possible.

The present paper presents an application of FEM and vision-based methods to analysis of cutting process in the aspect of scrap reduction. The proposed methodology enabling the realization of measurements and calculations in a quick and precise manner for the shearing processes. This allows the analysis of the cutting process at any time during the process. This makes it possible to observe the formation of surface defects and then develop recommendations for their minimization.

2. Finite Element modeling

The description of the nonlinearity of the material was conducted using an incremental model that takes into account the influence of the history of strains and strain rate. The object (the metal sheet that is being cut) is treated as a body in which elastic strains may occur (in the scope of reversible strains) together with viscous and plastic strains (in the scope of irreversible strains) with nonlinear strengthening. For the purpose of constructing the material model, the following was used: Huber-Mises-Hencky's nonlinear plasticity condition, the associated flow law and combined strengthening (i.e., isotropic and kinematic). The state of the material after the aforementioned processing was taken into account by introducing the following initial states: displacement, stresses, strains and their rate. The states of strains and strain rate were described with nonlinear dependences and no linearization. In this description, adequate measures were used for an increment of strains and for an increment of stresses (i.e., an increment of Green-Lagrange strain tensor and an increment of the second symmetric stress tensor of Pioli-Kirchhoff). The incremental contact model covered the contact forces, the contact rigidity, the contact boundary conditions and the friction coefficients in this area. The mathematical model was supplemented with incremental equations of the object's motion and the uniqueness conditions. An incremental function of the total energy of the system was introduced. From the stationary condition of this function, it is possible to derive a variational nonlinear equation to describe the motion and deformation of the object for a typical incremental step. This equation was untangled with spatial discretization using the finite element method, which resulted in discrete systems of equations for the motion and deformation of the object in the guillotining process.

2.1. Basic relationships

Components of the Green-Lagrange's strain tensor increment, for a typical time step Δt, for the non-linear isotropic material with mixed hardening, were calculated from the formula [2, 24, 25]:

$$\Delta\varepsilon_{ij} = \frac{1}{1-\widetilde{S}^{**}} \cdot \left(D_{ijkl}^{(E)} \cdot \Delta\sigma_{kl} - \frac{\frac{2}{3}\cdot[\sigma_Y(\cdot)]\cdot \dot{E}_T \cdot \Delta\dot{\varepsilon}_e \cdot \widetilde{S}_{ij}}{\widetilde{S}_{ij}\cdot C_{ijkl}^{(E)} \cdot \widetilde{S}_{kl} + \frac{2}{3}\cdot\sigma_Y^2(\cdot)\cdot\left(\widetilde{C}(\cdot)+\frac{2}{3}\cdot E_T\right)} \right) \tag{1}$$

Components of the Pioli-Kirchhoff's stress tensor increment, for a typical time step Δt, for the non-linear material with mixed hardening, were calculated using the formula:

$$\Delta\sigma_{ij} = C_{ijkl}^{(E)} \cdot \left(\Delta\varepsilon_{kl} - \psi \frac{\widetilde{S}_{kl}\cdot\left\{\widetilde{S}_{ij}\cdot C_{ijkl}^{(E)}\cdot\Delta\varepsilon_{kl} - \frac{2}{3}\cdot\sigma_Y(\cdot)\cdot\dot{E}_T^{(VP)}\cdot\Delta\dot{\varepsilon}_z^{(VP)}\right\}}{\widetilde{S}_{ij}\cdot C_{ijkl}^{(E)}\cdot\widetilde{S}_{kl} + \frac{2}{3}\cdot\sigma_Y^2(\cdot)\cdot\left(\widetilde{C}(\cdot)+\frac{2}{3}\cdot E_T\right)} \right) \tag{2}$$

Where ψ is the load factor and is $\psi = 1$ for loading and $\psi = 0$ for unloading processes, $\widetilde{S}^{**} = \widetilde{S}_{ij}^{*}\cdot C_{ijmn}^{(E)}\cdot\widetilde{S}_{mn}$ is a positive scalar variable, $\widetilde{S}_{ij} = S_{ij} - \alpha_{ij}$ $(i, j = 1 \div 3)$ are the stress deviator component, $\widetilde{\mathbf{D}}_\sigma$ and $D_{ijkl}^{(E)}$ are the components for the tensor $\mathbf{D}^{(E)} = \mathbf{C}^{(E)^{-1}}$ in time t, $C_{ijkl}^{(E)}$ are the elastic constitutive tensor components $\mathbf{C}^{(E)}$, $\widetilde{C}(\cdot) = \widetilde{C}(\varepsilon_e^{(VP)}, \dot{\varepsilon}_e^{(VP)})$ is the temporary translation hardening parameter in time t. $\sigma_Y(\cdot) = \sigma_Y(\varepsilon_e^{(VP)}, \dot{\varepsilon}_e^{(VP)})$ is the accumulated material yield stress, which depends on the history of the viscoplastic strain and strain rate, $\varepsilon_e^{(VP)}$ and $\dot{\varepsilon}_e^{(VP)}$ are the cumulative effective viscoplastic strain and strain rate, respectively, E_T - is the strain hardening modulus at time t, $\dot{E}_T$ - is the strain rate hardening modulus at time t [26, 27]. The instantaneous value of the yield stress σ_Y can be calculated from patterns present in the ANSYS program database, such as the Johnson-Cook material law [28] or Cowper–Symonds model [2].

2.2. Application to the shearing processes

A numerical example is shown for guillotining and shear-slitting processes. A three-dimensional finite element models were constructed using explicit finite element software package ANSYS/LS-DYNA.

During the first part of the guillotining process, the upper and lower knives indent the sheet, pulling down some surface material. This causes the sheet to bend over the cutting tools, creating the rollover of material. After some knives movement, shear deformation will take over from the indentation, forming the sheared edge of the product. This is generally a smooth surface, which shows some wear due to the contact with the cutting tools. At some point in the shearing phase, ductile material failure will occur in the vicinity of the cutting edge of the tools. This fracture propagates through the sheet in the direction of the opposite cutting tool, forming the fractured zone of the product. In guillotining process is important to obtain products without twisting and bowing (Fig. 2). These defects give rise to waste after cutting. Analysis of the degree of deformation of the sheet during cutting is possible by measuring the displacements of the various areas of the sheet. Then it is possible to investigate the cause of the formation of twisting and bowing defects. Fig. 2 shows the contours of the equivalent stresses during guillotining. The greatest stresses occur in the cutting zone adjacent the cutting edges of tools.

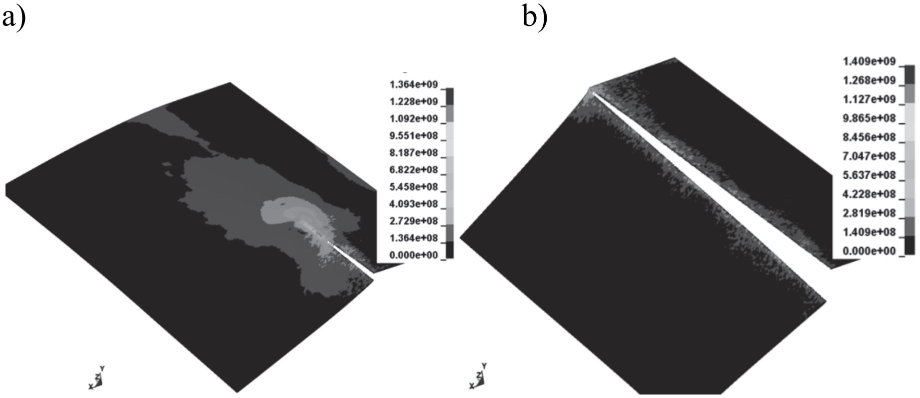

Fig. 2. Contours of the equivalent stress during guillotining of DC01 steel:
a) 30% step time, b) 100% step time

Rys. 2. Rozkład naprężeń zastępczych podczas cięcia na gilotynie stali DC01:
a) 30% zaawansowania procesu, b) 100% zaawansowania procesu

In shearing process in many cases a scrap formation is a result of fracture process because less steady and progresses in a nonuniform manner. A dramatic transition of the fracture mode from the “shear mode” to the “shear and tear mode” on cut surface can be observed

(Fig. 3). This result suggests that shearing under specific conditions is a three-dimensional rather than two-dimensional problem. The fracture process is unsteady and progressed in a nonuniform manner because of the stress and strain states created by the macroscopic cutting conditions.

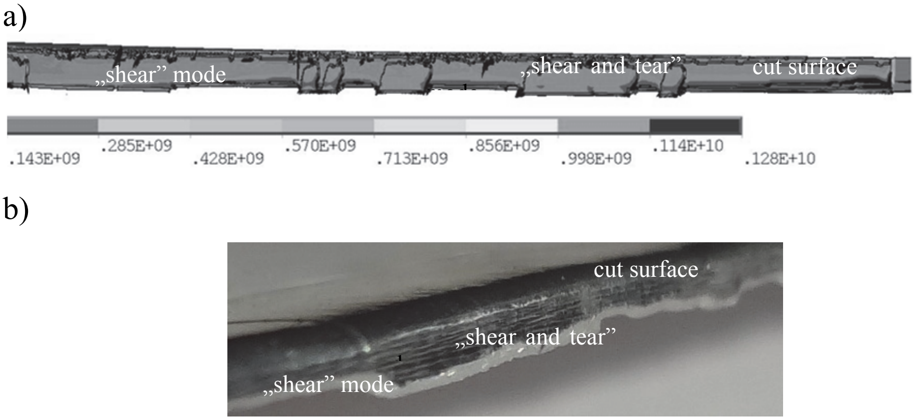

Fig. 3. Transition of the material fracture mode from the "shear" to the "shear and tear" mode during guillotining of aluminium alloy AA6111-T4:
a) simulation, b) experiment

Rys. 3. Zmiana charakteru pękania materiału podczas cięcia stopu aluminium AA6111-T4: a) symulacja, b) eksperyment

In slitting processes as the sheet slits, it moves tangentially to the blade. This causes the area of contact with the knive blade on the sheet to be inclined to the horizontal at an angle. The normal compressive stress is thus split into two components in the direction of the axes Z and Y contributing to the two normal stresses. The shear stress shows high values in the region where the sheet is expected to slit and the values drop down as the knives moves away from the region (Fig. 4). The high shear stress is caused by the shearing action of the two blades on either side of the sheet.

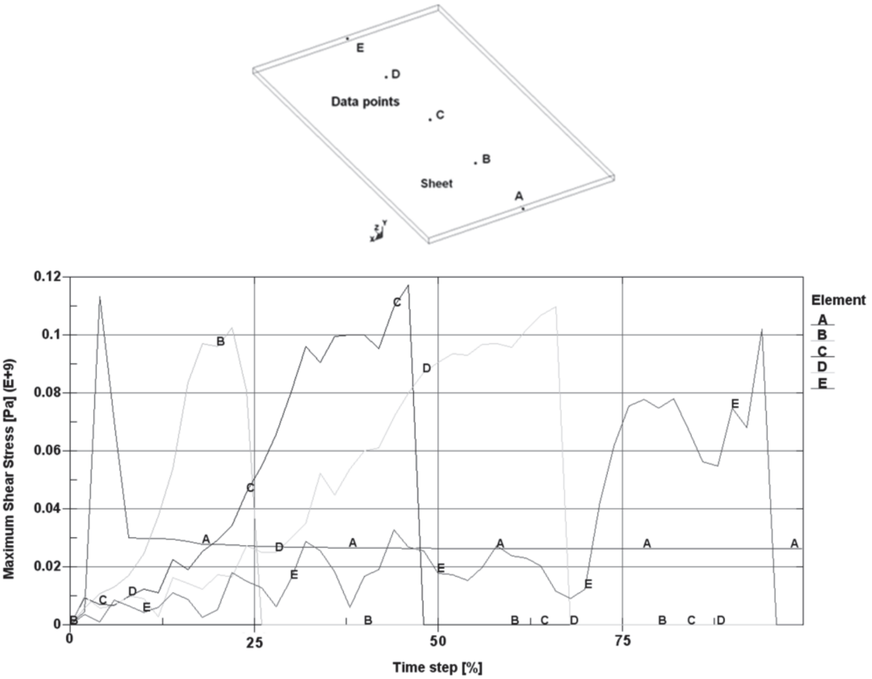

Fig. 4. Values of the maximum shear stresses measured in shearing region during slitting
Rys. 4. Wartości maksymalnych naprężeń ścinających mierzonych w strefie cięcia

The quality of the edge produced from the slitting of the sheet would depend upon the damage caused to the edge and the extent of the damage around the edge (Fig. 5). Measure the degree of damage can be done by the stress and strains analysis in the cut surface. Figs. 5 and 6 show the effective plastic strain distribution after process. The effective plastic strain is highest on the cut surface and decreases within the depth of the material and appear to stabilize at a depth of approximately 1.5 mm (Fig. 6). Obtained results can be used in analysis of size of degraded area.

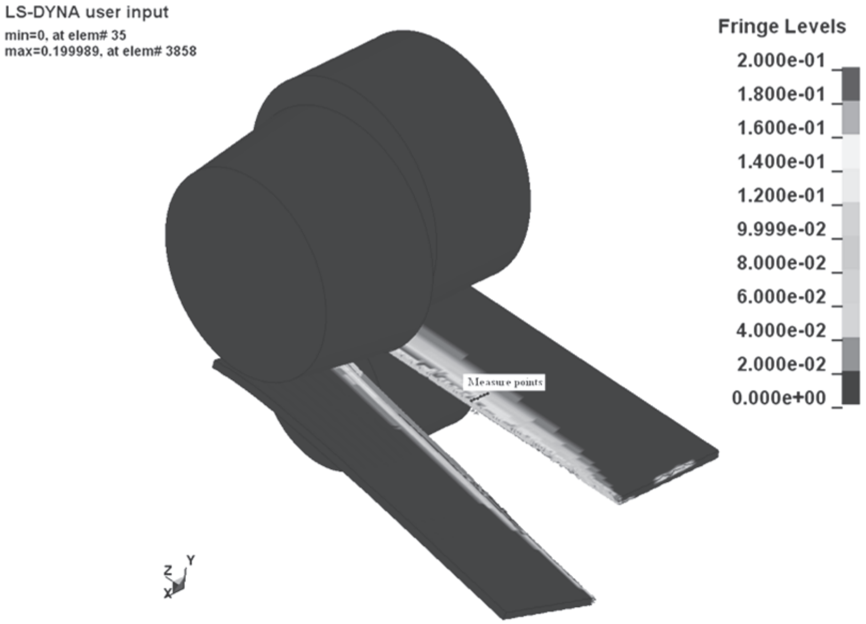

Fig. 5. The effective plastic strain distribution after process of slitting aluminum alloy AA6111-T4 (1.5 mm thick)
Rys. 5. Rozkład odkształceń zastępczych po procesie cięcia stopu aluminium AA6111-T4 o grubości 1,5 mm

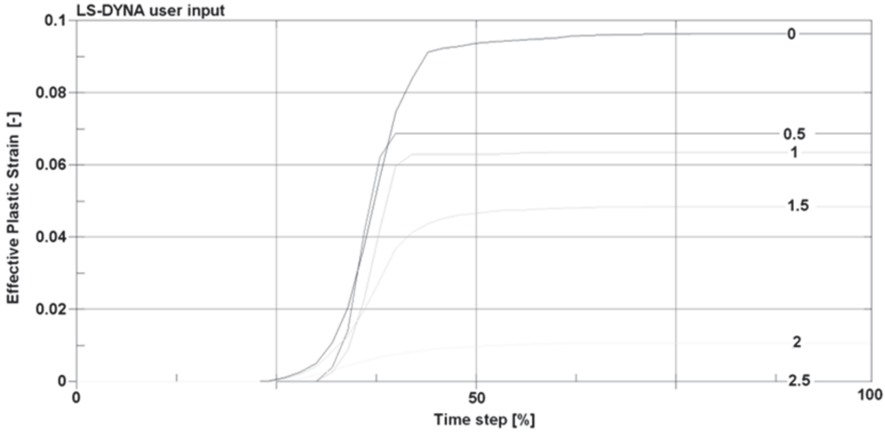

Fig. 6. Dependence of effective plastic strain on distance [mm] from the cut edge during slitting aluminum alloy AA6111-T4 (1.5 mm thick)
Fig. 6. Zależność odkształceń zastępczych od odległości [mm] od krawędzi cięcia stopu aluminium AA6111-T4 o grubości 1,5 mm

3. Vision-based measurement system

Full field displacement measurement methods have gained significant attention the last two decades, due to the great impact of the evolution of the digital imaging [9, 29, 30]. Modern digital cameras provide a cost-effective and highly reliable tool for recording and processing the images of an experiment with a personal computer. Image-based displacement and strain measurements are non-invasive. During the slitting process, a high-speed camera together with a computer controlled framegrabber can record a set of consecutive images of the sample surface (Fig. 7). A zoom lens is mounted on the high speed camera to focus on the small deformation zone. The optically track surface markers on the specimen during deformation is used to calculate the displacements and strains (Fig. 8d).

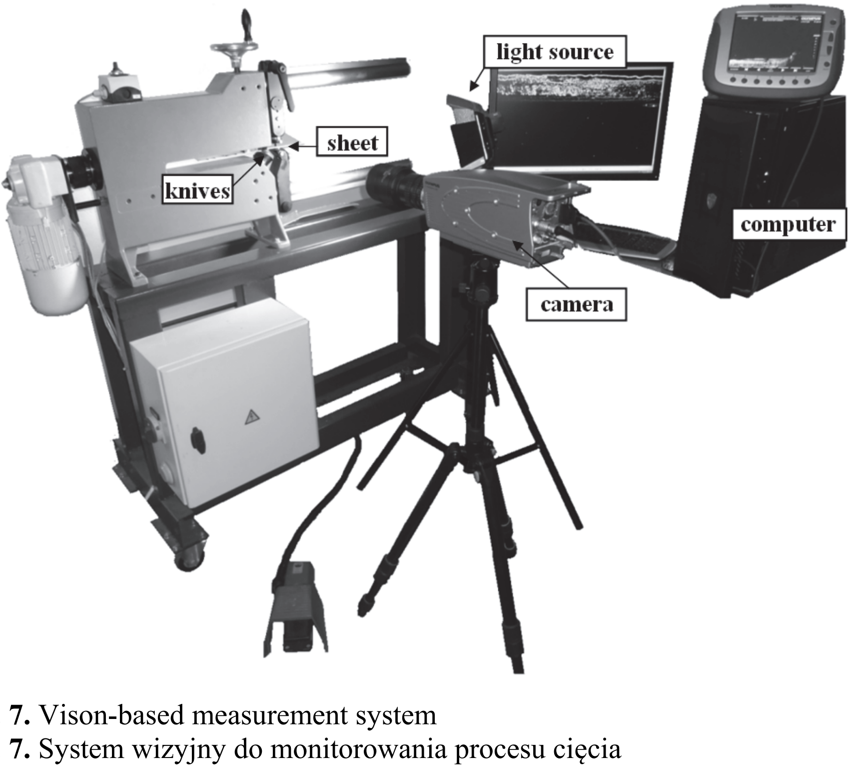

Fig. 7. Vison-based measurement system
Fig. 7. System wizyjny do monitorowania procesu cięcia

Vison-based measurement system allow for observation of the process of formation of defects in the form of burrs and bendings of the cut edges. Figure 8 show moment of final separation of sheet and a process of burr formation on the cut surface during slitting aluminum alloy AA6111-T4. It was found that this is caused by too much clearance between the knives. An interesting phenomenon is observed at final stage of process. Rapid crack propagation occurred after crack initiation with the burr closely following the shape of the upper knive. Analysis of displacements of markers allows to determine the deformation of the material being cut.

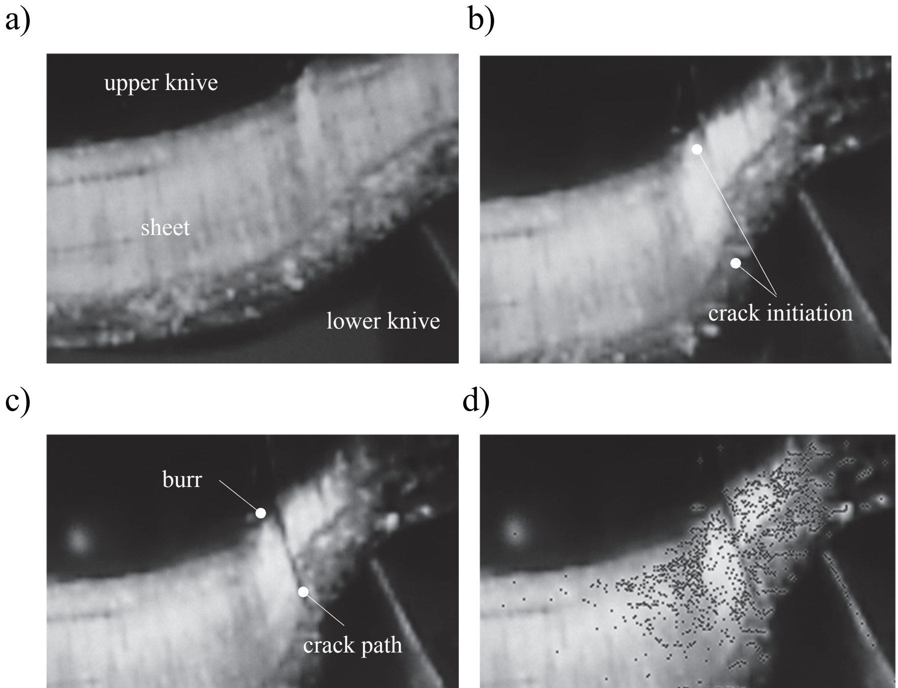

Fig. 8. Moment of final separation of sheet during slitting
Fig. 8. Moment całkowitego rozdzielenia materiału podczas cięcia na nożycach krążkowych

4. Conclusions

The paper presents the possibility of using FEM and vision-based techniques in the design of the cutting process. Using FEM and vision-based techniques allow for a detailed analysis of the physical phenomena occurring during the cutting and making developing of recommendations on the selection process conditions in terms of energy and scrap minimization. Vision-based techniques are a valuable tool for the validation of numerical models. The results obtained can be a great significance to the control of the properties of materials sheared and offer a possibility of an effective interference with the designing of the technological process and an adaptation of the technological quality is the adequate functional requirements and operating conditions. This will reduce energy consumption and negative impact of this process on the natural environment.

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Zastosowanie metody elementów skończonych i technik wizyjnych do analizy procesów cięcia w aspekcie redukcji odpadu

Streszczenie

Współczesne techniki wytwarzania nie są pozbawione problemów związanych z zapewnieniem odpowiedniej jakości wytwarzanych elementów przy jednoczesnej minimalizacji kosztów ich produkcji jak i wzroście wydajności procesu. W pracy przedstawiono możliwości zastosowania Metody Elementów Skończonych i technik wizyjnych do analizy zjawisk fizycznych zachodzących podczas procesów cięcia. Jednym z czynników ograniczających prawidłowy przebieg procesu cięcia są defekty na powierzchni przecięcia w postaci zadziorów i wiórów. Powoduje to niedokładne przyleganie blach, a w przypadku konieczności składania ich w pakiecie stanowi przeszkodę w prawidłowym montowaniu elementów ciętych w układach mechanicznych lub elektrycznych. Rozwiązanie tego problemu jest jednym z kluczowych zadań tej technologii, a jednym ze stosowanych sposobów jest analiza symulacyjna i doświadczalna poszczególnych faz procesu cięcia. Wyniki analiz mogą być wykorzystane do projektowania procesu cięcia, a także być podstawą doboru parametrów procesu w aspekcie jakości technologicznej wyrobu. Pozwoli to na podniesienie ich jakości i zmniejszenie odpadów materiałowych. Spowoduje to bezpośrednio zmniejszenie zużycia energii i przyczyni się do ograniczenia negatywnego wpływu tego procesu na otaczające środowisko.

Słowa kluczowe:
cięcie, stop aluminium, odpad, Metoda Elementów Skończonych,
techniki wizyjne

Keywords:
cutting, aluminum alloy, scrap, Finite Element Method, vision based solutions