CIRP Annals - Manufacturing Technology 60 (2011) 627–650

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Velocity effects in metal forming and machining processes

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ARTICLE INFO

Keywords:
Velocity
Forming
Machining

ABSTRACT

Velocity is probably the most important parameter in manufacturing, influencing performance, cost, productivity, energy and resources efficiency as well as safety and environmental issues. This paper presents basic phenomena as well as other important effects which are linked to velocity as a process parameter. In addition, applications, for example superplastic forming or high speed cutting, which have been founded on uncommon process velocities are discussed in the context of technological developments which have taken place over the past several years.

1. Introduction

Climate change and diminishing natural resources are two of the most daunting challenges facing manufacturing industry today. The principal objectives are therefore to reduce costs and to focus on the reduction of energy and resources employed in the production process but also to lower process emissions. A promising approach to gain a significant improvement is the use of lightweight design, which includes the use of lightweight materials and semi-finished products. In many cases, these lightweight materials and semi-finished products are associated with limited processing properties (e.g. machinability and formability) challenging the manufacturer to produce more complex components more efficiently. The increasing requirements in respect of the design and complexity of components as well as flexibility and quality lead to an even more demanding situation. Forming and machining technologies reach their limits as regards feasibility (material behaviour, quality and process forces) and profitability because manufacturing of complex components only becomes efficient with considerable effort in respect of process, tools and machines.

Exploiting the specific velocity effects and using velocity as a decisive parameter in production processes offers diverse opportunities to extend process limits. The present keynote paper focuses on the presentation and exemplification of velocity effects in production processes. The objective is to establish the significance of velocity as a process parameter for today's production engineering by focusing on the relevant processes of forming, shearing, joining and machining. Special emphasis is put on high velocity processes, which are closely related to an increase in profitability due to the production of a greater quantity of components in the same time period. As a result, production costs and energy consumption can be reduced.

Increasing the velocities in the production processes does not only affect profitability but influences the range of application of the process involved. Accordingly, a further emphasis of the keynote paper lies in describing the potential of velocity as a process parameter to influence the technological feasibility, required process forces, process reliability and process stability, achievable quality and for these reasons the extension of process limits. In this regard aspects of high velocity (e.g. high speed cutting) are presented and applications based on low velocities (e.g. superplastic forming) are also discussed.

The term "velocity" covers a broad spectrum of meaning, and the first section of the paper therefore deals with the various interpretations of the term velocity in connection with manufacturing processes. In addition, parameters linked to the velocity are outlined. Subsequently, the effects of velocity on material behaviour and on related forming mechanisms and chip formation mechanisms are analysed and discussed. This also includes the aspects of interface between tool and workpiece and tribological effects. Another aspect which is in the scope of this paper considers velocities in the simulation of processes including a discussion on their characteristics and boundary conditions. Finally, based on examples of different production processes, the effects of velocity on profitability, process performance and quality are presented and the requirements essential for exploiting the resulting potentials are highlighted.

2. Theory and basic phenomena

2.1. Definition of process velocity and related quantities

In the field of production technology today, the definition and application of process velocity is an important factor for profit-

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0007-8506/$ – see front matter © 2011 CIRP.
doi:10.1016/j.cirp.2011.05.001

ability. Production processes can only be made more efficient and cost-effective by increasing the process velocity in order to produce more components in a given time span or by reducing the time needed for component production. This is true for forming, shearing, cutting and non-conventional processes as well as joining operations which are based on forming processes.

In the field of forming, for example the manufacturing of car body components, the stroke rate is often used as a criterion to describe velocity. From an economic point of view it is important to increase the stroke rate. However, if technological aspects, especially tool and machine limitations, are taken into account, the stroke rate cannot be increased indefinitely even using the most modern servo press technology. As the infeed and the reset of the punch are also part of a stroke, using the stroke rate cannot be used as an exact indication of the real forming or process velocity. For this reason the punch velocity is often used for example in deep drawing processes.

In high velocity forming, shearing and joining, which are based on the use of acting media or acting energies, different terms are also used to describe process velocity. When, for example, active components are accelerated by chemical, electrical or physical energy their velocity is often specified (e.g. forming punch, shearing punch, and joining element). In explosive forming where the material is accelerated directly by the medium, the process velocity is often specified as the propagation velocity of the forming medium.

The specification of the strain rate or of the strain velocity offers the opportunity to characterise, classify and compare these various forming processes with regard to velocity. Here the strain rate is defined as the time derivative of the material strain. In a uniaxial case, it is defined as:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{d}{dt}\ln\left(\frac{l}{l_0}\right) \tag{1}$$

Also in superplastic forming the strain rate assists in classifying the process with regard to velocity. The diagram in Fig. 1 shows the strain rates of various forming processes.

The general definition of velocity or speed in cutting is the workpiece and/or tool time-rate change of distance. In cutting with defined edge, the characteristic velocity is a relative speed between the tool edge and the workpiece surface, including cutting speed and feed speed. Both the cutting speed and the feed speed might be carried out by the tool and/or the workpiece, depending on the process and the machining equipment. In turning, the cutting speed is normally defined by the peripheral velocity of the workpiece, while in milling the cutting speed is defined by the peripheral velocity of the tool. Normally the cutting speed is much higher than the feed speed. In grinding, using undefined cutting edges, the velocity is defined as the peripheral speed of the wheel combined with a much lower feed speed of the workpiece and/or the tool.

The variation of process velocity has a direct influence on the various phenomena in the cutting zone causing differences in the elastic and plastic behaviour, which results in different strain rates, cutting forces and stresses as well as chip flow and tool life.

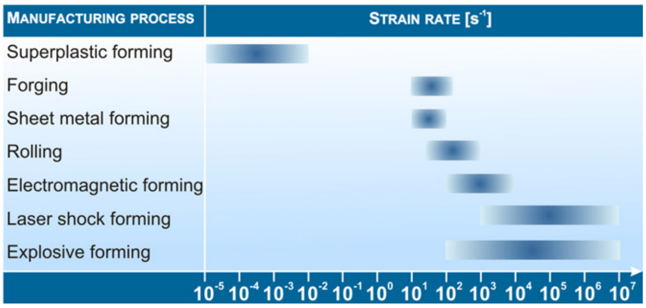

Fig. 1. Strain rates for conventional as well as nonconventional forming processes [206].

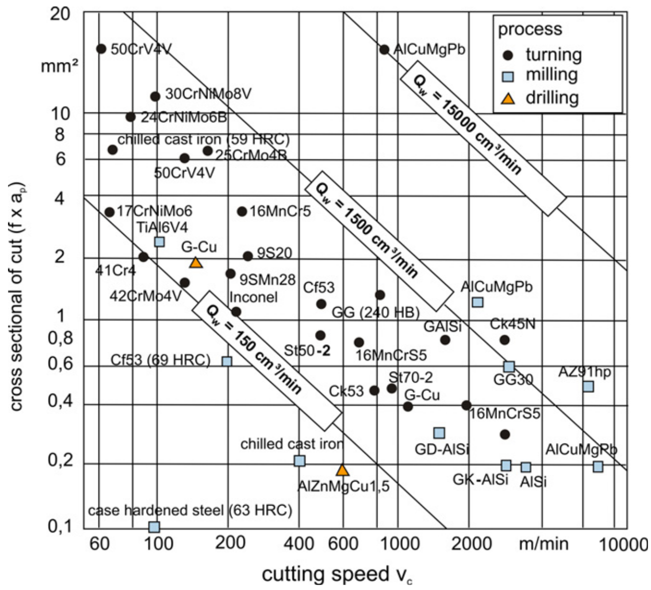

Fig. 2. Material removal rates for a range of materials [90].

In cutting, the velocity or speed is used as the main process parameter or performance criterion, while the strain rate in the primary shearing zone is mainly applied for analysing the basic physical phenomena. Cutting speeds for turning, milling and drilling applied in industry in combination with the chip cross-section which is defined by feed and depth of cut influence the material removal rates as shown in Fig. 2. To reach a higher removal rate for a specific chip cross-section, the cutting speed should be increased (high speed machining – HSM or high speed cutting – HSC). The limitations are workpiece composition and properties, machine capacity and stability as well as tool life and chip flow. However, shorter machining time or higher removal rate with medium speeds can also be achieved by using high performance cutting (HPC) with higher feeds and larger depth of cuts.

In forming and in cutting, strain rates with values below $10^{-1}\,s^{-1}$ based on the dynamic plastic behaviour of materials is categorised as slow process velocities. In superplastic forming (cf. Section 3.3) strain rates are typically between $10^{-5}\,s^{-1}$ and $10^{-3}\,s^{-1}$. A strain rate between $10^{-1}\,s^{-1}$ and $10^{2}\,s^{-1}$ is defined as intermediate, while a strain rate of more than $10^{2}\,s^{-1}$ and up to $10^{7}\,s^{-1}$ is defined as a high velocity depending on material composition and properties. Strain rates higher than $10^{4}\,s^{-1}$ usually correspond to the phenomena involved in shock wave propagation.

2.2. Basic physical and mechanical phenomena

For conventional applied velocities in forming (intermediate strain rates) the process can be assumed to be quasi-static and the material behaviour can be described as elastic–plastic. For high-velocity processes and also for low-velocity processes, time represents a significant process parameter. For low-velocity processes this is primarily related to the dominant visco-plastic material behaviour together with strain rate-dependent hardening and mostly higher process temperatures. In the case of high-velocity processes inertial effects may become significant; forming heat and frictional heat may not be neglected and strain rate hardening as well as thermal softening may take place. In both cases aspects such as:

- the thermal expansion of tool and workpiece;
- the heat transfer between tool and workpiece;
- the generation of frictional heat between workpiece and tool;
- the velocity- and temperature-dependent friction; and
- the increase in temperature in areas of higher strain rates may play an important role.