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Računalniško simuliranje - podpora učinkovitejšemu načrtovanju tehnoloških procesov

Computer Simulation - a Means for Improving the Efficiency of Technology Processes Design

BORIS ŠTOK

Današnje stanje razvoja matematičnega in numeričnega modeliranja omogoča obravnavo večine tehničnih problemov na podlagi numerične analize in računalniškega simuliranja. Načrtovanje tehnoloških postopkov vsebuje množico elementov, tako konstrukcijske kakor tudi tehnološke narave, katerih učinkovito razreševanje je mogoče v čedalje večji meri opreti na računalniško podprte analize in simuliranja. Uporaba slednjih je v prispevku prikazana skozi vrsto povsem konkretnih primerov iz industrijske prakse. V prikazu je poudarek na raznovrstnosti vidikov obravnave pripadajoče problematike, s čimer so izpostavljene velike potencialne možnosti, ki jih za snovanje in analizo elementov tehnoloških procesov ponujajo računalniško podprti izračuni in računalniško simuliranje.

Ključne besede: načrtovanje tehnoloških procesov, analize računalniške, analize orodij, analize izdelkov, analize procesov, simuliranje računalniško

The actual state of development in mathematical and numerical modelling enables most engineering problems to be investigated by means of numerical analysis and computer simulation. In a technology process design there are plenty of issues, being either of design or technological origin, which can be efficiently tackled by computer aided analyses and simulations. The application of this support is presented in the paper through a series of cases taken from the industrial practice. The emphasis in this review is given to the diversity of aspects from which a certain problem can be considered. Specific attention is given to the potential of computer aided analyses and computer simulations in the technology processes design and analysis.

Keywords: technological processes design, computer aided analysis,analysis of tools, analysis of products, analysis of processes, computer simulation

0 UVOD

Priča smo obdobju intenzivnega uvajanja računalnikov, ki je zaznamovalo skoraj vse veje človekove dejavnosti. V okviru t.im. *računalniško podprtih* tehničnih dejavnosti govorimo o računalniško podprtem konstruiranju (CAD), načrtovanju in krmiljenju proizvodnje (CAPP), zagotavljanju kakovosti (CAQ), izvajanju inženirskih preračunov in analiz (CAE), računalniško podprti proizvodnji (CAM) in drugih. Učinkovito povezovanje vseh teh predstavlja *tovarna bodočnosti,* ki naj bi delovala po načelih računalniško integrirane proizvodnje (CIM).

Uvajanje računalniško podprtih dejavnosti je dandanes imperativ ekonomsko učinkovite proizvodnje, kar velja nedvomno tudi za organizacijo dela v orodjarnah. Obseg vključevanja in raznovrstnost teh dejavnosti ter njihovo morebitno povezovanje so posredno odvisni od profila orodjarne. Ko se dejavnost orodjarne omejuje le na izdelavo orodja po naročilu in izdelanem načrtu orodja, sta potreba po računalniško podprtih dejavnostih in s tem tudi njihov obseg relativno majhna. Bolj ko se dejavnost orodjarne širi v smeri večjega lastnega deleža pri razvoju izdelka, bolj ko je ta inovacijsko in raziskovalno razvojno usmerjena, večja je potreba po vključevanju računalniško podprtih dejavnosti in njihovi povezavi.

0 INTRODUCTION

We are witnessing the age of intensive computerisation, which has marked almost every branch of human activity. In the case of so-called computer aided technical activities we talk about Computer Aided Design, CAPlanning & Production, CAQuality, CAEngineering, CAManufacturing and so on. Their effective integration is a basis for Computer Integrated Manufacturing and its vision of how a factory of tomorrow should operate.

The introduction of computer aided activites is nowadays an imperative of economically efficient production; this is also true for the organization of work in tool production enterprises. The extent of inclusion and the variety of included activities, as well as their eventual integration, is indirectly conditoned by the toolshop's profile. When the activities of a toolshop are restricted to the fabrication of tools on order and with the design documentation given, the need for computer aided activities is relatively small and so is their extent. By contrast, with the tendency for an increased implementation of our own know-how in the development of a product, and with activities that are much more innovatory, research and development oriented, the need for an integrated computer aided approach increases.

Zanesljivo je mogoče trditi, da se je računalniško podprto konstruiranje uveljavilo tudi v najmanjših proizvodnih obratih, prav tako tudi računalniško podprta proizvodnja s tehnologijami CNC. Obe dejavnosti sta nedvomno temeljni, saj zagotavljata upodobitev oblike proizvoda (izdelka ali orodja, potrebnega za njegovo izdelavo), prva v obliki konstrukcijskega načrta, druga v obliki materialno izdelanega proizvoda. Izredno pomembna faza pri razvoju izdelka, ki ju navedeni dejavnosti ne pokrivata, je idejna zasnova ter oblikovanje proizvoda skladno z zahtevano funkcionalnostjo. Funkcionalnost pa ni edini kriterij za oblikovanje. V proizvodnem ciklu nastajajoči izdelek je izpostavljen obremenitvam, ki niso nujno mehanskega izvora. Tudi končni izdelek v eksploatacijskih razmerah je obremenjen. Ker lahko preobremenjenost v kateremkoli od obeh ciklov, proizvodnem ali eksploatacijskem, vodi do okvar izdelka, je treba temu kriteriju pri razvoju pripisati še posebej pomembno vlogo.

Ne glede na dejstvo, ali orodjarna orodje le izdeluje ali ga v celoti konstruira, so posledice neustreznega orodja, ki se pokažejo med obratovanjem, bodisi na orodju samem ali na izdelku, za orodjarno finančno boleče, predvsem pa škodljive za njen ugled. Eden izmed ključnih razlogov za razhajanje med pričakovanim in dejanskim odzivom tiči v človekovi omejeni zmožnosti razumevanja in zaradi tega tudi napovedovanja fizikalnih sprememb, ki karakterizirajo proizvodni proces. V veliki meri bi bilo mogoče posledice te naravne človekove pomanjkljivosti odpraviti z uvajanjem računalniško podprtih tehničnih preračunov in analiz.

Iz navedenih razlogov mora napredna orodjarna, katere strategija je usmerjena v doseganje visoke stopnje dodane vrednosti, med svoje proizvodno "nujno" potrebne računalniško podprte dejavnosti vključiti tudi CAE. S tem bosta samo pridobili zanesljivost in kakovost dela.

V prispevku želimo prikazati možnosti, ki jih pri reševanju nekaterih tehniških problemov ponuja sodobna računalniška tehnologija v povezavi z visoko razvitimi programskimi orodji analize ter integriranim računalniškim simuliranjem. Glede na to, da izhajajo primeri, ki jih analiziramo v prispevku, iz neposredne prakse, je treba spremljajočemu razmišljanju in sklepom pripisati vso potrebno verodostojnost.

It can be said with certainty that CAD is present, and it has made itself valued in every, even the smallest manufacturing company. The same can also be stated for CAM, which relies on CNC technologies. From the viewpoint of the product's shape specification (either referring directly to the product itself or to the tool, needed for its fabrication) both activites are undoubtedly basic in the production process, the former by assuring the corresponding representation in the form of a design documentation, and the latter by assuring the corresponding materialization of the product. An extremely important stage in the development of a product, which the two above mentioned activities do not cover, is the modelling of the product in consistency with the demanded function. However, being functional is not the only criterion for the design. Actually, during its manufacture the product is exposed to loadings which are not necessarily of mechanical origin. Also in its regular exploitation as a structural component, the final product is expected to be somehow loaded. Since the occurrence of overloading in any of these two cycles, either manufacturing or exploitational, can result in a defective product, it is necessary, in the development phase, to attribute particular significance to this criterion.

Irrespective of whether, in the tool processing, the toolshop is involved only in its manufacture or, also in its design, the shortcomings that may eventually be manifested either during exploitation of the tool itself or during use of a product manufactured by this tool, due to improper tool-shaping, are certainly financially painful for the toolshop, but above all they are destructive for its reputation. One of the key reasons for the discrepancies experienced by investigation of a manufacturing process between expected and actual response lies in the human limited capability of understanding, and consequently, in the poor capability of predicting the evolution of characteristic physical quantities. The consequences of this natural human deficiency could be almost completely eradicated by the introduction of corresponding computer aided engineering analyses.

It is due to the above reasons that a progressive toolshop, with its strategy aiming at increasing the degree of added value, must also incorporate CAE within its "essential" computer aided activities. The benefits gained by using CAE will be manifested in the increased reliability and quality of the work.

With reference to the investigation of engineering problems we wish to demonstrate in this paper the potential which is given by corresponding computer simulations that rely on modern computer technology and on the existing advanced analysis packages. Since all cases discussed in the paper derive from the industrial practice, all the credibility should be attributed to the considerations and conclusions associated with the study of each individual case.

1 ELEMENTI TEHNOLOŠKEGA PROCESA

Če se omejimo na tehnološke procese v strojni predelovalni industriji, lahko pojem *tehnološki proces* opredelimo kot celoto, ki jo sestavljajo:
- vhodni material (surovec ali polizdelek),
- fizične komponente, potrebne za neposredno izdelavo izdelka,
- procesni pogoji, ki naj zagotovijo želeno preobrazbo vhodnega materiala.

Glede na tako postavljeno definicijo lahko zapletenost tehnološkega procesa ocenjujemo z več zornih kotov.

Z vidika števila fizičnih komponent je nedvomno najpreprostejši primer toplotne obdelave že končno oblikovanega polizdelka, npr. kaljenje v hladilni kopeli. Nasprotno pa je primer hladnega preoblikovanja v večstopenjskem preoblikovalnem orodju nadvse kompleksen.

Navedena primera se izrazito razlikujeta tudi v fenomenološkem značaju sprememb. Medtem ko gre v prvem primeru ob skorajda zanemarljivi spremembi oblike polizdelka predvsem za metalurške spremembe in spremljajoče spremembe mehanskega stanja kot posledico neenakomernega ohlajanja, gre v drugem primeru v prvi vrsti za spremembo začetne oblike vhodnega materiala kot posledico delovanja preoblikovalnega orodja. Prvi primer karakterizira termomehanska fenomenologija, drugega pa le mehanska, vendar s pretežno neelastičnim odzivom. Pri tem pa je mehansko stanje v končnem izdelku v obeh primerih nadvse prepleteno.

Oba obravnavana primera izkazujeta časovno spremenljivost, kar pomeni dodatno zapletenost. V prvem primeru se ta kaže v določitvi takšnih časovno spremenljivih procesnih pogojev, ki bodo zagotovili želene metalurške spremembe, v drugem primeru pa v ugotovitvi dejanskih mehanskih veličin stanja, odločujočih tako za obremenjenost orodja v mejah dopustnega kakor za pravilno preoblikovanje materiala. V nasprotju s tema primeroma izkazuje proces vlečenja žice izrazito ustaljenost, katere posledica je časovno nespremenljiva obremenitev orodja.

Že teh nekaj naštetih vidikov daje slutiti, da je načrtovanje tehnološkega procesa v celoti ali po delih nadvse zahtevno opravilo.

2 ZAKAJ RAČUNALNIŠKA ANALIZA?

Tehnološki proces je praviloma treba obravnavati kot razširjen fizikalni sistem, katerega obnašanje je opredeljeno s fenomenologijo posameznih podsistemov (orodje, obdelovanec,

1 ELEMENTS SPECIFYING A TECHNOLOGY PROCESS

Speaking only of technology processes in mechanical manufacturing engineering, the term technology process can be defined as a whole, specified by the following elements:
- input material (either a workpiece from a raw product or a semi-finished product),
- physical components, necessary for the direct manufacturing of a product,
- operational conditions that ensure the required transformation of the input material.

In accordance with this definiton, the complexity of the technology process can be regarded from different aspects.

The simplest case, regarding the number of physical components, is undoubtedly heat treatment of a final semi-finished product, such as quenching in a cooling bath. From the same point of view, the case of cold metal forming in a multi-step die is, by contrast considered as extremely complex.

The above two cases also differ considerably when regarded from a phenomenological point of view. While the former case is characterized above all by metallurgical transformations and corresponding changes in mechanical state due to nonuniform cooling the change of the product's shape being at the same time almost negligible it is actually the change of shape of a billet, which is subjected to the action of forming tools, that mostly characterizes the latter case. Although the first case are characterized by the thermomechanical phenomena, while the phenomena of the second case are purely mechanical, with nonelastic response prevailing, it should not be forgotten that mechanical states associated with the final product are very complex in both cases.

Since both cases considered are characterized by time variation, the complexity of the problem is still further increased. With respect to the first case, this is associated with the determination of such time variations of the process conditions as will ensure the desired metallurgical transformation. In consideration of the second case, complexity is associated with establishing the actual mechanical state, knowledge of which is decisive for loading a tool within permissible limits as well as for obtaining the correct shape change of the forming material. Unlike the cases just considered, wire drawing is a typically stationary process with loading of a tool being constant in time, in consequence.

Already from the above few considerations it can be anticipated that designing a technology process, either in its entirety or by parts, is a most demanding task.

2 WHY PERFORM COMPUTER ANALYSES?

In principle, a technology process should be treated as an extended physical system whose behaviour is determined in turn by phenomenologies of individual subsystems (tool, workpiece, surroundings), okolica), soodvisnostjo med posameznimi fizikalnimi pojavi v istem podsistemu ter z interakcijo med podsistemi. V tehničnem načinu obravnave problema, kjer si praviloma prizadevamo za poenostavljanje, s poudarkom na obravnavi delnih segmentov tehnološkega procesa, se moramo zavedati, da je objektivnost in s tem uspešnost takšnega postopka izključno odvisna od stopnje poznavanja in razumevanja problema na eni strani ter možnosti za čimbolj celovito upoštevanje vpliva za proces pomembnih dejavnikov na drugi strani. Medtem ko tako poznavanje kot razumevanje problema temeljita predvsem na pridobljenem teoretičnem znanju, minulih izkušnjah in sposobnosti intuitivnega razmišljanja, je upoštevanje vpliva posameznih procesnih dejavnikov v veliki meri vezano najprej na identifikacijo samega dejavnika, zatem pa še analizo njegove vplivnosti. Zgolj kakovostna ocena vplivnosti, zgrajena na sicer logičnem, vendar poenostavljenem miselnem modelu, je v pojavno zapletenih tehnoloških procesih, kjer je časovni razvoj prostorsko spreminjajočega se termomehanskega stanja soodvisen od sočasnega razvoja različnih fizikalnih pojavov, velikokrat zavajajoča in lahko vodi do zmotnih sklepov.

Prav zaradi pomanjkljivosti, ki izhajajo iz človekove omejene zmožnosti intuitivne analize tako zapletenega problema, so možnosti, ki jih ponuja računalniško podprto izvajanje tehničnih analiz, izrednega pomena. Uporabnik v ta namen uporabi računalniški program, v katerega so vgrajene matematično modelirane fizikalne zakonitosti. Z računalniškim simuliranjem problema, za katerega opredelitev je treba najprej podati geometrijski in materialni opis, zatem pa še definirati vse procesne podatke problema, je mogoče pridobiti celovito sliko o časovnem razvoju fizikalnih veličin. S tem je uporabniku omogočeno preverjanje izbranih tehnoloških rešitev in njihova preprosta sprememba na podlagi odkrivanja vplivnih povezav.

Načrtovanje tehnološkega procesa v celoti ali delno je z računalniškim simuliranjem časovno hitro in finančno ugodno, saj je mogoče neustreznost predvidene rešitve popraviti v zgodnji fazi razvoja, ko še niso izdelani posamezni elementi načrtovanega postrojenja.

3 KAKO IZKORISTITI MOŽNOSTI, KI JIH PONUJA RAČUNALNIŠKO SIMULIRANJE?

V nadaljevanju želimo prikazati široko paleto možnosti, ki jih ponuja računalniško simuliranje. Vsi v tem prispevku prikazani primeri so bili analizirani v Laboratoriju za numerično modeliranje in simulacijo v mehaniki Fakultete za strojništvo v Ljubljani. Pretežni

by interdependence between individual physical phenomena within the individual subsystem and by interaction between the subsystems. In the investigation of such a problem by following a traditional engineering approach simplifications are usually introduced, the emphasis being given to the consideration of partial segments of the technology process. If so, we should be aware that the objectivity and success of such an approach depends exclusively on the degree of knowledge and understanding of the problem, as well as on the possibility of taking, when analysing the problem, the influence of parameters affecting the process as thoroughly as possible into account. In contrast to the knowledge and understanding of the problem, which are based above all on the acquired theoretical knowledge, past experience and capability of intuitive thinking, the consideration of an individual process parameter's influence is to a great extent related to the identification of the parameter itself first, and only then to the analysis of its influence. Merely qualitative estimation of influence, based otherwise on a logical, but simplified manner of thinking, is often misleading and can result in false conclusions. This is particularly true in phenomenologically complex technology processes, with time evolution of the thermomechanical field and simultaneous development of diverse physical phenomena being interdependent.

It is right because of deficiencies, resulting from the human limited capability to analyse such a complex problem intuitively, that using computer aided analyses in engineering, and the possibilities given thereby, are of such great importance. For this purpose computer codes with mathematically modelled physical relationships built in are at the user's disposal. For a problem with a given geometrical and material description, together with the corresponding process data it is possible to obtain, by performing a computer simulation of the problem, an integral picture about the time development of the physical quantities. Thus, the inspected technological solutions can be validated and, if needed, easily modified in accordance with the influential relationships discovered.

Since the unsuitability of a designed technological solution can be corrected at an early stage of the design development, with individual components of the process structure not yet being manufactured, the technology process design - irrespective of whether it refers to the entire process or only to its partial parts - becomes, by computer simulation, time efficient and financially viable.

3 HOW TO TAKE ADVANTAGE OF COMPUTER SIMULATION?

In the sequel, a wide range of applications demonstrating the capability of computer simulations will be presented, all of them analysed at the Laboratory for Numerical Modelling & Simulation of the Faculty of Mechanical Engineering - Ljubljana. Most of the cases considered derived directly from Slovenian in-del obravnavanih primerov izhaja neposredno iz slovenskega gospodarskega prostora, potreba po njihovi analizi pa je nastala bodisi v zgodnji fazi razvoja, bodisi pozneje, ko je v proizvodnji prihajalo do težav.

Ker bodo prikazani primeri ne glede na njihovo morebitno preprostost še vedno dovolj zapleteni, bo žal pri takem pregledu težko sistematsko slediti določeni zamisli. Želja pisca je, da bi si bralec iz analize vsakega primera posamezno, kakor tudi iz primerjalne analize sorodnih primerov, ustvaril podobo o možnostih, ki jih vsak od teh primerov zase ponuja k izpopolnitvi našega vedenja. Pri tem ne gre pozabiti, da je računalniško pridobljena izkušnja prav toliko vredna kot empirična, je pa cenejša in vsebinsko polnejša.

3.1 Primeri analize orodja

Primarna naloga konstrukterja orodja je zagotoviti z ustrezno konstrukcijsko rešitvijo izpolnitev funkcionalnih zahtev, ki izhajajo iz tehnološkega procesa. Ob tem mora biti konstrukcijska rešitev takšna, da izpolnjuje še dodatne zahteve o nosilnosti, togosti, obrabni trdnosti itn.

Da bi konstrukter zadovoljivo skonstruiral orodje, mora ob funkcionalnih zahtevah poznati tudi obremenitve, ki neposredno izhajajo iz tehnološkega procesa in naj bi jih orodje prenašalo. Ob obremenitvi orodja, za katero v tem razdelku vzemimo, da je znana, se pojavi za konstrukterja izredno pomembno vprašanje: kako se na orodje delujoča obremenitev porazdeli po notranjosti orodja? Odgovor na to vprašanje je lahko že v primeru zgolj mehanskih obremenitev dovolj težaven, zanesljivo pa to velja za primer, ko se ob mehanskih obremenitvah v orodju pojavi še prostorsko spremenljivo temperaturno polje.

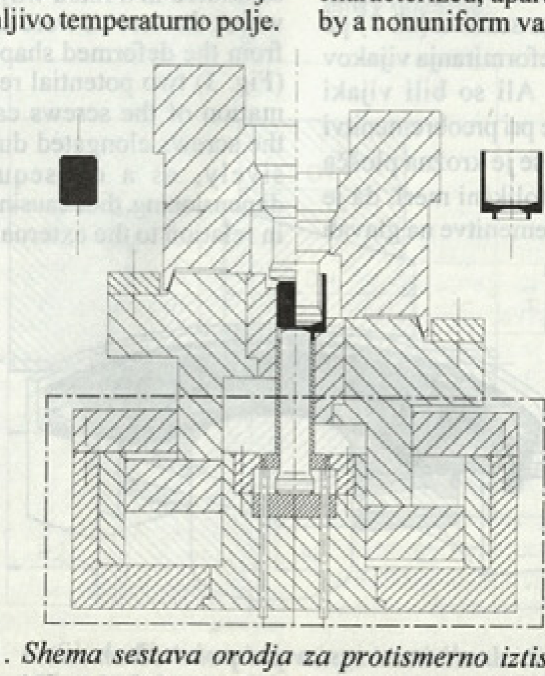
dustry, the necessity for their analysis being expressed either in early stages of development or later on, when associated with troubles in the production process.

Unfortunately, regardless of their eventual simplicity, the cases considered still remain complex, which makes it difficult to treat them systematically in such a review, following a certain concept. The author's wish is to enable the reader - through a consideration of the analyses of each case individually, as well as by considering comparatively the analyses of analogous cases - to form a picture about the possibilities that each of these cases offers to the improvement of our knowledge. Finally, it is worth emphasizing that, in comparison to the empirical experience, the experience acquired by computer analyses is of the same value, but in contrast to the former it is cheaper and richer in substance.

3.1 Tool analyses

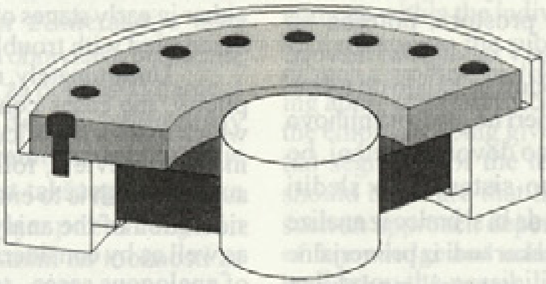
The primary task of a tool designer is to assure, by a suitable design solution, the fulfilment of the functional demands that are imposed by a technology process. In addition the design solution should also comply with demands on carrying capacity, rigidity, wear, etc.

Since a tool should be capable of carrying loads that arise directly from the technology process, a designer must know in order to construct a tool satisfactorily, in addition to the required functionality also those loads. With respect to the tool loads, which for convenience may be assumed as known in this section, a question important for the designer is: How does the applied load affect the internal stress distribution within the tool? To answer this question can be difficult even in cases of purely mechanical loadings, but this is certainly true in cases that are characterized, apart from mechanical loadings, also by a nonuniform variable temperature field.



Sl. 1. *Shema sestava orodja za protismerno iztiskovanje*

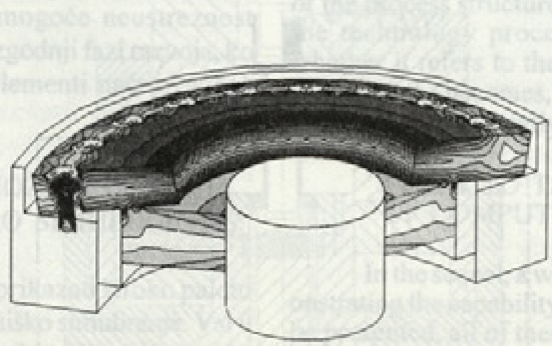
Fig. 1. *Scheme of the tool assembly for backward extrusion*



Sl. 2. *Geometrijski model analiziranih delov orodja*
Fig. 2. *Geometrical model of the analysed tool assembly*

Problem prenosa obremenitve z aktivnih površin orodja v notranjost je izrazit pri sestavljenih orodjih, kjer je ta prenos odvisen od interakcijskih vplivov med posameznimi konstrukcijskimi elementi orodja. Slika 1 prikazuje konstrukcijski sestav orodja za protismerno iztiskovanje, pri katerem je bila v fazi preizkušanja orodja ugotovljena prevelika deformacija dela orodja. V ta namen smo analizirali napetostno in deformacijsko stanje v delu orodja, ki je izkazovalo kritično deformiranost (senčeni deli na sliki 1). Geometrijski model, po katerem je bila izvedena računska mehanska analiza, je bil postavljen tako, da je zajel za opazovani pojav bistvene sestavne elemente (sl. 2). Ugotovitve, ki so izhajale iz analize, so pokazale, da je razlog za potencirano deformiranost v vijakih, ki so se pri delovnem tlaku hidravličnega olja plastično deformirali. Pri iskanju razloga za neustrezno dimenzioniranost vijakov bi le težko krivili konstrukterja, saj je ta pri svojem delu verjetno sledil utečenim konstrukcijskim napotkom, prav tako je velikost sile, ki naj bi jo vijaki prevzeli, ocenil na ustaljen način. Deformirana oblika analiziranega sestava (sl. 3) pa daje slutiti, da je do plastičnega deformiranja vijakov lahko prišlo iz dveh razlogov. Ali so bili vijaki neustrezno dimenzionirani in so se pri preobremenitvi pretirano raztegnili, zaradi česar se je krožna plošča glede na zunanji rob zasukala v tolikšni meri, da je povzročila dodatne upogibne obremenitve na glavah

The problem of transferring loads from the tool surface, where they are applied, to the interior is particularly relevant in the case of composed tools. Since such tools are assembled from several structural parts, the corresponding transfer of loads depends greatly on the interaction between individual tool components. Figure 1 shows the design of a tool assembly for backward extrusion, by which too large a deformation of part of the tool was noticed during testing. To find out the reason, we analysed stresses and deflections in the tool section, which showed the critical deformation (shaded area in Fig. 1). The geometrical model, on the basis of which a computational mechanical analysis should be carried out, was built in such a manner that all for the considered problem relevant assembly components were included (Fig. 2). The analysis revealed that the screws, which deformed plastically under the working pressure of hydraulic oil, were the cause of the extreme deformation. Yet, when searching for the reason for the unsuitable dimensioning of the screws, the designer could be hardly blamed. He probably followed the usual, well recognized design instructions, and also estimated in a fixed way the magnitude of the force which the screws were supposed to carry. However, from the deformed shape of the analysed assembly (Fig. 3) two potential reasons for the plastic deformation of the screws can be guessed. First, either the screws elongated during the loading too extensively, as a consequence of the unsuitable dimensioning, thus causing rotation of the circular plate in relation to the external edge to such an extent that



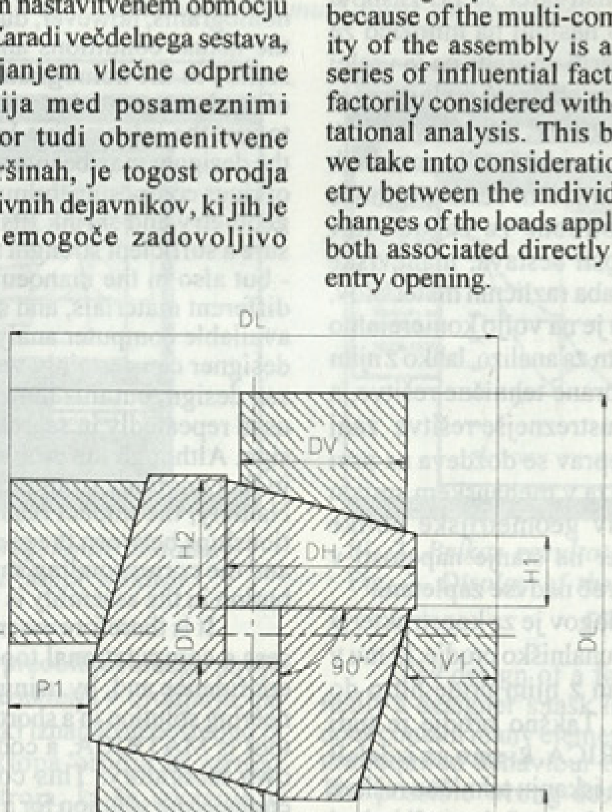
Sl. 3. *Analizirani sestav pri polni obremenitvi*
Fig. 3. *The analysed assembly under full loading*

vijakov in s tem nadaljnjo plastifikacijo ter ohlapnost celotne zveze, ali pa je bila privijačena plošča nezadostno toga in je zaradi lastne deformacije povzročila na vijakih dodatne upogibne obremenitve s plastifikacijo vijakov ter posledično nadaljnjim razrahljanjem zveze. Očitno gre v obeh primerih za podoben mehanizem razvoja nezaželene deformacije zaradi neustrezne togosti, v prvem primeru vijakov, v drugem pa plošče. Glede na ugotovljeno je popravek konstrukcijske rešitve mogoč s povečanjem togosti enega od obeh konstrukcijskih elementov ali kar obeh hkrati.

Razvoj orodja brez ustrezne podpore v računalniških analizah si je težko predstavljati v primerih, ko naj bi bilo to večnamensko ali dimenzijsko prilagodljivo. Takšno orodje je segmentna matrica, ki omogoča vlečenje profilov kvadratnega prečnega prereza (sl. 4). Dimenzijsko prilagodljivost orodja dosežemo z nastavitvijo lege kladic, ki sestavljajo matrico, z regulacijskimi vijaki. V geometrijskem pogledu je sicer konstrukcijska zasnova segmentne matrice na prvi pogled relativno neproblematična, a so problemi, s katerimi se mora konstrukter spopasti, številni. Ključno vprašanje zadeva velikost nastavitvenega območja, ta pa je odvisna od dosežene oblikovne natančnosti izdelka. Kot celota mora torej segmentno orodje v celotnem nastavitvenem območju zagotoviti zadostno togost. Zaradi večdelnega sestava, pri katerem se s spreminjanjem vlečne odprtine spreminja tako geometrija med posameznimi sestavnimi elementi kakor tudi obremenitvene razmere na delovnih površinah, je togost orodja zapletena funkcija vrste vplivnih dejavnikov, ki jih je brez računske analize nemogoče zadovoljivo upoštevati.

it resulted in the additional bending loading of the screw heads, which in turn was followed by further plastification and loosening of the entire junction; or secondly, the screwed plate was insufficiently rigid, which, because of its deflection caused the same bending effect and consequences as in the first case. It is obvious that a similar deformation mechanism developed undesirably as a result of insufficient structural rigidity: that of the screws in the first case and that of the plate in the second case. According to the established facts, a correction of the design solution is possible by increasing the rigidity either of one of the two involved structural components or of both at the same time.

It is hard to imagine tool development without a corresponding aid in computer analyses, particularly when the tool is supposed to be in multifunctional use or is dimensionally adjustable. Such a tool is a die made from several segments, which is used for the drawing of square section bars (Fig. 4). The dimensional adjustment of the tool is achieved by setting the position of small blocks within the die through the control screws. Although from the geometrical point of view the structural design of the segment-die seems to be relatively easy, the designer has to confront many problems. The key question concerns the size of the adjustment interval, which is in direct correlation with the achieved shape accuracy of the product. As a whole, the segment-tool should assure sufficient rigidity over the whole adjustment interval. But, because of the multi-component structure, the rigidity of the assembly is a complicated function of a series of influential factors, which cannot be satisfactorily considered without a corresponding computational analysis. This becomes even more clear if we take into consideration the changes of the geometry between the individual components as well as changes of the loads applied on the working surfaces, both associated directly with a variation of the die entry opening.



Sl. 4. *Shema sestava segmentne matrice*
Fig. 4. *Scheme of the segment-die assembly*

Za orodjarne, ki pogosto konstruirajo namensko podobna orodja, prilagojena različnim zahtevam končnega izdelka, je zanimiva še ena možnost, ki jo je v okviru računalniško podprtih analiz mogoče uporabiti. Gre za uporabo namenskih računalniških programov, izdelanih na zahtevo uporabnika, katerih cilj je pridobiti po najhitrejši poti čimbolj celovito informacijo o ustreznosti analizirane rešitve. Z uvajanjem zmogljivejših matematičnih sredstev v tak program je mogoče celo doseči, da je rezultat takšne integrirane analize kar "računalniško zasnovana" tehnična rešitev, ki zadovoljuje vse konstrukterjeve zahteve in omejitve. Praviloma je komuniciranje uporabnika s programom izredno preprosto, največkrat tako, da uporabnik definira le najosnovnejše podatke o geometrijski obliki orodja, materialih ter obremenitvah, ob možni računalniško zasnovani konstrukcijski rešitvi pa še konstrukcijske omejitve in zahteve. Glede na to, da je tak program namenski, je obseg iz računske analize pridobljenih informacij povsem prilagojen uporabnikovim potrebam.

Segmentna matrica s slike 4 in matrica za iztiskovanje s slike 5 sta prav gotovo primera, katerih konstrukcijsko rešitev je mogoče snovati na pravkar opisani način. V nadaljevanju se omejimo na obravnavo prednapete večplastne matrice za rotacijsko iztiskovanje. Konstrukter se pri zasnovi tehnične rešitve sicer lahko nasloni na množico že izdelanih nomogramov, katerih uporaba pa je vselej zgolj okvirnega pomena, saj se običajno realni primer kaj hitro razlikuje od pogojev, upoštevanih v nomogramih. Konstrukterja zanima število potrebnih obročev, ki naj sestavljajo matrični sestav, njihove dimenzije ter nadmere, potrebne za zagotovitev zadostne nosilnosti in togosti sestava, manevrske možnosti, ki jih ponuja uporaba različnih materialov, in še kaj. Konstrukter, ki mu je na voljo komercialno dosegljiv računalniški program za analizo, lahko z njim sicer preverja ustreznost izbrane tehnične rešitve, a je ta pot v primeru iskanja ustreznejše rešitve zanj največkrat kar zamudna. Čeprav se dozdeva na prvi pogled problem preprost, je ta v mehanskem smislu zapleten. Medsebojni vpliv geometrijske oblike obročev in njihovih nadmer na stanje napetosti v posameznih obročih je namreč nadvse zapleten.

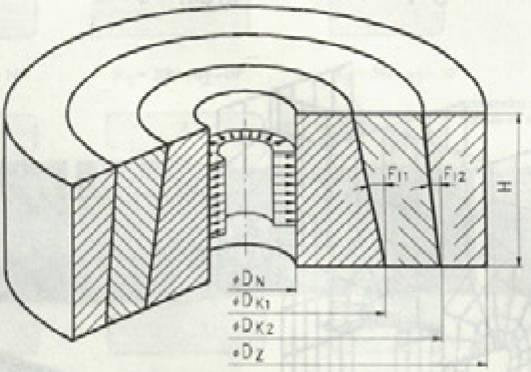
Zaradi navedenih razlogov je za konstrukterja izredno pomembno imeti računalniško orodje, ki mu v največji meri lahko zaupa in z njim pride hitro do uspešnih tehničnih rešitev. Takšno orodje je tudi računalniški program MATRICA, ki smo ga izdelali v laboratoriju in je namenjen iskanju tehnične rešitve večplastne matrice, skladno s postavljenimi konstrukcijskimi zahtevami. Program, ki je izdelan v, za uporabnika prijaznem, WINDOWS okolju, omogoča preprost vnos osnovnih konstrukcijskih podatkov (sl. 6) ter definicijo omejitev, ki naj jih

Computer aided analyses offer another interesting option for toolshops that often design tools for the production of products having a similar typology. In such cases the tool is correspondingly adapted to meet different demands of the final product. In order to acquire, as rapidly as possible, thorough information about the adequacy of the adapted solution a specialized computer code, built to meet the user's requirements, may be used. When such a code is additionally complemented by more powerful mathematical means it is possible to achieve, as a result of such integrated analysis, a proper "computer designed" engineering solution, which satisfies all the designer's demands and constraints. As a rule, the communication between an user and the computer program is very simple; often it is limited to the user's specification of the most basic data on the tool geometry, materials and loads. If, however, the computer-designed option is to be used, the user adds the corresponding structural demands and constraints. Since such a code is purpose-built, the amount of information that can be attained from computational analyses is completely adapted to the user's needs.

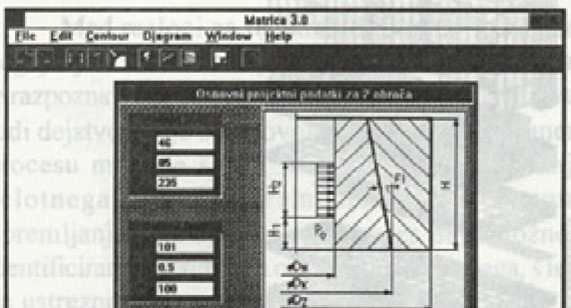
The segment-die in Figure 4 and the extrusion die in Figure 5 certainly belong to cases whose design solution can be traced following the above described way. In the sequel let us consider the latter case, which is a prestressed multi-layered extrusion die. When designing an engineeringl solution, the designer can certainly make use of many existing nomograms; however, due to the differences between the actual conditions and conditions that were assumed in the nomograms, which may happen quite often, it turns out that such a support may be reduced to just the informative level. In the case considered the designer may be interested not only in the number of rings composing the multi-layer die assembly, their geometry and shrink fits - all needed in order to assure a sufficient strenght and rigidity of the assembly - but also in the manoeuvring possibilities of using different materials, and so on. With a commercially available computer analysis code at his disposal the designer can certainly verify the adequacy of a chosen design, but this may become time consuming if used repeatedly in searching for a more suitable design. Although the problem may appear simple, it is in fact complex from the mechanical point of view. Namely, the impact resulting from the mutual relationships between the geometries of individual rings and the corresponding shrink fits on the stress distribution in the assembly is very complicated.

It is therefore essential for the designer to possess a computational tool which he can use with all confidence and, by using it, attain an effective engineering solution in a short time. Such a computational tool is MATRICA, a code that was designed in our own laboratory. This code enables searching of a engineering solution for a multi-layered die in accordance with the prescribed design demands. Since it is set in the user-friendly WINDOWS environment, communication with the code is easy, the information needed for its running being basic design data (Fig. 6) and specification of the constraints that the konstrukcijska rešitev izpolnjuje. Med slednje so vključene napetostne in deformacijske omejitve, katerih izpolnitev zagotavlja obremenjenost sestava v mejah dopustne trdnosti na eni strani, na drugi pa možnost izvedbe montaže glede na razpoložljivo opremo v orodjarni. Ob računalniško določeni geometriji kot ciljnem rezultatu računskih analiz, ki se izvedejo v potrebnem številu znotraj računskega programa brez posredovanja uporabnika, ima uporabnik na voljo še širok izbor možnosti pregleda pomembnih, za računalniško osvojeno rešitev veljavnih mehanskih veličin (sl. 7).

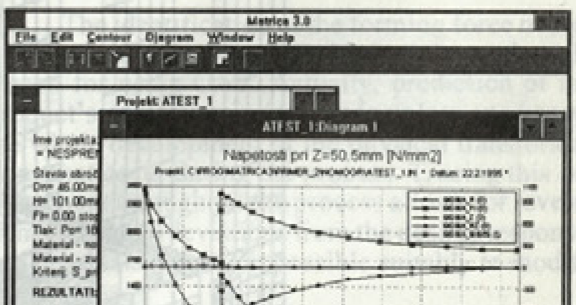
design solution should satisfy. Among the latter, the stress and deformation constraints assure, if fulfilled, first that the assembly is loaded within the permissible strength limits, and second that the assembly can be assembled according to the equipment available in the toolshop. The primary output of this specialized code is the design geometry, which can be completely determined by the computer. This determination relies on a series of analyses, executed automatically by the computer program as often as needed. In addition, the code has a large variety of options allowing for the inspection of relevant mechanical quantities associated with the determined design solution (Fig. 7).



Sl. 5. *Shema sestava večplastne matrice*
Fig. 5. *Scheme of the multi-layer die assembly*



Sl. 6. *Okno za vnos projektnih podatkov*
Fig. 6. *Project data input window*



Sl. 7. *Prikaz rezultatov računalniške analize*
Fig. 7. *Display of the computational analysis results*

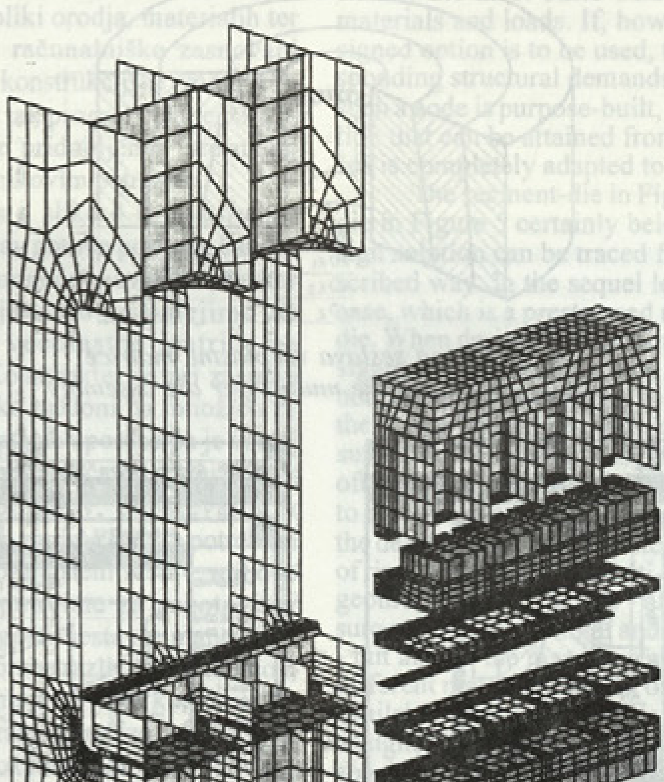
Čeprav konstrukcija preoblikovalnega stroja praviloma ni domena konstrukterja - orodjarja, pa vsebuje ta veliko elementov, ki izhajajo neposredno iz zahtevanega obnašanja sklopa orodja in stroja. Neustrezno oblikovanje stroja, ki se izkazuje v neprimernem deformiranju stroja, je namreč nemogoče popraviti z orodjem. Še posebej to velja za strogo namenske stroje visokega natančnostnega razreda, izdelane največkrat po naročilu. Podprto sicer z empiričnimi izkušnjami mora snovanje tehnične

The design of a forming press is usually not really a designer's task in the toolshop; however, it does contain many elements that derive directly from the required behaviour of the tool-press assembly. The possible wrong design of the press, which is proved by its deformation being improper, is practically impossible to correct on the tool side. In particular, this is true in the case of very specialized presses of the superior accuracy class, which are manufactured mostly by order. Though relying on empirical experience, the design of a press engineerrešitve stroja kot celote, kakor tudi njegovih posameznih delov, predvsem temeljiti na sintezi ugotovitev, ki jih dajejo računalniško analizirane variante. Ne zavedajoč se nuje po računalniški analizi ali celo njeno omalovaževanje pomeni pri snovanju tako zahtevne konstrukcije veliko neodgovornost.

Slika 8 prikazuje računski model konstrukcije preoblikovalnega stroja, katerega rešitev celotnega nosilnega dela s pehalom in delovno mizo smo zasnovali, upoštevajoč zgornja načela. Skladno s sprejeto rešitvijo izdelani stroj je izpolnil vse postavljene zahteve v zvezi s togostjo. Preverjanje deformacijskega obnašanja stroja je bila izvedena z meritvijo deformacij v mejah delovnega prostora.

ing as a whole, as well as of its individual parts, must be based above all on the synthesis made upon findings derived from computer analyses of several solution variants. In such a complicated design, as the press structure is, not being aware of the necessity for a computational analysis or even disregarding it, is highly irresponsible.

Figure 8 displays a numerical model of the forming press structure, designed globally by taking the above principles into account. The press, manufactured in accordance with the developed design, proved complete fulfilment of the required demands regarding rigidity. The experimental verification of the press deformation characteristic was carried out by measurement of deflections within the working area.



Sl 8. *Računski model konstrukcije preoblikovalnega stroja*

Fig. 8. *Numerical model of the forming press design*

3.2 Primeri analize izdelka

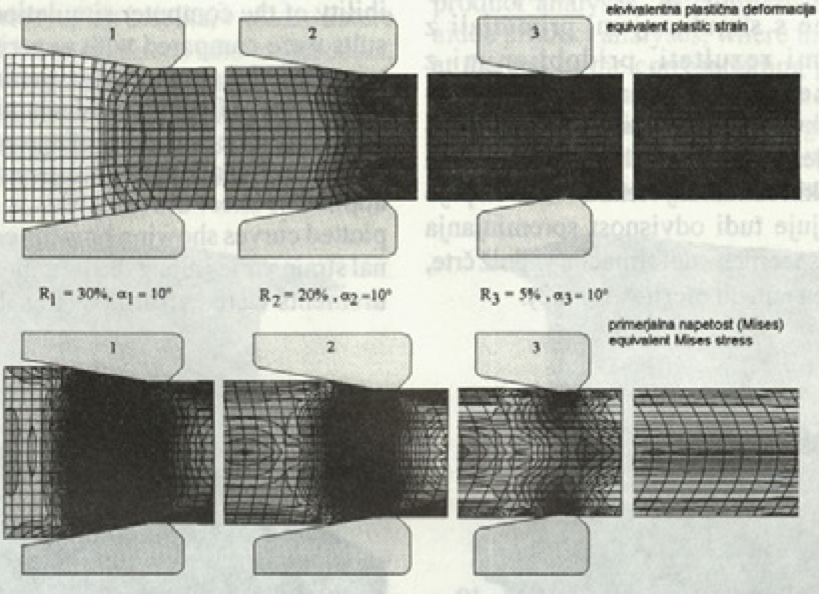
Obremenitve, ki naj bi jih konstrukter upošteval pri snovanju orodja, izhajajo neposredno iz tehnološkega procesa. Pri preoblikovalnih procesih izvirajo te obremenitve iz odpora, ki ga daje preoblikovani material pri spreminjanju oblike. Da bi lahko opredelili ta odpor, je treba mehanske spremembe, ki se dogajajo pri geometrijski preobrazbi,

3.2 Product analyses

The loadings that a designer should take into account when designing a tool derive directly from the related technology process. In metal forming processes, these loads result from the resistance that a formed material undergoes against the changing of its shape. In order to define this resistance it is necessary to quantify the mechanical changes that are associated with the given geometry transformation.

kvantificirati. Za preprostejše procese so sicer na voljo pripomočki v obliki nomogramov ali polanalitičnih rešitev, vendar je njihova prilagodljivost običajno majhna. Zmožnosti, ki jih dajejo računalniške analize, pridejo prav pri razpoznavanju tako zapletenega materialnega odziva do polne veljave.

For simpler processes, use can be made of several resources such as nomograms and semi-analytical solutions, but their versatility is usually rather poor. It is by the identification of a material response characterizing a complex process that the power of computational analyses is really asserted.



Sl. 9. *Analiza tristopenjskega vleka žice: porazdelitev deformacijskega in napetostnega stanja*
Fig. 9. *Analysis of the three-step wire drawing: strain and stress field distribution*

Med razlogi za računalniško podprto analizo dogajanja v izdelku na njegovi poti skozi proces pa ni le razpoznavanje potrebne preoblikovalne sile, marveč tudi dejstvo, da je o kakovosti izdelka po končanem procesu mogoče soditi izključno ob poznavanju celotnega razvoja sprememb med procesom. Spremljanje sprememb skozi proces daje možnost identificiranja morebitnih odstopanj od želenega, s tem pa ustrezne spremembe procesa.

Računalniško analizo izdelka na poti skozi proces prikazuje slika 9. Slika prikazuje razvoj plastične deformacije ter primerjalne napetosti v procesu tristopenjskega vlečenja žice. Stanje izdelka na izhodu iz procesa, predvsem je tu zanimivo stanje zaostalih napetosti, je v celoti odvisno od razvoja sprememb, te pa so posledica vrste dejavnikov: stopnje redukcije prereza, vlečnih kotov, hitrosti vlečenja, tornih razmer, utrjevalne karakteristike materiala itn. Iz analize razvoja deformacijskega in napetostnega stanja je mogoče objektivno sklepati o pravilnosti poteka procesa in pri nepravilnosti izvesti spremembo procesnih parametrov.

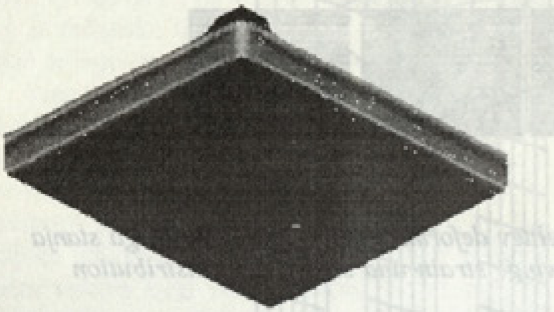
Pri globokem vleku pločevine je eden od pomembnih kazalcev dosežene kakovosti izdelka njegova debelina. Spreminjanje te glede na napredovanje procesa je mogoče opazovati z računalniškim simuliranjem vleka. Slika 10 prikazuje

The identification of the forming force necessary for the forming operation is certainly not the only reason for using CAE. Actually, prediction of the product's quality cannot be made unless one knows the whole development of the physical transformations that occur during the process. Tracing this development throughout the process allows for revelation of eventual deviations from the desired response, and hence also makes it possible suitably to modify the process.

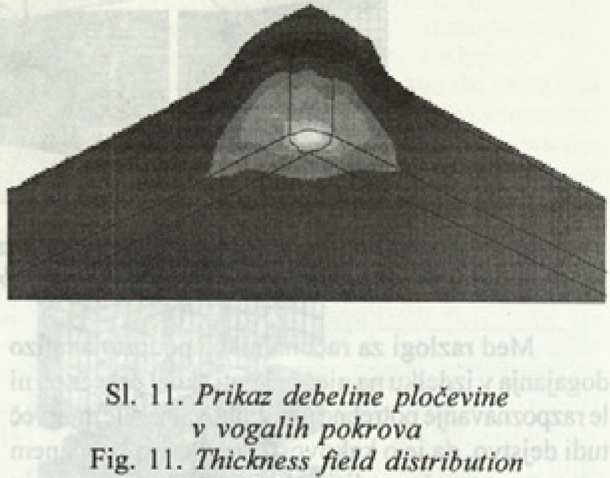
The results of such a computational analysis of a product on its way through the process are displayed in Figure 9. The process considered is the three-step wire drawing, and the quantities displayed are, respectively, the equivalent plastic strain and the equivalent stress. The state of the product exiting the process - the residual stresses being here most interesting - is entirely conditioned by the previous history of the physical changes, which are themselves affected by a series of factors: area reduction rate, die angles, drawing speed, friction, material hardening, etc. From the investigation of deformation and stress field evolution one can objectively judge about the regularity of the process course, and in case of irregularity a modification of the process parameters can be made.

The product quality attained in deep sheet drawing can be directly correlated with its thickness, the variation of which through the drawing process can be quantitatively followed by computer simulation. In this context we consider drawing of a flat končno obliko četrtine pokrova, katerega vlek je bil računalniško simuliran. Na sliki so lepo vidna ušesa, ki nastanejo v vogalih pokrova. Prav tako je v detajlu izvlečenega vogala (sl. 11), kjer je prikazano spreminjanje debeline, izredno jasno vidno mesto, kjer je debelina pločevine po vleku kritična. Da bi potrdili verodostojnost računalniškega simuliranja, smo rezultate, dobljene s simuliranjem, primerjali z eksperimentalnimi rezultati, pridobljenimi z grafometrično metodo v Laboratoriju za preoblikovanje na Fakulteti za strojništvo v Ljubljani. Dosežena stopnja ujemanja je bila velika, kar zagotavlja izvajanje računalniških simuliranj vleka z veliko stopnjo zaupanja. To potrjuje tudi odvisnost spreminjanja računsko določene specifične deformacije vzdolž črte, kjer je bila izvedena ena od meritev (sl. 12).

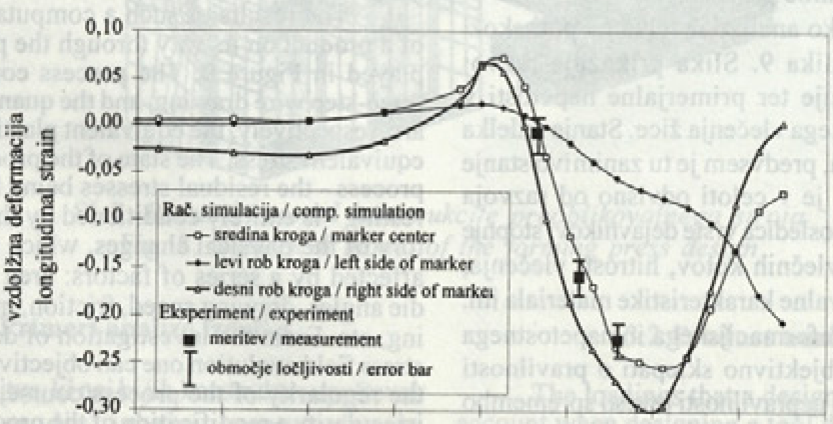
cover. From the picture in Figure 10, showing a quarter of the drawn cover, such as obtained by simulation, ears that result in the corners of the cover can be easily found out, while from a detail of the zoomed corner area displaying variation of the sheet thickness (Fig. 11) a place critical with respect to the thinning is clearly visible. In order to confirm the credibility of the computer simulation the computed results were compared with experimental results, obtained by the graphometric method in the Forming laboratory of Faculty of Mechanical Engineering in Ljubljana. The high level of agreement attained gives a firm confidence to the computer simulations, when applied to sheet drawing; this is also proved by the plotted curves showing how the computed longitudinal strain varies along the line, along which the measurements were performed (Fig. 12).



Sl. 10. *Končna oblika četrtine pokrova*
Fig. 10. *Final shape of the cover (a quarter segment)*



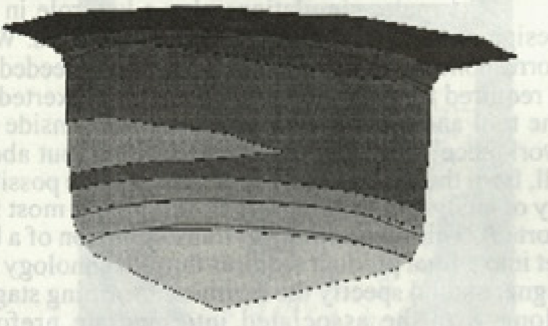
Sl. 11. *Prikaz debeline pločevine v vogalih pokrova*
Fig. 11. *Thickness field distribution in the cover corner area*



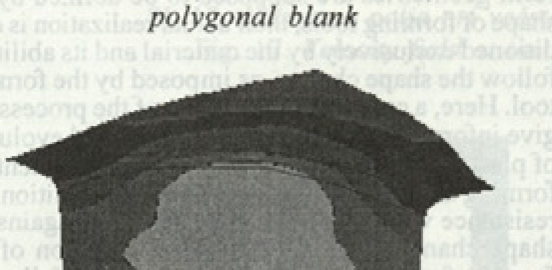
Sl. 12. *Primerjava izračunanih z izmerjenimi deformacijami*
Fig. 12. *Computation versus experiment strain comparison*

3.3 Primeri analize procesa

V poprejšnjem razdelku smo ugotovili, da je analizo končnega izdelka nemogoče izvesti, ne da bi pri tem simulirali tehnološki proces. Računalniško orodje, ki ga potrebujemo za analizo procesa, je torej povsem enako kakor pri analizi izdelka. Glede na računalniško podprto analizo izdelka, v okviru katere smo ugotavljali, kakšen je izdelek na izhodu iz procesa, gre pri analizi tehnološkega procesa za nasprotno nalogo. Cilj računalniško podprte analize procesov je določitev procesnih parametrov, ki bodo zagotovili izdelek zahtevanih lastnosti in kakovosti.



Sl. 13. *Debelina pločevine pri 16-kotni platini*
Fig. 13. *Thickness field distribution by 16-side polygonal blank*

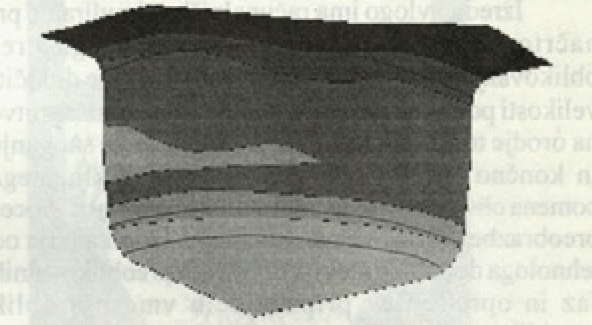


Sl. 15. *Debelina pločevine pri 4-kotni platini*
Fig. 15. *Thickness field distribution by 4-side polygonal blank*

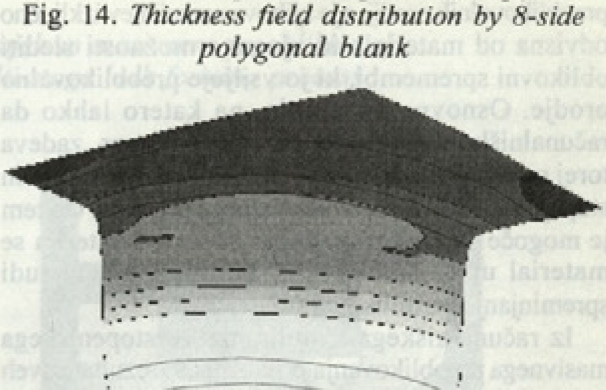
Spekter možnosti, ki jih daje računalniško simuliranje, začnimo s primerom globokega vleka pločevine v posodo rotacijske oblike. V okviru izbire procesnih parametrov smo analizirali najprej vpliv začetne oblike pločevine, zatem pa še vpliv držalne sile. Ob privzetju 16-, 8- in 4-kotne začetne oblike pločevine smo pri isti držalni sili analizirali potrebno vlečno silo ter končno debelino izdelka. Iz porazdelitev debeline, ki so prikazane na slikah 13, 14 in 15, je mogoče razbrati vpliv začetne oblike pločevine na njen

3.3 Process analyses

It has been established in the preceding section that it is impossible to analyse a final product without simulating the associated technology process. Therefore, the computational means needed for process analyses are much the same as those met in product analyses. In comparison to the computer aided product analyses, where the state of a product at the end of the corresponding process is to be established, the analysis of a technology process deals with a just inverse task, its main goal being the specification of process parameters, which will yield the product the required properties and quality.



Sl. 14. *Debelina pločevine pri 8-kotni platini*
Fig. 14. *Thickness field distribution by 8-side polygonal blank*



Sl. 16. *Debelina pločevine pri 4-kotni platini in večji držalni sili*
Fig. 16. *Thickness field distribution by 4-side polygonal blank and increased blank holding force*

Let a spectrum of possibilities enabled by computer simulation be started with the case of deep drawing of a sheet into a cup of axisymmetrical shape. In the parametric analysis, we analysed first the influence of the blank geometry, and afterwards the influence of the blank holding force. By assuming consecutively a 16-, 8- and 4-sided regular polygon as the blank shape, while keeping the blank holding force constant, we analysed how this affected the drawing force and thickness of the product. From the thickness field distributions plotted in Figures 13, tok prek robu vlečne matrice. Porazdelitvi debeline na slikah 15 in 16 pa prikazujeta vpliv različne držalne sile. S slike 16, na kateri je prikazana debelina za primer 35% večje držalne sile, je razvidno izrazito zmanjšanje debeline v dnu izvlečene posode, ki vodi do pretrga. Tudi ti računalniško analizirani primeri so bili eksperimentalno potrjeni.

Iz takšne analize globokega vleka je mogoče izvesti še vrsto raziskav. Tako so vselej zanimiva vprašanja v zvezi z največjo preoblikovalnostjo, najmanjšimi dopustnimi vlečnimi polmeri, koncentracijami kontaktnega pritiska, ki vpliva na obrabo orodja, vplivom, ki ga imajo različna mazalna sredstva itn.

Izredno vlogo ima računalniško simuliranje pri načrtovanju večstopenjskega masivnega preoblikovanja. Pri tem, da je z analizo mogoče določiti velikosti potrebne preoblikovalne sile in obremenitve na orodje ter stanje v preoblikovancu, je za snovanje in končno načrtovanje takega procesa ključnega pomena obstoj možnosti analize toka materiala. Proces preobrazbe od surovca do končnega izdelka terja od tehnologa določitev števila potrebnih preoblikovalnih faz in opredelitev pripadajočih vmesnih oblik preoblikovanca.

Oblika slednjih naj bi sicer bila določena z obliko preoblikovalnih orodij, a je njihova uresničitev izključno odvisna od materiala in njegove možnosti slediti oblikovni spremembi, ki jo vsiljuje preoblikovalno orodje. Osnovno vprašanje, na katero lahko da računalniško simuliranje procesa odgovor, zadeva torej materialni tok, razvoj plastične deformacije in stopnjo izpolnitve preoblikovalnega prostora. Ob tem je mogoče spremljati velikost odpora, s katerim se material upira spremembi oblike, in s tem tudi spreminjanje preoblikovalne sile.

Iz računalniškega simuliranja večstopenjskega masivnega preoblikovanja prikazujemo rezultate dveh vmesnih faz preoblikovanja. Slika 17 prikazuje razvoj hitrostnega tokovnega polja za štiri lege orodja v vsaki stopnji. Iz oblike preoblikovanega materiala ob koncu posamezne preoblikovalne stopnje je mogoče razbrati, da je stopnja izpolnjenosti preoblikovalnega prostora zadovoljiva. Za analizo je pomembna tudi velikost plastične deformacije, ki se navzven sicer kaže s spremembo geometrijske oblike, a je njena prostorska porazdelitev predvsem odločilna kot merilo notranjega odpora. Spremljanje prostorskega razvoja plastične deformacije omogoča tudi lociranje morebitnih mest, kjer bi zaradi prevelike deformacije lahko prišlo do razpok. S slike 18, na kateri je prikazan razvoj polja plastične deformacije za proces, obravnavan na sliki 17, je mogoče razbrati, da se mesta največje plastične deformacije pojavijo ob dnu pestiča. Odpor, ki ga je treba pri nastanku te deformacije premagati, se neposredno prenaša na pestič, ki je na tem mestu izpostavljen največji obrabi.

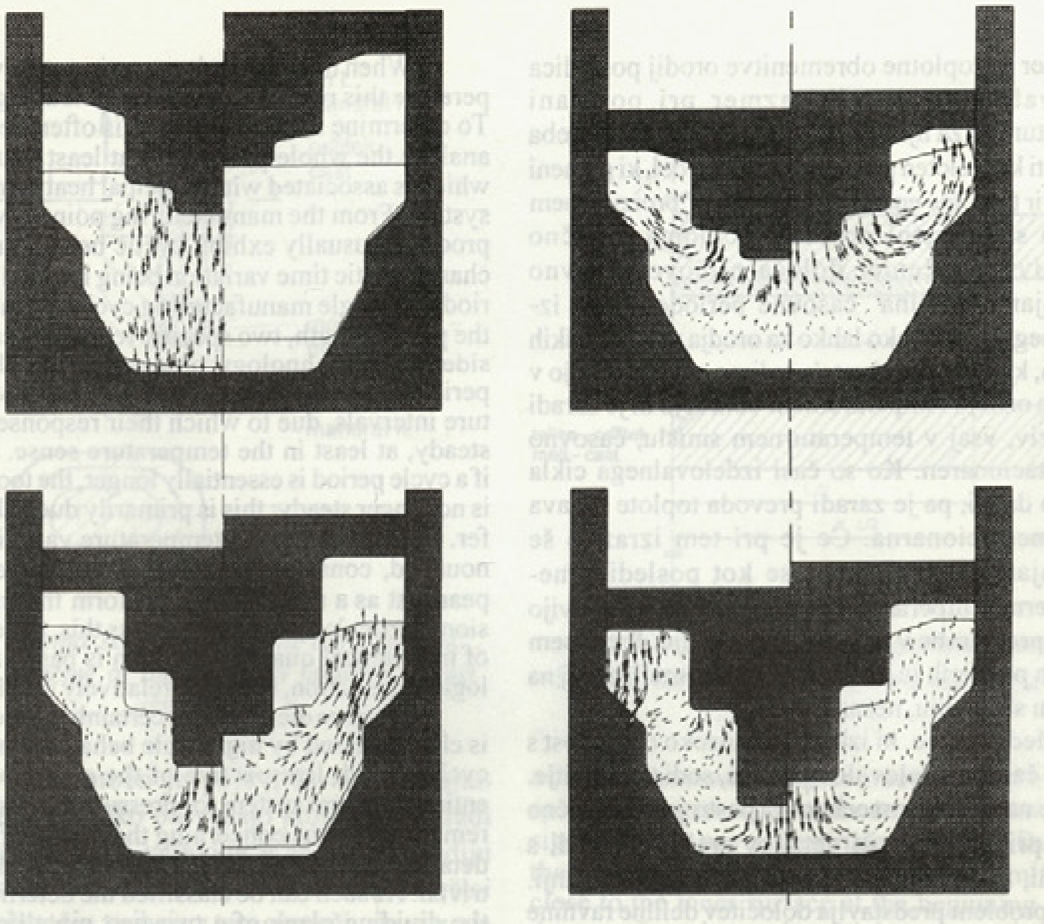
14 and 15, the influence of the blank shape on the material flow across the die edge can be guessed. The corresponding distributions in Figures 15 and 16, which refer to the same blank shape, show however the influence of different blank holding forces. A 35% increase in the blank holding force causes, as is seen from Figure 16, a significant reduction in thickness at the bottom of the cup, which leads to its fracture. All the above computationally obtained results have been experimentally confirmed as well.

On the basis of such deep drawing analysis a series of further issues could be investigated. Issues concerning deformability limits, maximum admissible die curvatures, concentrations of contact pressure in relation to tool wear, influence of different lubricants, etc. are always of great interest.

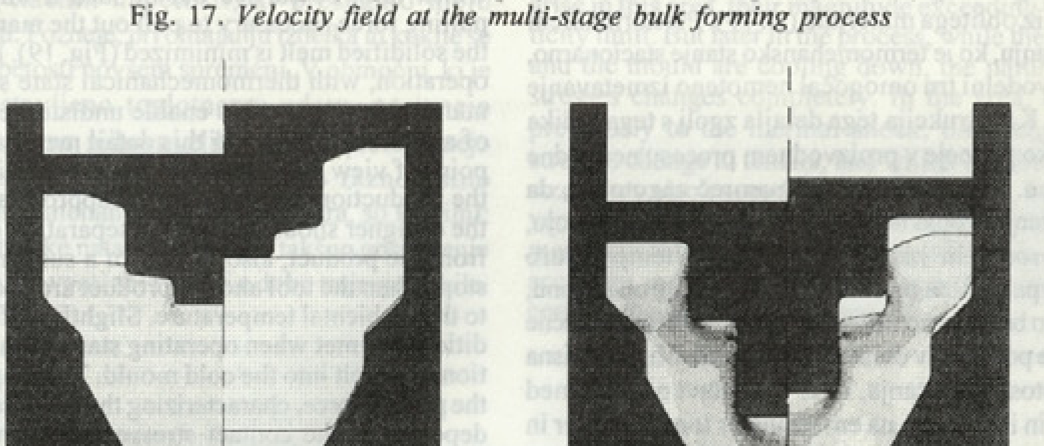
Computer simulations play a key role in the design of multi-stage bulk forming processes. With corresponding analyses, the forming force needed for a required forming - as well as loadings exerted on the tool and associated mechanical state inside the workpiece - can of course be quantified, but above all, from the designing point of view it is the possibility of analysing the material flow which is most important. This means that the transformation of a billet into a final product requires that a technology designer should specify the number of forming stages, along with the associated intermediate preform geometries needed for the given transformation.

Although it is true that the intermediate preform geometries are supposed to be defined by the shape of forming tools, their actual realization is conditioned exclusively by the material and its ability to follow the shape change, as imposed by the forming tool. Here, a computer simulation of the process can give information on the material flow and evolution of plastic deformation, as well as to what extent the forming area is filled by the material. In addition, the resistance with which the material fights against its shape change, and the associated variation of the forming force through the process, can be followed.

From computer simulations of a multi-stage bulk forming case the results of two intermediate forming stages will now be shown. Figure 17 displays the corresponding velocity fields associated with four distinct tool positions within each forming stage. The material contours obtained at the end of each forming stage confirm that the degree of filled forming area is satisfactory. Another important quantity for the investigation is the degree of plastic deformation, which is actually visualized externally through a corresponding change of the preform geometry, but it is its internal distribution which is decisive for the internal forming resistance. Furthermore, those areas which, because of too large deformation, might eventually crack, can be efficiently located by tracing the spatial evolution of plastic deformation. Observation of the plastic deformation fields in Figure 18 - as they are developed during ongoing of the process considered in Figure 17 - reveals that the areas of largest plastic deformation appear at the bottom of the punch. This zone, being subjected to the loads of great intensity which arise while overcoming the material resistance against deformation, is inevitably exposed to intensive wear.



Sl. 17. *Hitrostna polja pri večstopenjskem masivnem preoblikovanju*
Fig. 17. *Velocity field at the multi-stage bulk forming process*



Sl. 18. *Razvoj stanja plastičnih deformacij pri večstopenjskem masivnem preoblikovanju*
Fig. 18. *Development of the equivalent plastic strain at the multi-stage bulk forming process*

Že v uvodu smo omenili, da so orodja pri mnogih tehnoloških procesih lahko izpostavljena obremenitvam, ki so posledica delovanja procesa v temperaturno spremenljivih razmerah. Najosnovnejši primer, a še zdaleč ne najpreprostejši, je toplotna obdelava orodij. Z njo se srečamo še preden začne orodje delovati v svoji osnovni namenski funkciji. Ker je problem izredno fizikalno zapleten, bomo v nadaljevanju posvetili pozornost le preprostejšim, a še vedno dovolj zahtevnim, predvsem pa dovolj značilnim primerom.

As mentioned in the introduction, in many of the technology processes tools can be exposed to loads that result from a process which is operating under temperature dependent conditions. Such a case is the heat treatment of tools, which is perhaps the most basic, but certainly not the simplest case. It should be stressed that heat treatment is performed even before a tool starts to operate in accordance with its regular working function. Due to the extraordinary physical complexity of such problems only simple cases - but still exacting and above all characteristic enough - will be considered in the sequel.

Ker so toplotne obremenitve orodij posledica obratovalnih procesnih razmer pri povišani temperaturi, je za njihovo določitev največkrat treba analizirati kar celoten proces ali vsaj tisti del, ki pomeni ključni vir toplotne energije v sistemu. V proizvodnem pomenu so tovrstni procesi večinoma ciklično ponovljivi, pri čemer določa njihovo časovno spreminjanje dolžina časovne periode enega izdelovalnega cikla. Tako lahko za orodja v tehnoloških procesih, kjer je ta čas kratek, trdimo, da obratujejo v relativno ozkem temperaturnem območju in je zaradi tega odziv, vsaj v temperaturnem smislu, časovno skoraj stacionaren. Ko so časi izdelovalnega cikla bistveno daljši, pa je zaradi prevoda toplote narava odziva nestacionarna. Če je pri tem izrazito še spreminjanje temperature, se kot posledica neenakomerne temperaturne razteznosti lahko pojavijo znatne spremembe v napetostnem stanju. Predvsem v takšnih primerih je ocena stanja, ki temelji zgolj na logičnem sklepanju, nezanesljiva.

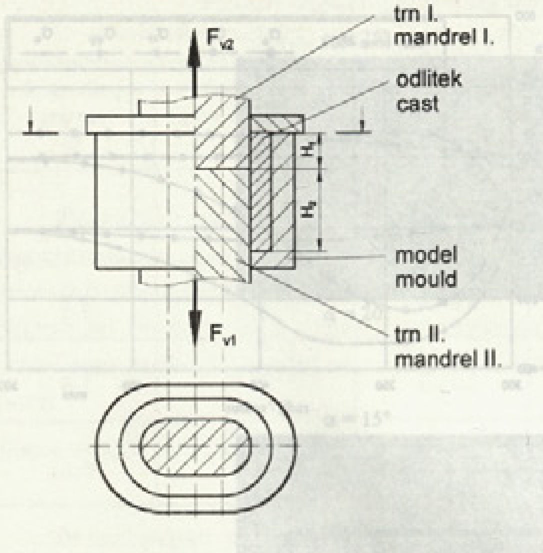
Med procese, ki izkazujejo visoko cikličnost s kratkim časom izdelovalnega cikla, sodi tlačno litje. Ne glede na zapletenost celotnega postrojenja za tlačno litje se pri konstrukciji detajlov srečujemo tudi s problemi, ki so relativno preprosti, a ne vsakdanji. Takšen problem predstavlja določitev delilne ravnine dvodelnega trna glede na najmanjšo potrebno silo pri izvleku iz oblitega materiala (sl. 19). Pri normalnem obratovanju, ko je termomehansko stanje stacionarno, naj bi dvodelni trn omogočal nemoteno izmetavanje izdelka. Konstrukcija tega detajla zgolj s tega vidika ima lahko pozneje v proizvodnem procesu neugodne posledice. Konstrukter mora namreč zagotoviti, da bo ločevanje orodja in izdelka mogoče tudi pri zastoju, ko se orodje in izdelek ohladita na temperaturo okolice, pa tudi, da bo obratovanje mogoče ob zagonu, ko zlitino brizgnemo v hladno orodje. Velikost izvlečne sile, ki je potrebna v obravnavanih primerih, je odvisna od napetostnega stanja, ki se vzpostavi na meji med trnoma in izdelkom, na eni strani ter tornih razmer in delilne ravnine na drugi strani. Problem določitve delilne ravnine je v primeru, ko je porazdelitev temperaturnega polja po višini simetrična, trivialen, kar seveda ne bi veljalo v primeru po višini spremenljive geometrije izdelka.

Še bolj poučen je primer spreminjanja napetostnega stanja v kokili stroja za rotacijsko litje (sl. 20). Čas enega cikla je v tem primeru dolg, temperaturne spremembe, katerim je izpostavljena kokila, pa velike (sl. 21). Analiza pokaže, da je vpliv rotacije in centrifugalne sile na napetostno stanje v kokili zanemarljiv v primerjavi z napetostmi, ki nastanejo zaradi toplotne razteznosti. Spreminjanje napetosti v obliki, kakor ga prikazujejo odvisnosti na sliki 22, bi le težko napovedali brez poprejšnjih

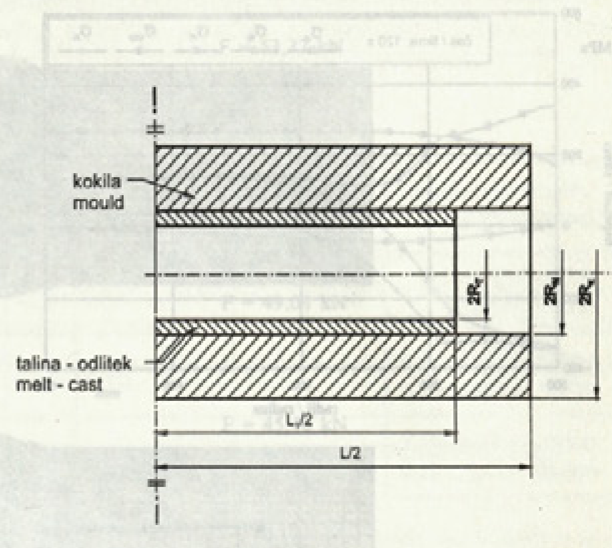
When the process is operating at elevated temperature this results in the thermal loading of a tool. To determine such a loading it is often necessary to analyse the whole process, or at least that part of it which is associated with principal heat sources in the system. From the manufacturing point of view, such processes usually exhibit cyclic behaviour with the characteristic time variation being implied by the period of a single manufacturing cycle. With respect to the period length, two specific responses can be considered. In technology processes with short cycle periods, tools operate in relatively narrow temperature intervals, due to which their response is almost steady, at least in the temperature sense. However, if a cycle period is essentially longer, the tool response is no longer steady; this is primarily due to heat transfer. If, in addition, the temperature variation is pronounced, considerable changes in stresses can appear just as a result of non-uniform thermal expansion. Particularly in cases such as this, the estimation of mechanical quantities, which is based merely on logical deduction, becomes relatively unreliable.

Pressure die casting is certainly a process which is characterized by high cycle behaviour and a short cycle period. Irrespective of the complexity of the entire structural system for pressure die casting, there remain problems concerning the design of structural details; these are relatively simple, but certainly not trivial. As such can be classified the determination of the dividing plane of a two-part metallic mandrel, which is to be carried out in such a way that the pulling force necessary to pull out the mandrel from the solidified melt is minimized (Fig. 19). By regular operation, with thermomechanical state steady, the mandrel is supposed to enable undisturbed ejection of a product. Designing this detail merely from that point of view may lead later on to complications in the production process. For, by appropriate design, the designer should assure the separation of the tool from the product, also in case of a sudden irregular stop, when the tool and the product are cooled down to the ambiental temperature. Slightly different conditions are met when operating starts with the injection of a melt into the cold mould. The magnitude of the pulling force, characterizing the cases considered, depends on the contact stresses between the two-part mandrel and the product on the one hand, and on friction conditions and position of the dividing plane on the other. In the case of temperature field distribution, which is symmetrical along the axial direction, the determination of the dividing plane is trivial. This, however, is not true if the product's geometry does not show symmetry.

Even more instructive is the stress analysis of a mould in rotary casting processes (Fig. 20). Here, the duration of a single cycle is rather long, and hence the temperature changes to which the mould is exposed are large (Fig. 21). The analysis shows that in comparison to stresses caused by thermal expansion, the rotation and centrifugal forces have a relatively negligible influence on the stress state in the mould. The variation of stresses, as shown in Figure 22, clearly demostrates how difficult it would be to predict such



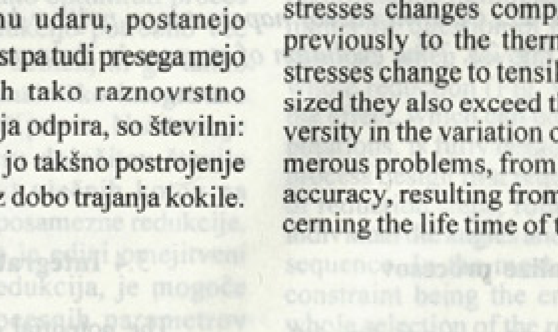
Sl. 19. *Shema sestava dvodelni trn - izdelek*
Fig. 19. *Scheme of the two-part mandrel - cast assembly*



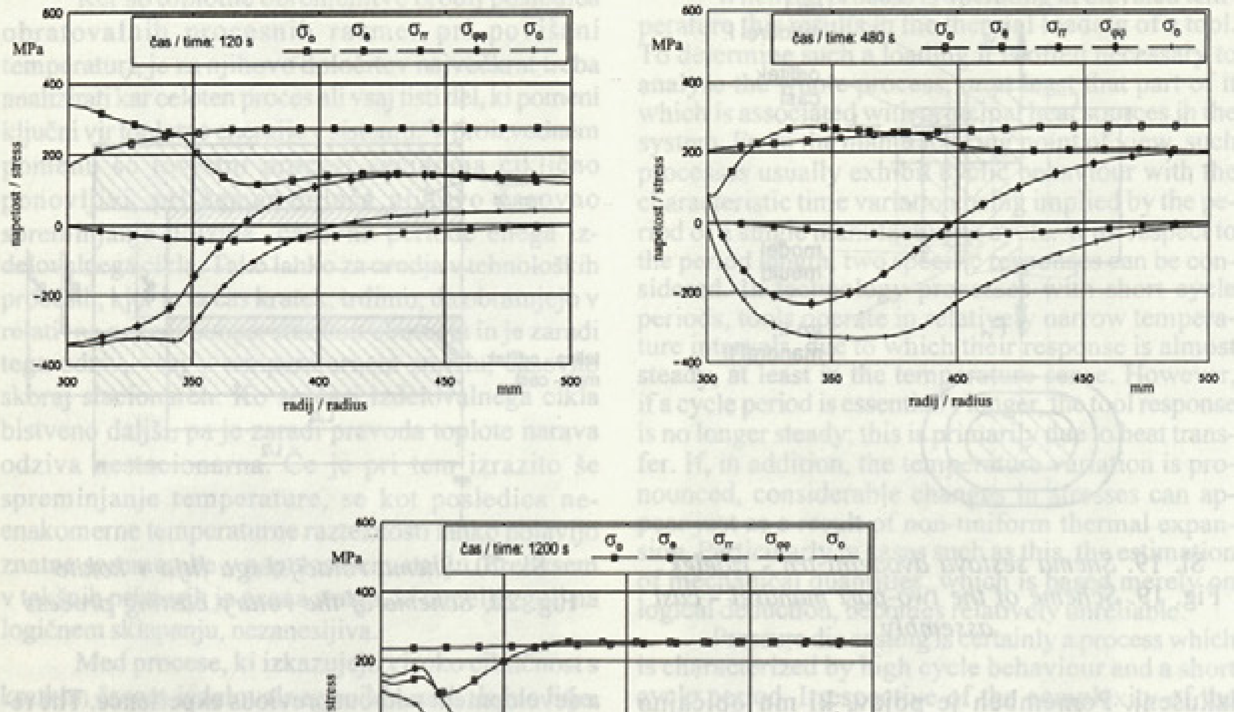
Sl. 20. *Shema rotacijskega litja v kokilo*
Fig. 20. *Scheme of the rotary casting process*

izkušenj. Pomemben je pojav, ki mu običajno konstrukterji le redko posvečajo pozornost. Zaradi toplotnega udara, ki učinkuje v začetnem stadiju obratovalnega cikla le na omejenem, notranji površini bližnjem območju, prihaja v tem območju do razvoja pretežno tlačnih napetosti, ki presegajo mejo elastičnosti. Pozneje, pri ohlajanju izdelka in kokile se narava napetosti povsem spremeni. V območju, ki je bilo izpostavljeno toplotnemu udaru, postanejo napetosti natezne, njihova velikost pa tudi presega mejo elastičnosti. Problemi, ki jih tako raznovrstno spreminjanje mehanskega stanja odpira, so številni: od geometrijske natančnosti, ki jo takšno postrojenje lahko daje, do vprašanj v zvezi z dobo trajanja kokile.

a development without previous experience. The response is governed by a phenomenon to which designers rarely pay appropriate attention. Due to the thermal shock, which acts merely in a limited area, close to the inner surface at the beginning stage of the manufacturing cycle, mainly compressive stresses arise in this area, their magnitude exceeding the elasticity limit. But later in the process, while the product and the mould are cooling down, the nature of the stresses changes completely. In the area, exposed previously to the thermal shock, the compressive stresses change to tensile, and which is to be emphasized they also exceed the elasticity limit. Such a diversity in the variation of mechanical state raises numerous problems, from those regarding geometrical accuracy, resulting from such a system, to those concerning the life time of the mould.



Sl. 21. *Časovni razvoj temperaturnega polja v sestavu odlitek - kokila*
Fig. 21. *Time evolution of temperature in the cast - mould assembly*



Sl. 22. *Časovni razvoj napetostnega polja v kokili*
Fig. 22. *Time evolution of stresses in the mould*

3.4 Integrirane analize procesov

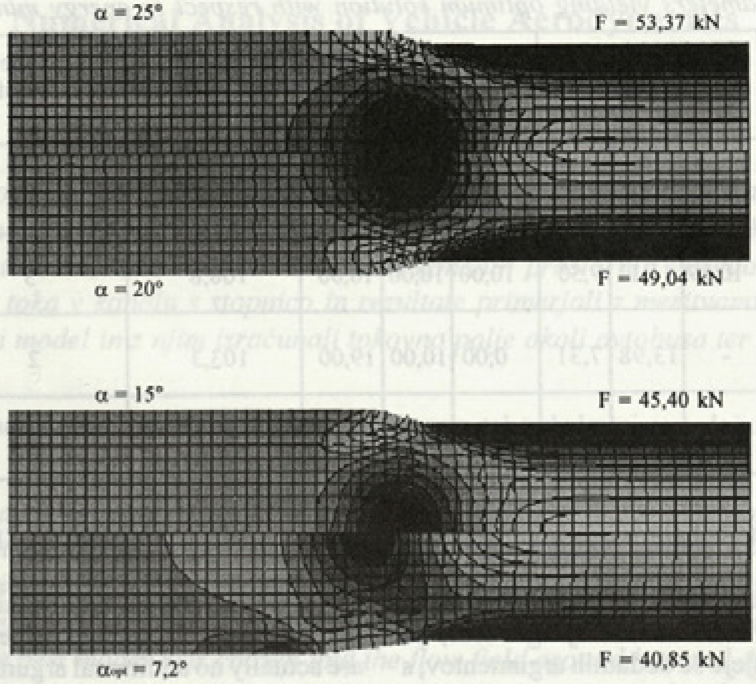
Primeri, ki smo jih v prejšnjih razdelkih prikazali, prepričljivo potrjujejo moč računalniško podprtih analiz. Obvladovanje teh omogoča nadaljnje možnosti, predvsem v smeri matematičnega optimiranja tehnoloških procesov, kar je moč doseči z integracijo računalniških orodij numerične analize in matematičnega optimiranja. Predvsem pri serijski proizvodnji je optimiranje pomembna ekonomska postavka.

V nadaljevanju obravnavajmo optimiranje procesa vlečenja žice. Že iz analize vlečenja skozi stožčasto matrico pri predpisani redukciji prereza, ki je prikazan na sliki 23, je več ko očiten vpliv vlečnega kota matrice na potrebno silo vlečenja, s tem pa na energijo, ki jo moramo zagotoviti v procesu.

3.4 Integrated process analyses

The potential of computer aided analyses is proved very convincingly by the cases considered in the previous sections. Mastering them gives further possibilities, above all in the mathematical optimisation of technology processes, which can be attained by integrating computer codes of numerical analysis with a corresponding mathematical optimisation program. Especially in serial production, the optimisation has an important economical impact.

In the sequel, the optimisation of the wire drawing process will be considered. Yet from the analysis of drawing through conical dies of different geometry at a prescribed area reduction, as shown in Figure 23, the influence of a die angle on the magnitude of drawing force, and consequently on the amount of energy needed to perform the process, is more than apparent.



Sl. 23. *Porazdelitev vzdolžne napetosti pri vlečenju žice*

Fig. 23. *Axial stress field distribution in the wire drawing process*

Vlečenje z enostopenjsko redukcijo je v literaturi že zadovoljivo popisano tudi glede optimiranja, vendar se zastavi vprašanje, kako optimirati proces vlečenja, ko je za celotno redukcijo potrebno več stopenj (sl. 9). Nedvomno se učinek, ki ga lahko dosežemo z obravnavano računalniško integrirano metodologijo, pokaže v polni moči prav tu. Načrtovanje procesa obsega v tem primeru določitev števila redukcijskih stopenj, velikost vlečnih kotov na posamezni stopnji ter velikost posamezne redukcije. V najsplošnejšem primeru, ko je edini omejitveni podatek celotna zahtevana redukcija, je mogoče prepustiti celotno izbiro procesnih parametrov računalniški odločitvi. Preglednica 1 prikazuje alternativne variante takšnega optimalnega izračuna. Izhajajoč iz začetne zasnove, ki jo je načrtoval tehnolog v obliki tristopenjskega vleka s predpisanimi procesnimi parametri, sta računalniško izbrani optimalni varianti predvideli le dve stopnji. Ko je tehnolog vztrajal na predpisanih stopenjskih redukcijah, torej tudi na številu redukcijskih stopenj, in je računalniku dopustil le izbiro vlečnih kotov, je bilo zmanjšanje celotne, za vlečenje potrebne sile skorajda nepomembno (optimalna rešitev I.). Do bistvenega zmanjšanja potrebne preoblikovalne energije pa pride, ko povsem sprostimo omejitve in računalniku prepustimo prosto izbiro števila redukcijskih stopenj in tudi velikosti redukcij in vlečnih kotov (optimalna rešitev II.b).

The knowledge about drawing in a single reduction step is fairly well described in literature, also regarding the optimisation issues. Yet there still remains the question of how to optimise the drawing process, when several steps are necessary for the whole reduction (Fig. 9). It is in this very case that the effect, which can be obtained by integrated computations, is fully demonstrated. The corresponding process design first requires definition of the number of reduction steps, followed by specification of the individual die angles and corresponding reduction rate sequence. In the most general case, with the only constraint being the entire required reduction, the whole selection of the remaining process parameters can be left to the computer. A review of such optimum computation for three alternative variants is tabulated in Table 1. Starting from the initial design, as specified by a technologist who assumed three-step drawing at given process parameters, two computationally chosen variants yield only two steps. If one insists on the initially prescribed reduction sequence, and consequently on the number of reduction steps, the decrease in the total drawing force, obtained by computer merely by the optimisation of die angles, is almost insignificant (optimum solution I.). When, however, the parameter limitations are completely dropped and free choice of reduction steps, together with the corresponding reduction rate and die angle sequence is left to the computer, the necessary forming energy decreases considerably (optimum solution II.b).

Preglednica 1. *Konstrukcijski parametri, ki definirajo energijsko optimalno rešitev*
Table 1. *Design parameters yielding optimum solution with respect to energy minimization*

	vlečni koti die angles °			stopnja redukcije reduction rate %			vlečna sila drawing force kN	št. stopenj number of steps	prihranek saving %
izhodiščna rešitev initial design	10,00	15,00	7,00	10,00	10,00	10,00	112,0	3	0,0
optim. rešitev - I. optim. design - I.	10,39	11,11	7,50	10,00	10,00	10,00	108,8	3	2,9
optim. rešitev - II.a optim. design - II.a	-	13,98	7,31	0,00	10,00	19,00	103,3	2	7,8
optim. rešitev - II.b optim. design - II.b	9,80	-	6,97	19,00	0,00	10,00	88,9	2	20,6

4 SKLEP

Prikazani primeri ter z njimi povezana razmišljanja so sami zase že dovolj zgovorni, da pravzaprav ne potrebujejo še dodatnih argumentov, s katerimi bi utemeljevali primernost računalniško podprtih analiz ter računalniškega simuliranja. Zahtevnost problemov, s katerimi se srečujeta tehnolog in konstrukter pri snovanju in postavljanju tehnološkega procesa, je v splošnem tolikšna, da je odklanjanje podpore, ki nam jo ponuja CAE, skrajno neodgovorno.

4 CONCLUSION

Since all the cases considered, together with the associated discussions, are eloquent enough there are actually no additional arguments needed to prove the reason for computer aided analyses and computer simulations. The complexity of the problems, which is dealt with by the technologists and designers by designing and setting up a technology process, is in general of such extent that to refuse the aid offered by CAE would be extremely irresponsible.

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