Universitatea
Politehnica
Timișoara

Politehnica University Timișoara

Awarding the academic title of
DOCTOR HONORIS CAUSA
to

Academician Dorel BANABIC

Timișoara
May 11th, 2023

Universitatea Politehnica Timişoara

Decernarea Titlului Academic de

DOCTOR HONORIS CAUSA

domnului

Academician Dorel BANABIC

Timişoara
11 Mai 2023

UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA

Universitatea
Politehnica
Timişoara

Academician Dorel BANABIC

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Laudatio

adresat domnului

Academician Dorel BANABIC

din partea
Senatului Universităţii Politehnica Timişoara

addressed to

Academician Dorel BANABIC

by
Politehnica University Timișoara Senate

Laudatio

Distinşi oaspeţi şi colegi,
Onorată asistenţă,
Doamnelor şi domnilor,

Senatul Universităţii Politehnica Timişoara (UPT) s-a reunit astăzi în şedinţă festivă în vederea decernării titlului academic de DOCTOR HONORIS CAUSA domnului Academician Dorel BANABIC de la Universitatea Tehnică din Clun-Napoca pentru remarcabilele sale realizări în activităţile didactice, de cercetare şi cooperare naţională şi internaţională, inclusiv cu universitatea noastră.

Scurtă prezentare a personalităţii ştiinţifice a domnului Academician Dorel BANABIC

Comisia de specialitate, numită prin Decizia nr. 543/112/C din data de 03.05.2023 a Consiliului de Administraţie în componenţa:

Preşedinte :
  Prof.dr.ing.Liviu Marşavina, Membru corespondent al Academiei Române
Membri:
  Academician Dan DUBINĂ
  Academician Ion BOLDEA
  Prof.univ.dr.ing. Radu-Emil PRECUP, Membru corespondent al Academiei Române
  Conf. univ. dr. ing. Florin DRĂGAN

Domnul academician Dorel Banabic s-a născut în 3 octombrie 1956 la Ciceu-Giurgesti, judeţul Bistriţa-Năsăud. A urmat cursurile liceului Andrei Mureşanu, Dej, la clasa specială de matematică, pe care l-a absolvit în anul 1975.

A absolvit Institutul Politehnic din Cluj-Napoca, Facultatea de Mecanică, secţia Tehnologia Construcţiilor de Maşini în anul 1980. În perioada 1980-1984 a lucrat în industrie, ca inginer proiectant, întâi la Întreprinderea "Mecanica" din Sibiu, apoi la Fabrica de maşini de rectificat din Cluj-Napoca.

Din 1984 a devenit cadru didactic al Institutul Politehnic din Cluj-Napoca, actuala Universitate Tehnică, fiind profesor al acestei prestigioase instituţii de învăţământ din anul 1996.

În perioada elaborării tezei de doctorat, precum şi imediat după susţinerea acesteia a efectuat stagii de specializare sub coordonarea unora dintre cei mai cunoscuţi şi apreciaţi specialişti în domeniul deformărilor plastice din Europa la acea vreme, profesorul Zdzislaw Marciniak de la Universitatea Tehnică din Varşovia, Polonia, profesorul Jean-Loup Chenot de la Ecole des Mines de Paris, Franţa şi profesorul Klaus Siegert de la Universitatea din Stuttgart.

În 1993 susţine teza de doctorat cu titlul "Cercetări privind deformabilitatea tablelor metalice subţiri", o lucrare de referinţă pe plan naţional şi internaţional în domeniu, care pune bazele unei activităţi ulterioare de cercetare prodigioase, care aveau să se materializeze în numeroase cărţi, lucrări, proiecte de cercetare ale academicianului Dorel Banabic şi ale discipolilor şi colaboratorilor acestuia.

Din anul 1999 devine conducător de doctorat în domeniul Ştiinţe Inginereşti, tezele de doctorat finalizate sub coordonarea sa constituind de asemenea lucrări de referinţă în domeniul deformărilor plastice. Academicianul Dorel Banabic, pe lângă numeroasele teze de doctorat din Romania cărora le-a acordat girul său ştiinţific în calitate de membru în comisia de susţinere, a fost invitat în 16 comisii de doctorat din străinătate (Franţa, Portugalia, Norvegia, Germania, Olanda, Iran si India).

Academicianul Dorel Banabic este de asemenea şi formatorul şi coordonatorul unor colective de cercetare prestigioase, fiind din anul 2000 director al Centrului de Cercetări în Tehnologia Deformării Tablelor (CERTETA) din cadrul Universităţii Tehnice din Cluj Napoca (acreditat de CNCSIS din 2002).

Academicianul Dorel Banabic este invitat să predea şi să coordoneze cercetări în calitate de profesor invitat la universităţile din Stuttgart, Paris Nord, Chemnitz, Aachen, Belfast, Metz, Moscova, Palermo, Erlangen, Warwick, Warangal (India), Xian (China). Academicianul Dorel Banabic desfăşoară şi o activitate susţinută de management academic şi ştiinţific, atât în cadrul Universităţii Tehnice din Cluj-Napoca unde este vicepreşedinte al Consiliului Cercetării şi director al Şcolii Doctorale a Facultăţii de Inginerie Industrială, Robotică şi Managementul Producţiei, cât şi pe plan naţional unde este vicepreşedinte al Consiliului Naţional de Atestare a Titlurilor, Diplomelor şi Certificatelor Universitare (CNATDCU). De asemenea, în intervalul 2006-2014 domnul academician Dorel Banabic a fost membru al Comisiei Prezidenţiale pentru Analiza şi Elaborarea Politicilor din Domeniul Educaţiei şi Cercetării, membru al Comisiei de Ştiinţe Inginereşti a Consiliul National al Cercetării Ştiinţifice din Învăţământul Superior (CNCSIS), respectiv Consiliul Naţional al Cercetării Ştiinţifice (CNCS). În intervalul 2011-2016 a fost Membru al Colegiului Consultativ al Cercetării, Dezvoltării şi Inovării (CCCDI) al Agenţiei Naţionale pentru Cercetare Ştiinţifică (ANCS). Recunoaşterea internaţională a capacităţilor ştiinţifice şi manageriale ale academicianului Dorel Banabic este certificată şi prin alegerea lui în fruntea celui mai înalt for ştiinţific european în domeniul deformărilor plastice, Asociaţia Europeană de Deformarea Materialelor (ESAFORM), al cărui preşedinte a fost în perioada 2012-2016. Este în continuare membru în Consiliul Director a ESAFORM şi editor principal al Buletinului ESAFORM.

Ca o recunoaştere a prodigioasei activităţi ştiinţifice a academicianului Dorel Banabic cesta a fost votat membru corespondent al Academiei Române în anul 2009, iar apoi în anul 2015 a devenit membru titular al Academiei Române. În prezent este Preşedintele Secţiei de Ştiinte Tehnice la Academia Română şi membru la prezidiului acesteia. De asemenea este vicepreşedinte al Comitetului Român de Istoria si Filosofia Ştiinţei şi Tehnicii (CRIFST) al Academiei Romane şi este editor principal a două jurnale cu specific ingineresc editate de Academia Română, Proceedings of the Romanian Academy şi Romanian Journal of Technical Sciences–Applied Mechanics.

A fost numit membru în comitetul ştiinţific la peste 100 de conferinţe internaţionale. Menţionăm aici doar prestigioasele serii de conferinţe NUMISHEET, NUMIFORM, ESAFORM, Metal Forming şi SHEMET, cele mai importante manifestări ştiinţifice din domeniul deformărilor plastice

Desigur, în urma activității și rezultatelor științifice obținute, academicianul Dorel Banabic a obținut și numeroase premii, dinte care amintim aici Premiul Traian Vuia al Academiei Romane pe anul 2002 pentru lucrarea "Formability of Metallic Materials", Premiul Leonardo da Vinci pe anul 2006 al Comisiei Europene pentru programul de e-learning ALUMATTER, Medalia de bronz a Președinției Germaniei pe anul 2006 pentru programul de e-learning ALUMATTER, Lee Hsun Award pe anul 2015 acordat de Institute of Metal Research Shenyang of the Chinese Science Academy precum și Ordinul național „Steaua României" în grad de Cavaler, Decembrie 2016.

Activitatea publicistică a academicianului Dorel Banabic este mai mult decât remarcabilă. Este printre primii oameni de știință din România care au obținut recunoașterea științifică internațională care i-a permis să publice cărți la unele dintre cele mai prestigioase edituri tehnice din lume: Springer (4 cărți) și Hermes Paris (1 carte).

Expertiza academicianului Dorel Banabic este solicitată de numeroase organizații internaționale de finanțare a cercetării, în calitate de evaluator al proiectelor depuse la competiții din Belgia, Canada, Germania, Italia, Olanda, Norvegia, Portugalia, Singapore. De asemenea, domnul academician a coordonat numeroase contracte de cercetare cu finanțare națională și internațională. Putem aminti aici contractele de cercetare finanțate în cadrul programelor europene FP6 și FP7, contractele finanțate de către fundația Humboldt și de către Swiss National Foundation.

Trebuie menţionată şi activitatea antreprenorială a domnului Dorel Banabic. A fost cofondatorul şi coacţionarul unei firme de succes, cu peste 1200 de angajaţi, din domeniul IT din România, firma FORTECH. Firma, înfiinţată în anul 2003, a fost vândută anul trecut concernului japonez Hitachi prin intermediul filialei sale de IT din Silicon Valley, firma Global Logic. Tranzacţia a fost considerată de succes, fiind cea mai mare tranzacţie a unei firme integral româneşti de după anul 1990 ridicând prin aceasta semnificativ valoarea celorlalte firme de IT din România.

Dl. Academician Dorel Banabic a desfăşurat o foarte intensă activitate de cercetare ştiinţifică pe plan naţional şi internaţional, coordonând peste 25 proiecte de cercetare naţionale şi a fost implicat în 12 proiecte de cercetare internaţională (în calitate de cercetător invitat la universităţi din Franţa şi Germania). Această activitate a condus la obţinerea unor rezultate semnificative cu un puternic impact atât în comunitatea ştiinţifică, cât şi industrială pe plan mondial. Principalele contribuţii ştiintifice aduse în domeniul în care lucrează şi recunoscute pe plan mondial sunt prezentate sintetic mai jos.

Dintre principalele contribuţii amintim:

- Punerea in evidență atât experimental cât și teoretic a solicitării pulsatorii asupra curbelor limita de deformare,
- Utilizarea pentru prima dată a criteriului de plasticitate Hill din 1993 în modelarea unor procese de deformare a tablelor, precum și verificarea experimentala a criteriului Hill,
- Introducerea (in colaborare cu Prof. Pöhlandt si Prof. Lange de la Universitatea din Stuttgart, Germania) a conceptului de coeficient de anizotropie biaxiala și aplicarea acestui coeficient la determinarea suprafețelor de curgere,
- Elaborarea unor modele analitice pentru umflarea hidrostatica,
- Introducerea unui criteriu de plasticitate (BBC2000) pentru medii ortotrope. Dezvoltarea ulterioară a criteriului BBC2000 în forma BBC2005 si BBC 2008,
- Elaborarea programului comercial de calcul al curbelor limita de deformare FORM-CERT,
- Elaborarea primului model teoretic al Benzilor Limita de Deformare,
- Analiza influentei presiunii hidrostatice asupra Curbelor Limita de Deformare,

- Implementarea criteriului BBC2005 in programul comercial de Element Finit AUTOFORM, utilizat de peste 95% din producătorii de autovehicule de pe plan mondial (in colaborare cu firma AUTOFORM, Zurich, Elvetia),
- Colaborarea cu Institutul de Fabricaţie Virtuala de la ETH Zurich pentru dezvoltarea modelului Hora de predictie a Curbelor Limita de Deformare,
- Colaborarea cu Catholic University of Leuven, Belgia, pentru cuplarea unui model de material bazat pe textura (Alamel) cu cel fenomenologic (BBC 2008), dezvoltat de Acad. Banabic,
- Colaborarea cu firma RENAULT pentru implementarea criteriului BBC2005 in programele de simulare pentru procesele de deformarea ale tablelor utilizate de firma,
- Colaborarea cu firma VIRTUAL VEHICLE din Graz pentru dezvoltarea de modele avansate de predicție a Curbelor Limita de Deformare,
- Colaborarea la realizarea unui curs interactiv pe internet «ALUMATTER» (redactarea capitolului de Plasticitate si Anizotropie),
- Contributia cu două capitole la prima enciclopedie de Ingineria Productiei editată de Springer in anul 2014: Encyclopaedia of Production Engineering,
- Traducerea in limba chineză de către editura Science Press Beijing a Academiei de Stiinte din China a cărtii « Sheet Metal Forming Processes » (Springer, 2010), aceasta fiind prima carte de inginerie a unui autor roman tradusă in limba chineză.
- Impactul activității de cercetare și recunoașterea internațională sunt reliefate de parametrii scientometrici din baza de date Clarivate Analytics: articole publicate indexate Web of Science 118, citari pe Web of Science 2125, indicele Hirsch 20, respectiv peste 5850 citări si indice Hirsh 35 pe Scholar Google.

Relațiile și cooperarea cu Universitatea Politehnica Timișoara

Din punct de vedere a colaborării domnului Academician Dorel Banabic cu Universitatea Politehnica din Timişoara menționam câteva aspecte. Domnia sa a început această colaborare în anul 1986 prin participarea la conferința organizată de colectivul de Tehnologii de deformare a catedrei de TCM şi ulterior la celelalte conferințe organizate de acest colectiv. A recomandat şi a susținut cadre didactice ale Politehnicii Timişorene în Secția de Ştiințe Tehnice a Academiei Române precum şi în Academia de Ştiințe Tehnice din România. A propus şi susținut cadre didactice şi cercetători din UPT în organisme ale Ministerului Educației şi Ministerului Cercetării, precum CNATDCU şi CNCS. A recomandat candidați din UPT pentru premiile Academiei Române şi/sau premii acordate de alte organizații. A participat activ cu prelegeri la simpozioane şi conferințe organizate de Politehnica din Timişoara şi/sau de Filiala din Timişoara a Academiei Române. A promovat cercetători şi grupuri de cercetare timişorene în proiecte europene. A invitat specialişti ai Politenicii Timişorene în Comitetele Editoriale ale revistelor sau cărților coordonate de Domnia Sa (Proceedings of Romanian Academy, Romanian Journal of Technical Sciences-Applied Mechanics respectiv Istoria Tehnicii şi Industriei Româneşti).

Distins auditoriu,

Ar mai fi încă multe de spus pentru a completa imaginea realizărilor și personalitatea domnului Academician Dorel BANABIC. O imagine mai completă se poate obține prin consultarea dosarului de Doctor Honoris Causa, care conține realizările profesionale, manageriale și științifice excepționale ale domniei sale. Totuși dosarul nu poate reliefa și caracterul unui om în adevăratul sens al cuvântului pe care numai prin colaborare ai privilegiul să îl descoperi.

Având în vedere cele menționate, comunitatea academică din Universitatea Politehnica Timișoara este onorată astăzi să-i acorde domnului academician Dorel Banabic titlul de Doctor Honoris Causa ca dovadă a alesei prețuiri a întregii sale activități desfășurate pentru dezvoltarea învățământului superior și a cercetării științifice românești.

Stimate domnule Academician Dorel BANABIC

Vă rog să-mi permiteți, ca în numele întregii comunități academice a Universității Politehnica Timișoara, să vă felicit pentru întreaga activitate și mai ales pentru titlul academic de Doctor Honoris Causa primit astăzi! Domnule academician, vă mulțumim și vă dorim în continuare, succes, multă sănătate și bucurii!

Vivat, crescat, floreat!

Timişoara, la 11 Mai 2023

Curriculum Vitae

Academician Dorel BANABIC

Universitatea Tehnică din Cluj-Napoca

CURRICULUM VITAE
Academician Dorel BANABIC

- DATE PERSONALE

Numele	BANABIC
Prenumele	DOREL
Data nasterii	3 octombrie 1956
Locul nasterii	Ciceu-Giurgeşti, Bistriţa-Năsăud
Adresa	Univ. Tehnica din Cluj-Napoca Facultatea de Construcţii de Maşini Dept. de Ingineria Fabricaţiei B-dul Muncii, 103-105, Cluj-Napoca, ROMANIA

- Tel.0264-401733
- e.mail: banabic@tcm.utcluj.ro

2. FORMARE PROFESIONALĂ

1971-1975	Liceul Andrei Muresanu, Dej (Clasa Speciala de matematica)
1975-1980	Institutul Politehnic din Cluj-Napoca Facultatea de Mecanica, Sectia TCM
1980	Diploma de inginer mecanic
1989-1993	Doctorand în specialitatea Deformari Plastice
nov.1993	Sustinerea tezei de doctorat cu titlul"Cercetari privind deformabilitatea tablelor metalice subtiri"
oct.-dec. 1990	Stagii de specializare la Universitatea Tehnica din
oct.-nov. 1991	Varsovia, Polonia (Prof. Z. Marciniak)
oct.1992-ian.1993	Varsovia, Polonia (Prof. Z. Marciniak)
mai-iul.1993	Stagii de specializare la Ecole des Mines de Paris,
dec.1995	CEMEF Sophia Antipolis (Prof. J.L. Chenot)
nov.-dec.1994	Stagii de specializare la Universitatea din Stuttgart, Institut fur
nov.-dec.1995	Umformtechnik (Prof. K. Siegert)

3. ACTIVITATEA PROFESIONALĂ

1980-1984	Inginer proiectant la Intreprinderea "Mecanica" din Sibiu si Fabrica de masini de rectificat "Napomar" din Cluj-Napoca
1984-1996	Asistent universitar, Sef de lucrari si Conferentiar la Institutul Politehnic din Cluj-Napoca, Catedra TCM

Din 1996	Profesor la Universitatea Tehnica din Cluj-Napoca, Catedra TCM
1994-1996	Director al Departamentului de Cercetare Stiintifica al CCSTTII din Universitatea Tehnica din Cluj-Napoca
Din 2000	Director al Centrului de Cercetari in Domeniul in Tehnologia Deformarii Tablelor (CERTETA) din cadrul Universitatii Tehnice din Cluj Napoca (acreditat de CNCSIS din 2002)
Din 1999-	Conducator de doctorat in Stiinte Ingineresti
1996-1998	Cercetator invitat la Institutul de Deformari Plastice, Universitatea din Stuttgart, Germania, in cadrul unei burse Humboldt
Iul-Oct. 1999	Cercetator invitat la Institutul de Deformari Plastice, Universitatea din Stuttgart
Iun-Iul.1999	Cercetator invitat la Universitatea Paris Nord, Franta
Ian-Mar 2000	Profesor invitat la Universitatea Franche-Comte, Besancon, Franta
Iun-Iul 2000	Profesor invitat la Universitatea Paris Nord, Franta
Nov. 2001	Profesor invitat la Universitatea Tehnica din Chemnitz, Germania
Iulie 2002	Profesor invitat la RWTH Aachen, Germania
2000-2004	Profesor la Universitatile din Stuttgart, Germania si Universitatea Tehnica din Cluj-Napoca
Dec. 2006	Profesor invitat la Universitatea Ulster din Belfast, UK
Iun-Iul 2007	Profesor invitat la Universitatea din Metz, Franta
Sept 2010	Profesor invitat la Universitatea Tehnica de Stat din Moscova, Rusia
Sept. 2009	Profesor invitat la Scoala de vara SMART 2009, Univ. din Palermo, Italia
Sept. 2011	Profesor invitat la Scoala de vara SMART 2011, Univ. din Erlangen, Germania
Sept 2013	Profesor invitat la Scoala de vara de la Universitatea Tehnica de Stat din Moscova, Rusia
Oct 2013	Profesor invitat la Scoala de vara SMART 2013, Univ. din Palermo, Italia
Dec 2013	Profesor invitat la Universitatea Warwick, Anglia
Nov 2018	Profesor invitat la Universitatea din Palermo, Italia
Nov-Dec 2019	Profesor invitat la IIT Warangal (Programul GIAN)
	Membru in 16 comisii de doctorat din strainatate (Franta, Portugalia, Norvegia, Germania, Olanda, Iran si India)
Ian 2021-	Honorary professor Xian University, China
2006-2014	Membru al Comisiei de Stiinte Ingineresti a CNCSIS, respectiv CNCS
2006-2014	Membru al Comisiei Prezidentiale pentru Analiza si Elaborarea Politicilor din Domeniul Educatiei si Cercetarii
2011-2016	Membru al Colegiului Consultativ al Cercetarii, Dezvoltarii si Inovarii (CCCDI) al ANCS
2010-2012 si din 2020-	Vicepresedinte al Consiliului Național de Atestare a Titlurilor, Diplomelor şi Certificatelor Universitare (CNATDCU)
din 2012	Vicepresedinte al Consiliului Cercetarii al Universitatii Tehnice din Cluj Napoca
din 2012	Director al Scolii Doctorale a Facultatii de Constructii de Masini din cadrul Universitatii Tehnice din Cluj Napoca

4. ACTIVITATEA ȘTIINȚIFICĂ

1990-2012	Participant activ la peste 100 conferinte internationale in: Germania, Anglia, Franta, Portugalia, Norvegia, Belgia, Austria, Italia, SUA, China, Grecia, Corea de Sud, Japonia, India, Australia, Ungaria, Polonia, Cehia, Bosnia, Bulgaria, Slovenia, Serbia, Spania, Romania.
2004-2009	Coordonator al grupului de cercetare in proiectul «Virtual Inteligent Forging» in cadrul FP6
2004-2008	Director al proiectului de cercetare Sheet metal formability for special metal forming processes (superplastic forming and hydroforming at very high pressure), finantat de Fundatia Humboldt
2004-2008	Co-Director al proiectului de cercetare Improvement of performances of formability models for sheet metals using new constitutive laws, finantat de Swiss National Foundation.
2009-2012	Coordonator grup cercetare in proiectul FP7 Virtual Factory Framework
2010-2013	Director al proiectului PCCE Modelarea continua - de la micro la macro scara - a materialelor avansate in fabricatia virtuala

Membru in Comitetele stiintifice a peste 100 de conferinte internationale:

NUMISHEET'99, Besancon-Franta ; NUMISHEET 2002, Seul-Corea de Sud ; NUMISHEET 2005, Detroit-USA; NUMISHEET 2008, Interlaken-Elvetia; NUMISHEET-2011, Seoul, Korea; NUMISHEET-2014, Melbourne, Australia; NUMISHEET-2016, Bristol, UK; NUMISHEET-2018 Tokyo, Japan; NUMISHEET-2021, Toronto, Canada; NUMIFORM 2007, Porto, Portugalia; NUMIFORM 2010, Gyongiu-Corea de Sud ; NUMIFORM 2013, Shenyang, China; NUMIFORM 2016, Troys, France; NUMIFORM 2019, New Hampshire, US ; ESAFORM 2001, Liege-Belgia; ESAFORM 2002, Cracovia-Polonia; ESAFORM 2003, Salerno-Italia; ESAFORM 2004, Torndheim-Norvegia; ESAFORM 2005 (Presedintele comitetului de organizare), Cluj Napoca, Romania; ESAFORM 2006, Glasgow, UK; ESAFORM 2007, Zaragoza, Spania; ESAFORM 2008, Lyon, Franta; ESAFORM 2009, Enshede, Netherlands; ESAFORM 2010, Brescia, Italy; ESAFORM 2011, Belfast, UK; ESAFORM 2012, Erlangen, Germania; ESAFORM 2013, Aveiro, Portugalia; ESAFORM 2014, Helsinki, Finland; ESAFORM 2015, Graz, Austria; ESAFORM 2016, Nantes, France; ESAFORM 2017, Dublin, Ireland; ESAFORM 2018 Palermo, Italia; ESAFORM 2019 Vitoria, Spania; ESAFORM 2020, Coburg, Germania; ESAFORM 2021, Liege, Belgia; ESAFORM 2022, Braga, Portugal; ESAFORM 2023, Krakow, Poland; EUROMECH 2002, Liege-Belgia; SIA 2007, Caen-Franta ; ICTP 2007, Gyeongju-Corea de Sud ; ICTP 2011, Aachen, Germany ; ICTP 2014, Nagoya, Japan; ICTP 2017, Cambridge, UK ; ICTP 2021, Columbus, US; ICTMP 2010, Nisa, Franta ; ICIT'99, ICIT 2001, Maribor, Slovenia ; AMME'97, AMME'98, AMME'99, AMME 2000, AMME2001, AMME2002, AMME2003, AMME2005 Gliwice-Poland ; DEMI '98, DEMI 2000 Banja Luka-Bosnia ; SMF 2007, Bombay, India; ICCMM 2011, Guwahati, India; KOMPLASTECH 2009, KOMPLASTECH 2011, KOMPLASTECH 2013, KOMPLASTECH 2015, KOMPLASTECH 2017, KOMPLASTECH 2019 Krakow, Poland; DIE-MOLDS 2009, Kusadasi, Turkey; DIE-MOLDS 2011, Ankara, Turkey; DIE-MOLDS 2013, Antalya, Turkey; DIE-MOLDS 2015, Turkey; SHEMET 2007, Palermo, Italia; SHEMET 2009, Birmingham, UK; SHEMET-2011, Leuven, Belgia; SHEMET-2013, Belfast, UK; SHEMET 2015, Erlangen, Germany; SHEMET 2017, Palermo, Italy; SHEMET 2019, Leuven, Belgia; SHEMET 2021, Erlangen, Germany; SHEMET 2023, Leuven, Belgium; AEPA 2008, Daejon, Korea; AEPA 2010, Wuhan, China; AEPA 2012, Singapore; AEPA 2018 Jeju, Korea; ECCOMAS 2012, Aveiro, Portugalia; ICNFT 2012, Harbin, China; ICNFT 2018, Bremen, Germania; IDDRG 2012, Bombay, India; IDDRG 2013, Zurich, Elvetia; IDDRG 2014, Paris, Franta; IDDRG 2015, Shanghai, China; IDDRG 2016, Linz, Austria; IDDRG 2017, Munchen, Germania; IDDRG 2018 Waterloo, Canada; IDDRG 2019, Eindhoven, Olanda; IDDRG 2020, Busan, Korea; IDDRG 2021, Stuttgart, Germany; CIRP-CMS-2016, Stuttgart, Germania; Metal Forming 2016, Krakow, Poland; Metal Forming 2018, Krakow, Poland; Metal Forming 2020, Krakow, Poland; Metal Forming 2010, Toyohashi, Japonia; ICAFT 2018 Chemnitz, Germania; Industrial Technology and Management (ICITM 2019), Cambridge, UK; Int. Conf. Computational Methods in Manufacturing, 2019, Guwahati, India;

AEROSPATIAL 2018, Bucuresti, Romania; AEROSPATIAL 2020, AEROSPATIAL 2022 Bucuresti, Romania; ModTech 2020, Eforie Nord, Romania; NewTech 2020, Bucegi, Romania; NewTech 2022, Rennes, Franta; SISOM 2018, SISOM 2019, SISOM 2020, SISOM 2021, Bucuresti, Romania; MTeM2001, MTeM2003, MTeM2005, MTeM2007 MTeM2009, MTeM2011, MTeM2013, MTeM-2015, MTeM-2017, MTeM-2019, MTeM-2021, MTeM-2023, Cluj-Napoca; MSE 2003, MSE 2007, MSE-2009, MSE-2011, MSE-2013, MSE-2015, MSE-2017, MSE-2019, MSE-2021 Sibiu, Romania; ASTR 2009, Cluj Napoca, Romania (Co-presedinte al comitetului de organizare) ; SISOM 2019, SISOM 2020 , SISOM 2021, SISOM 2022, SISOM 2023, Bucuresti, Romania (Co-presedinte al comitetului de organizare) ; TPR2000 Cluj-Napoca, Romania (Presedintele comitetului de organizare).

5. MEMBRU ÎN ORGANIZAȚII ȘTIINȚIFICE

2012-2016	Presedinte al Asociatiei Europene de Deformarea Materialelor (ESAFORM) (www.esaform.org)
Din 1998	Membru al Asociatiei Europene de Deformarea Materialelor (ESAFORM)
Din 1999	Membru al Comitetului stiintific al Asociatiei Europene de Deformarea Materialelor (ESAFORM)
Din 2000	Membru al Consiliului Director al Asociatiei Europene de Deformarea Materialelor (ESAFORM) (www.esaform.org)
2000-2008	Secretar al Asociatiei Europene de Deformarea Materialelor (ESAFORM) (reales in 2002, 2004 si 2006)
2008-2012	Vicepresedinte al Asociatiei Europene de Deformarea Materialelor (ESAFORM)
Din 2013	Membru titular al Academiei de Stiinte Tehnice din Romania, sectia de Stiinta si Ingineria Materialelor (corespondent din 2005) (www.astr.ro)
Din 2014	Membru titular al Academiei Internationale de Ingineria Productiei (CIRP) (corespondent din 2005) (www.cirp.net)
Din 2015	Membru titular al Academiei Romane (corespondent din anul 2009) (www.academiaromana.ro)
Din 2015	Presedintele Sectiei de Stiinte Tehnice a Academiei Romane (www.acad.ro/sectii/sectia08_tehnica/teh_presedinte.htm)
Din 2015	Membru al Prezidiului Academiei Romane
Din 2018	Presedintele Diviziei de Istoria Tehnicii a CRIFST
Din 2018	Vicepresedinte al Comitetului Roman de Istoria si Filosofia Stiintei si Tehnicii (CRIFST) al Academiei Romane.

6. EVALUATOR PENTRU PROIECTE DE CERCETARE PENTRU URMATOARELE AGENTII

- The Research Council of Norway
- German Research Foundation (DFG)
- National Research Council Canada
- Italian National Agency for the Evaluation of Universities and Research Institutes
- Research Foundation Flanders (FWO), Belgium

- Netherlands Organisation for Scientific Research (NWO)
- New Eurasia Foundation, Russia
- Science & Engineering Research Council, Singapore
- Chile´s Research Council
- The Fundação para a Ciência e a Tecnologia, Portugal
- Membru in Supervisor Board al centrului de excelenta in Stiinţa Materialelor şi Biomateriale al Universitatii Tehnice din Gliwice, Polonia
- Editor in Chief al Revistei Proceedings of the Romanian Academy, Editura Academiei Romane
- Editor in Chief al Revistei Romanian Journal of Technical Sciences—Applied Mechanics, Editura Academiei Romane
- Editor in Chief al Buletinului Asociatiei Europene de Deformarea Materialelor (ESAFORM)
- Associate Editor al Revistei International Journal of Material Forming, Springer, Germania
- Associate Editor al Revistei International Journal of Forming Processes, Hermes, Paris, Franta
- Membru in Editorial Board al Revistei Memoirs of the Scientific Sections of the Romanian Academy, Editura Academiei Romane.
- Membru in Editorial Board al Revistei NOEMA, Editura Academiei Romane.
- Membru in Editorial Board al revistei Forging & Stamping Technology, Beijing, China
- Membru in Editorial Board al revistei Iranian Journal of Materials Forming, Shiraz, Iran
- Membru in Editorial Board al Revistei Computed Method in Materials Science, Polonia
- Membru in Editorial Board al Revistei Journal of Production Processes and Systems, Ungaria
- Membru in Editorial Board al Revistei Forging and Stamping Production (Kuznecino Stampovocinoe Proizvosdvo), Moscova
- Membru in Editorial Board al Revistei Manufacturing Review, EDP Science, Franta

7. PREMII, DISTINCŢII ŞI NOMINALIZĂRI BIOGRAFICE

- Premiul Traian Vuia al Academiei Romane pe anul 2002 pentru lucrarea "Formability of Metallic Materials"
- Premiul Leonardo da Vinci pe anul 2006 al Comisiei Europene pentru programul de e-learning ALUMATTER
- Medalia de bronz a Presedentiei Germaniei pe anul 2006 pentru programul de e-learning ALUMATTER
- Lee Hsun Award pe anul 2015 acordata de Institute of Metal Research Shenyang of the Chinese Science Academy
- Doctor honoris Causa al Universitatilor Petru Maior din Târgu Mureş, Academia Fortelor Terestre din Sibiu, Universitatea Lucian Blaga din Sibiu, Universitatea Dunarea de Jos din Galati.

8. PUBLICAȚII

- **Carti publicate in tara** 17
- A coordonat doua volume de **Istoria Tehnicii din cadrul seriei Civilizatia Romaneasca a Editurii Academiei Romane**
- **Carti publicate in strainatate** 8 (la editurile Springer (6), Science Press Beijing (1), Hermes (1))
- Contributii cu capitole in carti 12 (4 in tara si 8 in strainatate in editurile Elsevier, Wiley, Springer, CRC Press)

Articole publicate sau prezentate:	375
-Conferinte nationale	47
-Conferinte internationale	205
din care cotate ISI	50
-în reviste:	137
din care cotate ISI	116
Brevete de inventii	1

Peste 120 de articole publicate in colaborare cu cercetatori din Germania, Franta, Suedia, Elvetia, Anglia, Portugalia, Polonia, Belgia, Iran, Arabia Saudita, China, Suedia, Norvegia, Olanda, Corea de sud, Bielorusia, Ucraina, Turcia, Japonia, Slovenia, USA.

Citari pe ISI Web of Science	2354
Indicele Hirsch (ISI Web of Science)	23
Citari pe Scholar Google	6341
Indice Hirsch (Scholar Google)	37

Informatii suplimentare se gasesc pe pagina de web :
http://users.utcluj.ro/~banabic/

9. LISTA PROIECTELOR DE CERCETARE COORDONATE DE CANDIDAT (ULTIMII 5 ANI)

PROIECTE INTERNE

1. 2006-2008 Cresterea performantelor simularii proceselor de deformare plastica in fabricatia virtuala prin utilizarea de modele constitutive noi, Programul Cercetare de Excelenta CEEX (Proiect de cercetare în sprijinul programelor post-doctorale)
2. 2006-2008 Platforma integrata pentru simularea proceselor de deformare in fabricatia virtual-VIRFAB, Programul Cercetare de Excelenta CEEX (Proiecte de cercetare complexe, M1)
3. 2007-2008 Modelarea stohastica a curbelor limita de deformare, un nou instrument in scopul cresterii robustetii simularii proceselor de deformare plastica a tablelor metalice, Contract CNCSIS-A.
4. 2007-2010 Modelarea curbelor limita de deformare, un nou instrument al fabricatiei virtuale in procesele de deformare a tablelor metalice, Programul PN II-IDEI.
5. 2008-2010 Modele avansate pentru descrierea anizotropiei si deformabilitatii tablelor metalice, PN II Resurse Umane, Proeict de Cercetare pentru Simulareau Revenirii in Tara (RP), Programul PN II-Resurse Umane
6. 2010-2013 Modelarea continua - de la micro la macro scara - a materialelor avansate in fabricatia virtuala, Proiect complex de cercetare exploratorie, Programul PN II-IDEI.

10. PROIECTE EXTERNE

1. 2004- 2008 Virtual Intelligent Forging, Excellence Network, Financed by European Community, Contract no. NMP2-CT-2004-507331.
2. 2005- 2008 Sheet metal formability for special metal forming processes (superplastic forming and hydroforming at very high pressure). Joint research project between Institute for Metal Forming Technology, Stuttgart University and CERTETA, Financed by Humboldt Foundation, Germany, Project No.: V-Fokoop-RUM/1036802, 2004
3. 2005- 2008 Improvement of performances of formability models for sheet metals using new constitutive laws. Joint research project between Institute for Virtual Fabrication, ETH Zurich and CERTETA, Financed by Swiss National Science Foundation, Switzerland, Project No.: IB7320-110974/1, 2005
4. 2005-2008 3D extension of the BBC2005 yield criterion, Financed by AutoForm Engineering GmbH, Switzerland.
5. 2009-2013 VFF Holistic, extensible, scalable and standard Virtual Factory Framework, Collaborative Project FP7 Program- Large-scale integrating project, NMP-2008-3.4-1.
6. 2012-2015 K2 Mobility – Sustainable Vehicle Technologies, Project with Virtual Vehicle GmbH Graz, Austria

11. PRINCIPALELE CONTRIBUȚII ÎN DOMENIUL DE SPECIALITATE

1. Punerea in evidenta atit experimental cit si teoretic a solicitarii pulsatorii asupra curbelor limita de deformare
2. Utilizarea pentru prima data a criteriului de plasticitate a lui Hill din 1993 in modelarea unor procese de deformare a tablelor
3. Verificarea experimentala a criteriului Hill din 1993
4. Introducerea (in colaborare cu Prof. Pöhlandt si Prof. Lange de la Universitatea din Stuttgart, Germania) a conceptului de coeficient de anizotropie biaxiala.
5. Utilizarea coeficientului de anizotropie biaxiala in determinarea suprafetelor de curgere
6. Elaborarea unor modele analitice pentru umflarea hidrostatica
7. Introducerea unui criteriu de plasticitate (BBC2000) pentru medii ortotrope
8. Dezvoltarea criteriului BBC2000 in forma BBC2005 si BBC 2008
9. Elaborarea programului comercial de calcul al curbelor limita de deformare FORM-CERT
10. Elaborarea primului model teoretic al Benzilor Limita de Deformare
11. Analiza influentei presiunii hidrostatice asupra Curbelor Limita de Deformare
12. Implementarea criteriului BBC2005 in programul comercial de Element Finit AUTOFORM, utilizat de peste 95% din producatorii de autovehicole de pe plan mondial (in colaborare cu firma AUTOFORM, Zurich, Elvetia)
13. Colaborarea cu Institutul de Fabricatie Virtuala de la ETH Zurich pentru dezvoltarea modelului Hora de predictie a CLD
14. Colaborarea cu Catholic University of Leuven, Belgia, pentru cuplarea unui model de material bazat pe textura (Alamel) cu cel fenomenologic (BBC 2008), dezvoltat de autor.
15. Colaborarea cu firma RENAULT pentru implementarea criteriului BBC2005 in programele de simulare pentru procesele de deformarea ale tablelor utilizate de firma
16. Colaborarea cu firma VIRTUAL VEHICLE din Graz pentru dezvoltarea de modele avansate de predictie a Curbelor Limita de Deformare

17. Colaborarea la realizarea unui curs interactiv pe internet «ALUMATTER» (redactarea capitolului de Plasticitate si Anizotropie)
18. Contributia cu două capitole la prima enciclopedie de Ingineria Productiei editată de Springer in anul 2014: Encyclopaedia of Production Engineering.
19. Traducerea in limba chineză de către editura Science Press Beijing a Academiei de Stiinte din China a cărtii « Sheet Metal Forming Processes » (Springer, 2010), aceasta fiind prima carte de inginerie a unui autor roman tradusă in limba chineză.

Publicații

Publications

Academician Dorel BANABIC
Universitatea Tehnică din Cluj-Napoca

A. Cărţi

A.1 CĂRŢI PUBLICATE ÎN ROMÂNIA

1. Tapalaga I., Achimas Gh., Iancau H., Banabic D., Coldea A., Tehnologia presarii la rece (Indrumator de lucrari de laborator), Litografia I.P.C.N., Cluj-Napoca, 1986, 244 pag.
2. Deacu L., Banabic D., Radulescu M., Ratiu C., Tehnica hidraulicii proportionale, Editura Dacia, Cluj-Napoca, 1989, 312 pag.
3. Banabic D., Dörr I.R., Deformabilitatea tablelor metalice subtiri. Metoda curbelor limita de deformare, Editura OIDICM, Bucuresti, 1992, 246 pag., ISBN 973-95641-1-9.
4. Banabic D., Dörr I.R., Modelarea matematica a proceselor de deformare plastica a tablelor metalice, Editura Transilvania Press, Cluj-Napoca, 1995, 226 pag., ISBN -973-97041-9-0.
5. Banabic D., Introducere in teoria plasticitatii, Universitatea Tehnica din Cluj-Napoca, 1994, 56 pag.
6. Vida Simiti I., Banabic D., Bicsak E., Canta T., Domsa S.,, Kerekes L., Soporan V., Deformabilitatea materialelor metalice, Editura Dacia, Cluj-Napoca, 1996, 362 pag., ISBN 973-35-0555-2.
7. Banabic D., Lucrarile Conferintei "Tehnologii si masini pentru prelucrarea prin deformare plastica a metalelor", Editor: Banabic D., Editura Printek 2000, Cluj Napoca, 2000, 286 pag. (ISBN 973-97486-5).
8. Banabic D., Cold Metal Forming, Proc. of the "TPR 2000" Conference, Printek 2000, Cluj-Napoca, 2000, 226 pag., ISBN 973-97486-3.
9. Banabic D. (Editor), Proceedings of the 8th ESAFORM Conference on Material Forming, The Publishing House of the Romanian Academy, Bucharest, 2005, Vol 1 and Vol. 2, XXII+539, XXII+584 pag. (Vol.1, ISBN: 973-27-1174-4, Vol. 2, ISBN: 973-27-1175-2).
10. Wagner S., Baur J., Banabic D., Umformtechnik, UTPRESS, Cluj Napoca, 2011, 336 pag (ISBN 978-973-662-544-2)
11. Munteanu R., Banabic D., Ingineria Românească: Trecut, Prezent şi Viitor, Lucrările celei de-a Treia Conferințe Naționale a Academiei de Ştiinţe Tehnice din România, Mediamira, Cluj Napoca, 2008, 470 pag. (ISBN 978-973-713-223-9).
12. Lăzărescu L., Părăianu L., Banabic D., Bazele proceselor de deformare plastică, Aplicaţii practice, UTPRESS Cluj Napoca, 2011, 206 pag (ISBN 978-973-662-659-3).
13. Lăzărescu L., Comşa D.S., Banabic D., Proiectarea tehnologiilor si a matritelor pentru prelucrarea tablelor metalice, Casa Cărţii de Ştiinţă, Cluj Napoca, 2017, 266 pag. (ISBN 978-606-17-1119-2)
14. Lăzărescu L., Comşa D.S., Banabic D., Analiza cu elemente finite a proceselor de prelucrare prin deformare plastică, Casa Cărţii de Ştiinţă, Cluj Napoca, 2018, (ISBN 978-606-17-1314-1)
15. Frangopol P., Banabic D., David D., Educaţia şi cercetarea românească. Starea prezentă şi perspectiva, Casa Cărţii de Ştiinţă, Cluj Napoca, 2018, 288 pag. (ISBN 978-606-17-1284-7)
16. Banabic D, Bădescu V., Leonăchescu, N., Marin V, (Coordonatori) Ingineri români. Dicţionar enciclopedic, Vol. III, Editura Mira, Bucureşti, 2019, 364 pag. (ISBN 978-606-543-724-1).

17. Banabic D, Bădescu V., Rusu D., Marin V, (Coordonatori) Ingineri români. Dicţionar enciclopedic, Vol. IV, Editura Mira, Bucureşti, 2020, 400 pag. (ISBN 978-606-543-724-1).
18. Banabic D., (Coordonator), Istoria tehnicii şi industriei româneşti (Mecanica, tehnicile de prelucrare şi construcţiile), Editura Academiei Române, Bucureşti, 2020, ISBN 978-973-27-3054-6.
19. Banabic D., (Coordonator), Istoria tehnicii şi industriei româneşti (Electrotehnica, energetica, transporturile şi învăţământul tehnic), Editura Academiei Române, Bucureşti, 2020, ISBN 978-973-27-3055-3.

A.2 CĂRȚI PUBLICATE ÎN STRĂINĂTATE

1. Banabic D., Bünge H.J., Pöhlandt K., Tekkaya A.E., Formability of Metallic Materials, Editor: Banabic D., Springer Verlag, Heidelberg, 2000 (358 pag), ISBN 3-540-67906-5.
2. Banabic D., (Editor), Advanced Methods in Material Forming, Springer, Heidelberg, 2007 (376 pag), ISBN 3-540-69844-2.
3. Banabic D., (Guest Editor), Modelling and Experiments in Material Forming, Hermes-Lavoisier, Paris, 2007, ISBN 978-2-7462-1775-1 (134 pag).
4. Banabic D. Sheet Metal Forming Processes, Springer, Heidelberg, 2010 (307 pag) (ISBN 978-3-540-88112-4).
5. Banabic D., Sheet Metal Forming Processes, Science Press, Beijing, 2015 (250 pag) (in chineza)
6. Banabic D., Multiscale modelling in sheet metal forming, Springer, Heidelberg, 2016, (425 pag) (ISBN 978-3-319-44070-5)
7. Banabic D. (Coord.), History of Romanian technology and industry (Mechanics, processing techniques and construction), Springer, Heidelberg, 2023 (in publication).
8. Banabic D., (Coord.), History of Romanian technology and industry (Electrical engineering, energetics, transport and technology education), Springer, Heidelberg, 2023 (in publication).

B. CONTRIBUȚII LA CĂRȚI

B.1 PUBLICATE IN ROMANIA

1. Deacu L., Banabic D., Radulescu M., Ratiu C., Sisteme hidraulice proportionale, In: TCMM, Vol.2, Editura Tehnica, Bucuresti, 1987, p.152-187.
2. Banabic D., Cercetarea aplicata in domeniul tehnologiilor de fabricație din Romania, În: Pentru excelență în știința românească (Eds.: Frangopol P., Zamfir N.V., Braun T.), Casa Cărţii de Ştiinţă, Cluj Napoca, 2008, p. 113-132 (ISBN 978-973-133-405-9).
3. Banabic D., Axenciuc V., Evoluția numărului de absolvenți de învățământ tehnic din românia în perioada 1871-2016, În: Educația şi cercetarea românească. Starea prezentă şi perspectiva, Eds. Frangopol P., Banabic D., David, D., Casa Cărţii de Ştiinţă, Cluj Napoca, 2018, p.89-107.
4. Banabic D., Filip I., 70 de ani de promovare a ştiinţei şi tehnicii româneşti, În: Editura Academiei Române-70, Editura Academiei Române, Bucureşti, 2018, p. 265-270 (ISBN 978-973-27-2991-5).

B.2 PUBLICATE IN STRAINATATE

1. Banabic D., Sheet metal predicted by using the new (1993) Hill's yield criterion, In: Advanced Methods in Materials Processing Defects (Studies in Applied Mechanics Serie, Vol. 45), (Editors: Predeleanu M., Gilormini P.), Elsevier Science, Amsterdam, 1997, p.257-265, ISBN 0-444-82271-2.
2. Barlat F., Cazacu O., Zyczkowski M., Banabic D., Yoon J.-W., Yield surface plasticity and anisotropy, In: Continuum Scale

Simulation of Engineering Materials. Fundamentals-Microstructures-Process Applications, (Editors: D. Raabe, L.-Q. Chen, F. Barlat, F. Roters), Wiley-VCH, Weinheim, 2004, p.145-185, ISBN 3-527-30760-5.

3. Banabic D., Tekkaya E.A., Forming Simulation, In: Virtual Fabrication of Aluminum Alloys: Microstructural Modeling in Industrial Aluminum Production, (Editor: J. Hirsch), Wiley-VCH, Weinheim 2006, p. 275-303 (ISBN: 3-527-31363-X).
4. Banabic D., Barlat F., Cazacu O., Kuwabara T., Anisotropy and formability, In: Advances in Material Forming-ESAFORM 10 Years on, (Editors: Chinesta F., Cueto, E.), Springer, Heidelberg, 2007, p.143-173 (ISBN: 978-2-287-72142-7).
5. Banabic D., Material models in sheet metal forming simulation, In: Automotive sheet metal forming, (Editors: Verma R.K., Bhattacharjee D.), McGraw Hill, 2008, p.42-48 (ISBN: 978-0-07-025218-9).
6. Felice L., Banabic D., Formability and damage, In: (Eds.: L. Laperrière, G. Reinhart, Encyclopedia of Production Engineering), Springer, Heidelberg-Berlin, 2014, p.539-547 (ISBN 978-3-642-20616-0)
7. Brosius A., Banabic D., Anisotropy, In: (Eds.: L. Laperrière, G. Reinhart, Encyclopedia of Production Engineering), Springer, Heidelberg-Berlin,2014, p. 40-47 (ISBN 978-3-642-20616-0)
8. Banabic D, Fliessortkriteria, In: (Ed.: Siegert K., Blechumformtechnik, Springer, Heidelberg-Berlin, 2015, p. 309-323 (ISBN 978-3-540-02488-0).
9. Banabic D., Comsa D.S., BBC2005 yield criterion used in the numerical simulation of sheet metal forming processes, In: (Eds.:Tekkaya E.A., Homberg W., Brosius A., 60 Excellent Inventions in Metal Forming), Springer, Heidelberg Berlin, 2015, p. 11-17 (ISBN 978-3-662-46311-6)
10. Banabic D., Lazarescu L., Comsa D.S., An innovative procedure for the experimental determination of the Forming Limit Curves, In: (Eds.:Tekkaya E.A., Homberg W., Brosius A., 60 Excellent Inventions in Metal Forming), Springer, Heidelberg Berlin, 2015, p. 49-55 (ISBN 978-3-662-46311-6)
11. Banabic D., Bălan T., Comşa D.S., Anisotropic Yield Criteria for Aluminum Alloy Sheets, In: (Ed. Totten G., Encyclopedia of Aluminium and its Alloys), CRC Press, New York, 2019, p.93-106 (ISBN 9781466510807)
12. Brosius A., Banabic D., Anisotropy, In: (Eds.: S. Chatti, L. Laperrière, G. Reinhart, T. Tolio, CIRP Encyclopedia of Production Engineering), Springer, Heidelberg-Berlin, 2019, p. 66-72 (ISBN 978-3-662-53119-8)
13. Banabic D., Felice L., Formability, In: (Eds.: S. Chatti, L. Laperrière, G. Reinhart, T. Tolio, CIRP Encyclopedia of Production Engineering), Springer, Heidelberg-Berlin, 2019, p.720-726 (SBN 978-3-662-53119-8)

C. ARTICOLE PUBLICATE IN REVISTE

C.1 PUBLICATE IN REVISTE ISI

1. Banabic D., Valasutean S., The effect of vibratory straining upon Forming Limit Diagrams, In: Journal of Materials Processing Technology, Elsevier, Amsterdam, Vol.34(1992), p.431-437 (IF=2.041)
2. Banabic D., Dorr I.R., Prediction of the Forming Limit Diagrams in pulsatory straining, Journal of Materials Processing Technology, Elsevier, Amsterdam, 45(1994), No.1-4, p.551-556 (IF=2.041).
3. Banabic D., Analysis of punch-stretching in vibratory regime, Journal of Materials Processing Technology, Elsevier, Amsterdam, 60(1996), No.1-4, June, p.201-204 (IF=2.041).
4. Banabic D., Formability of aluminium sheets in pulsatory straining, Materials Science Forum, 217-222(1996), p. 1335-1342.
5. Banabic D., Limit strains in the sheet metals by using the 1993 Hill's yield criterion, J. of Materials Processing Technologies, 92-93(1999), p.429-432 (IF=2.041).
6. Banabic D., Dannenmann E. The influence of the yield locus shape on the limits strains, J. of Materials Proc. Techn.,

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Simulation of metal forming Visualization of invisible phenomena in the digital era
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Abstract

The simulation of manufacturing processes has significant importance. The research and development of metal forming simulation started in the 1960s from the elastoplastic analysis of a simple plastic deformation, and it now covers a wide range of forming processes. The accuracy and applicability of metal forming simulation have significantly progressed, driven by the development of plasticity theory and numerical methods such as the remeshing technique and contact analysis algorithm. Now the targets of metal forming simulations are undergoing a transition from the macroscale analysis of deforming bodies to coupled analyses of deformations of deforming bodies and tools, and multiscale analyses of microstructure and texture. Past chievements of metal forming simulation show that it has reached the level of 'visualizing forming phenomena', but it will continue to evolve in the digital era, impacting the digital society and factories of the future, where machines work autonomously without human intervention. Emergent technologies require advanced materials, augmented reality, and, of course, metal forming simulation. In this paper, we reinforce the role of simulation as a means of performing computational (virtual) experiments and as a tool for the high-fidelity numerical visualization and quantification of unknown, unmeasurable, and invisible phenomena in formed components and their assembly. We will also discuss simulationmachine interactions, such as online simulation with process operation, to realize the triad of 'process operation data simulation' in the near future

Keywords: Simulation; Metal forming; Modelling; Visualization; Digital twin

Introduction

The digital era began in the 1960s. Cyber-physical space, in which different systems with different computer capabilities and data are interconnected, is being realized in the 21st century. Such a movement will help sustain the future growth of the world through industrial innovations.

Metal forming is highly suited to the cyber age. It requires the simulation of the complex deformations of materials to predict the final geometry of a part after forming and the required forming force sing a digital computer. The appearance of the digital computer and the development of the modeling of plasticity and numerical methods opened the door to the modern 'simulation of metal forming' in the 1960s. Now, the simulation of metal forming is widely regarded as indispensable in the analysis and design of tools, forming processes, and process operations. Simulation results are one of the key types of data in realizing manufacturing in cyber-physical space. In fact, analytical calculation and empirical methods for metal forming, such as physical simulation (modeling) using wax, clay, and lead, have been extensively applied in the past.

The modern simulation of metal forming provides computational (virtual) experiments and tools for the high-fidelity numerical visualization and quantification of the unknown, unmeasurable, and invisible phenomena in formed components and their assembly. Also, simulationmachine interactions, such as online simulation with process operation, will realize the triad of 'process operation data simulation' in the near future. The appropriate design of forming operations is highly demanding because of their invisibility.

On the other hand, the visualization of plastic deformation inside the die and tools would be highly valuable to understand, design, and optimize forming sequences. Therefore, this is one of the major driving forces behind developments in the simulation of metal forming as it will enable the visualization of invisible phenomena. Simulation is divided into physical modeling and numerical simulation. Physical modeling had been conducted using clay or wax to visualize the plastic deformation of a deforming metal to explore phenomena occurring inside dies and tools [243]. It was used to model some forming processes until the early 1990s, but numerical simulation, which reproduces plastic deformation using igital computing units, took over the role of visualizing the deformation of plastically deforming materials in the late 20th century.

As described above, metal forming has an invisible nature. This invisibility can be divided into three levels. General metal forming requires tooling, which hides plastically deforming metals from our line of sight, resulting in the first invisibility. In general, the surface of an object makes the inside invisible. This may be called 'geometric invisibility'. The second invisibility originates from the impossibility of measuring the force inside an object or workpiece. Even if we can see the deformation by overcoming the invisibility by tooling, we cannot measure the internal force, although we can measure the deformation and strain on the surface. We need a constitutive equation to define stress by converting strain into stress. We call this second invisibility definitional invisibility' or 'continuum mechanics invisibility'. In addition to the above two invisibilities on the macroscale, in situ measurements of microstructure evolution, texture, and damage are extremely difficult and result in the third invisibility, 'scale invisibility'. Modern forming requires information on plastic deformation inside tools, stresses, and microscopic phenomena. There is only one method to acquire this information at one time: the numerical simulation of metal forming processes. The metal forming community is motivated to overcome the three types of invisibility, and numerous investigations have been carried out in the past. Past achievements of simulating metal forming show that it has reached the level of 'visualizing forming', but more investigations must be carried out in the future. In fact,metal forming simulationmust be developed further to contribute to the progress of manufacturing in the digital era and impact the digitized society and factories of the future.

At present, the simulation of metal forming is moving in several directions. One is the direction of complexity. Needless to say, the thermomechanical simulation of metal forming processes is very popular, but we need to introduce more complex and multi-physics phenomena such as electro-thermomechanical or magneto-thermomechanical modeling. A second direction is high accuracy, which is in continuous demand and is still driving the research on the modeling of plastic anisotropy, flow stress, physical constants, and so forth.

A third direction is that of easy-to-use software. From the 1960s to the 1980s, the simulation of metal forming was part of the realm of scientists, and many in-house software packages were developed.

Since the 1960s, commercial software has appeared on the market and has been developed to widen the coverage of the forming process and make it easier to use. The simulation of metal forming has expanded from an activity carried out by a few select people to the public domain, and it is still evolving to incorporate modern achievements in metal forming science. We start our review by describing the simulation of metal forming to highlight its basis and historical progress.

All numerical simulations require a governing equation. For the continua, momentum Eq. (1) is the governing equation that must be solved for bodies in the equilibrium state. Then, an equation of heat conduction (2) can be used to visualize the temperature distribution across the deforming materials as well as the forming tools: The above governing equations

$$\rho \dot{u}_i = \frac{\partial \sigma_{ji}}{\partial x_j} + \rho g_i \tag{1}$$

$$\rho c \frac{\partial T}{\partial t} = \dot{Q} + \frac{\partial}{\partial x_i}\left(\kappa \frac{\partial T}{\partial x_i}\right) + \sigma_{ij} \frac{\partial u_j}{\partial x_i} \tag{2}$$

The above governing equations are common to many phenomena in nature such as the collision of galaxies in space, as illustrated in Fig. 1. A simulation to reproduce the transformation of galaxies [44,160] cannot be reproduced experimentally, and we cannot turn back time. No one can see the collision of galaxies dynamically unless a numerical simulation based on acceptable governing equations is realized. The birth of a galaxy is not similar to the deformation of plastically deforming materials inside dies and tools, but it is similar in terms of the invisible nature. Invisibility requires an appropriate governing equation and its accurate solution and modeling. Neglect- ing the body force, Eq. (1) yields the equilibrium equation for the dynamic analysis of metal forming with the effect of inertia. More- over, if we assume that the acceleration in the left of momentum Eq. (1) is much smaller than the gradient of stress, then the equilib- rium equation of quasi-static phenomena in metal forming can be obtained.

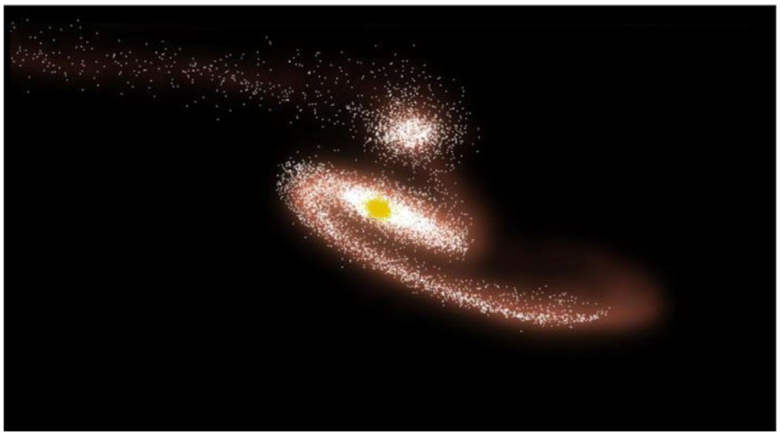


Fig. 1. Simulated collision of galaxies by NASA jet propulsion laboratory. [274].

If forming is within the scope of analysis, the elastoplastic response of a body becomes a key issue. The elastoplastic response is expressed by the following set of three equations:

1) yield criteria (yield condition or function),
2) hardening criteria, and
3) a flow rule, which yields the elastoplastic constitutive equation. As the constitutive equation is expressed using the plastic strain increment as a representative parameter, the displacement strain relationship is needed to solve the deformation of a plastically deform- ing body, which obeys the equilibrium equation and the elastoplastic response of a deforming body.

The above-mentioned analytical scheme was already available for isotropic bodies in the 1940s, but we had to wait for a few more decades for the capability to realize satisfac- tory numerical simulations. Several simulation methods have been investigated and utilized in the numerical simulation of forming, such as analytical methods (elementary, energy, and slip line field meth- ods). Most of the numerical simulations of forming are now based on the finite element method (FEM). FEM is mainly utilized in the macro- scale analysis of a plastically deforming material. Fig. 2 shows the progress of FEM over several decades. The first application of FEM was the structural analysis of lightweight bodies such as airplanes [225]. It was extended to nonlinear analysis in the 1960s, and the analysis of plastically deforming materials using the small-strain FEM became possible from this period [146,255,256]. Large-scale finite element analysis using the total Lagrangian [94] and updated Lagrangian [167] formulations became possible in the early 1970s. FEM has been used in metal forming since the 1970s, especially after the flow formulation was proposed by Cornfield and Johnson [64] and Zienkiewicz and God- bole [266], and rigid-plastic formulation by Lung and Mahrenholtz
[140] and Lee and Kobayashi [123,128]. The time integration scheme was extended from static-explicit to static-implicit and dynamic- explicit. The development of the remeshing algorithm provided the capability to apply the numerical simulation of metal forming to large plastic deformations. Then, the linkage of FEM with computer-aided design (CAD) allowed FEM

to be part of the tool design process in the forming process. Along with the progress of FEM at the macroscale, methods of mesoscale or microscale analysis such as cellular automata (CA), the representative volume element method (RVE) [144], molecular dynamics (MD) [261], and crystal plasticity (CP) [9] were introduced. Presently, the numerical simulation of metal forming uses more computer resources than ever before. Its applications have been greatly extended, and it can now be performed on personal computers in small- and medium-scale metal forming industries, enabling the digital transformation in line with the concept of Industry 4.0 and even Industry 5.0.

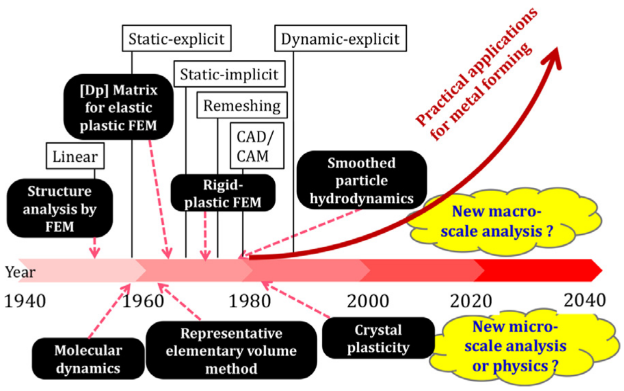


Fig. 2. Progress of numerical simulation

The development of electric devices and optical fibers led to the high-speed computation and communication required to drive the progress of many industrial sectors and societies. The essential driving force behind the above-mentioned progress of numerical methods and the spread of the simulation of metal forming to different industries was the increase in computational speed and the downsizing of computers. Fig. 3 shows the increase in CPU speed, one of the benchmarks, since 1990. This was realized through the refinement of semiconductor patterns and reflects Moore's law [197]: the number of transistors in a dense integrated circuit doubles approximately every two years. Moore originally referred to the economics of the integrated circuit, stating that the cost per component is nearly inversely proportional to the number of components.

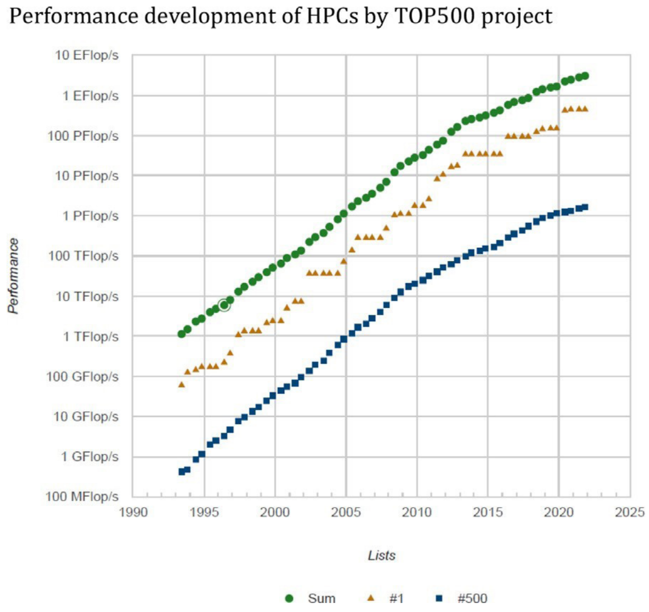


Fig. 3. HPC performance. [275]

As mentioned, the simulation of metal forming can visualize invis- ible phenomena, such as a plastically deforming material inside dies and tools, the stress and temperature fields in materials and dies, microstructure and texture evolution, and the mechanical properties of formed components. There are many aspects of metal forming research being intensively pursued to realize this visualization. In this keynote, important aspects of the simulation of metal forming allowing the visualization of invisible phenomena will be reviewed. Particular focus will be on the current progress of the modeling of plasticity, numerical methods, and multiscale simulations. After summarizing the past noteworthy results that have significantly affected research on the numerical simulation of metal forming, current trends as well as some forecast 'simulations toward a digitized soci- ety' will be presented. The deformation of a metal obeys governing equations such as the momentum and heat conduction equations. The simulation of metal forming can be conducted if the material response under plastic deformation is correctly modeled in appropri- ate numerical schemes or methods. The modeling of metal forming processes such as plasticity and observed physics, and numerical methods will be described in the succeeding sections.

2. Modeling of plasticity

Simulation of metal forming processes requires knowledge of the behavior of materials in the plastic field. This behavior is described by three sets of equations: yield criteria, hardening laws and the flow rule. In choosing a particular model by the user there is a conflict between its accuracy and flexibility, its user-friendliness and robust- ness, and its CPU time consumption and cost. This section presents a summary of these models, presenting the advantages and disadvantages of different yield criteria and hardening laws in order to facilitate the selection of the most appropriate one.

2.1. Characteristics of the simulation of metal forming processes for sheet and bulk forming

In the current context of globalization and aggressive competition between the actors of the global market, the quality, price, and manufacturing time of a product, as well as the reduction in energy consumption associated with the manufacturing processes, are fac- tors that determine competitiveness in the digital era. An efficient method for improving these factors is the numerical simulation of the manufacturing processes. Metal forming procedures are exten- sively used in the automotive and aerospace industries. Because the forming tools are very expensive, any defect or redesign of the tech- nological process may lead to a considerable increase in the price and manufacturing cost of the product. Thus, numerical simulations must be as realistic and accurate as possible, so that products can be directly manufactured without the need of a physical prototype, thus reducing both the manufacturing time and cost of product prices. The FEM is nowadays an extensively used instrument for the numerical simulation of metal forming processes.

FEM for the simulation of metal forming is based on physics that considers the governing equation of motion (Eq. (1)) and the theory to describe the kinetic response of a metal under forming, that is, the modeling of plasticity. Fig. 4 shows the characterization of physics and physically based models. The area of future investigations in metal forming simulations is shown by the region representing circle of observed (understood) physics. The governing equation is in the region representing modeled physics, but the anisotropic response of sheet metal still remains in the region representing observed physics [194]. The most effective strategy for enhancing the performance of this computational method is to adopt realistic and accurate constitu- tive models, especially for the stamping of a sheet with anisotropy. However, most of the bulk forming process could be analyzed only by examining the flow curve and friction conditions because the anisotropy of most of bulk materials under forming is very weak. The plasticity of bulk metal under forming can be categorized as modeled physics, but interface phenomena under high pressure such as fric- tion and lubrication lie in observed physics, where there remain wider fields of scientific investigation.

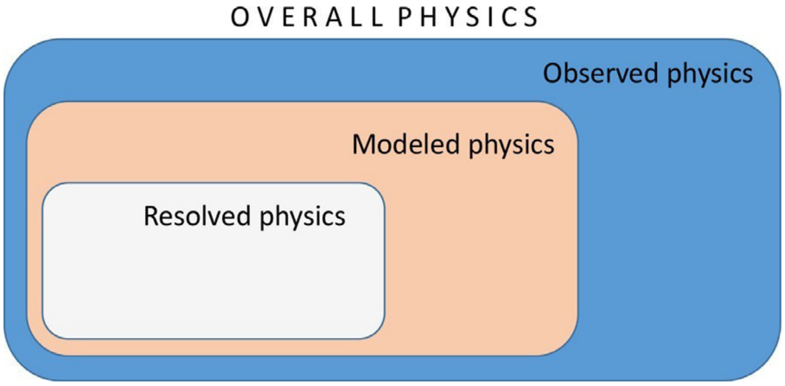


Fig. 4. Physics-based modeling. Modeling is based on first principles but only part of the known physics can be modeled owing to assumptions at different stages.

The properties of the products obtained by forming procedures change during the manufacturing process (i.e., the properties depend on the history of the forming process). Having accurate information about these properties is essential for assessing the functional perfor- mance characteristics of the finished product. Essential macroscopic properties such as geometry, resilience, and residual stress are the essential targets of metal forming simulations. Simulations for predict- ing mechanical properties such as yield point, strength, and formabil- ity require microscale coupled analysis. Fatigue strength, anisotropy, and crash resistance are difficult to simulate at present, and microscale analysis has great potential for these difficult-to-simulate properties. In fact, predicting these properties will be important steps toward acti- vating the simulations of metal forming in digitized societies.

The main areas of investigation in plasticity modeling are the flow rule, yield locus, and constitutive modeling of anisotropic sheet metals. Thus, for the macroscopic scale of plasticity-related models, we take the stamping of anisotropic sheet metal as a representative process to describe the simulation of forming processes.

2.2. Plasticity-related models

The input data needed for the finite element (FE) simulation of sheet metal forming processes consists of parameters that describe the mechanical response of the blank material [23]. Fig. 5 shows the material data delivered as the input to the FE programs used for the numerical simulation of sheet metal forming processes. Since 1993, several benchmarks have been proposed by the organizers of the NUMISHEET conferences with the aim of assessing the performance characteristics of FE programs used for the simulation of sheet metal forming processes. The benchmarks are chosen to assist the compari- son of experimental data with numerical predictions obtained by using different material models, frictional models, and so forth. In addition to the accuracy of numerical predictions, the computational efficiency (CPU time) of different FE programs is also compared. Fol- lowing the development of the FE programs used in the industrial environment, the NUMISHEET benchmarks have gradually evolved from the analysis of simple parts to the analysis of more complex parts, usually belonging to automobile structures.

The plastic response is expressed by the following set of three equations: 1) yield criteria (yield condition or yield function), 2) hardening law, and 3) the flow rule. In addition, the damage and fric- tion models are used to accurately predict fracture.

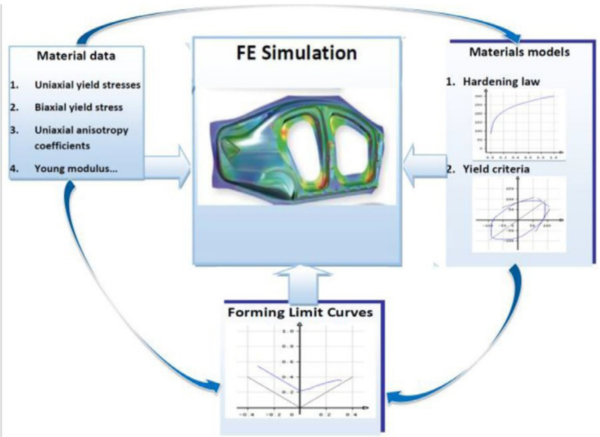


Fig. 5. Material data used as the input for the FE simulation of sheet metal forming processes.

2.3. Modeling of anisotropy

The objective of this section is not to review all the anisotropic yield criteria in the literature (these criteria are detailed in the refer- ences [15,19,21-26,30,33,34,43,50,210,258], and so forth. We will focus our attention on the critical discussion of the most commonly used models in commercial FE simulation programs. The isotropic plasticity models developed by Tresca [223], Mises-Huber [115,156], Drucker [71], and Hershey [93] provided anisotropic formulations to give a more accurate description of the mechanical response of sheet metals subjected to forming. Mises [157] generalized the isotropic flow theory based on a plastic potential and introduced an aniso- tropic yield criterion by generalizing his isotropic plasticity model proposed in 1913, without describing how to identify the new yield criterion. Hill [95] was the first researcher to develop an anisotropic yield criterion using the anisotropy coefficients for identification pur- poses (the anisotropy coefficients were first introduced and experi- mentally determined by Jackson, Smith, and Lankford [119]). The anisotropy coefficient is defined as the ratio of width strain to thick- ness strain in a uniaxial tensile test. Hill's 1948 yield criterion is still widely used owing to its advantages, as shown in Table 1. With the aim of obtaining more accurate descriptions of the mechanical response of aluminum alloys, Hill proposed several generalizations of his 1948 model in the form of non-quadratic yield criteria containing an increased number of adjustable coefficients [98-100,]. About the same time, Hosford [108,109] developed an anisotropic generaliza- tion of the isotropic non-quadratic yield criterion proposed by Her- shey [93]. Barlat and Richmond [27] also proposed a more general form of Hershey's isotropic yield criterion by expressing it in an x, y, z coordinate system, not necessarily coincident with the principal directions of the stress tensor. Later, Barlat and Lian [28] extended this formulation to the anisotropic case.

By applying linear transformations to the deviatoric stress tensor, Barlat and co-workers developed several anisotropic extensions of Hershey's yield criterion. Among these anisotropic yield criteria, the most flexible are Yld2000 [29], Yld2004 13p, Yld2004 18p [31], Yld2011 18p, and Yld2011 27p [7]. Banabic and co-workers adopted a more direct approach for generating anisotropic yield cri- teria under plane-stress conditions. Namely, they used the isotropic formulation proposed by Barlat and Richmond [27], in which adjust- able material parameters were incorporated. A series of anisotropic yield criteria were obtained in this manner: BBC2000 [14,16], BBC2003 [17], BBC2005 [18,21,189], and BBC2008 [22,63]. Cazacu and Barlat used the theory of tensor representation to define general transformations acting on the second and third invariants of the deviatoric stress. By using this approach, they extended the isotropic yield criterion proposed by Drucker [71] to the case of orthotropic materials [47-49,190]. Vegter and van den Boogaard also defined a very flexible yield criterion for describing the mechanical response of anisotropic sheet metals under plane-stress conditions. Their approach is based on the Bezier interpolation of representative stress states [230,231]. Raemy et al. [192,193] proposed a new approach based on Tong's idea [222]. The Fourier asymmetric yield (FAY), to describe the anisotropy and asymmetry of metallic materials. The model was implemented by Manopulo and Carleer [145] in the Auto- form code.

More recent ways to describe the anisotropic behavior of sheet metals have been introduced by Yoshida et al. [260], Hu et al. [112,113], Chen et al. [54,55], and Hao [91] and so forth. For more details, see [26].

The advantages and disadvantages of these plasticity models are summarized in Table 1. As one may observe in Table 1, the Barlat 2000, BBC 2005, and Vegter yield criteria exhibit similar advantages. This fact explains why these plasticity models are used in commercial FE codes for industrial applications:

The most important factors that must be considered when choosing the yield criterion are as follows.

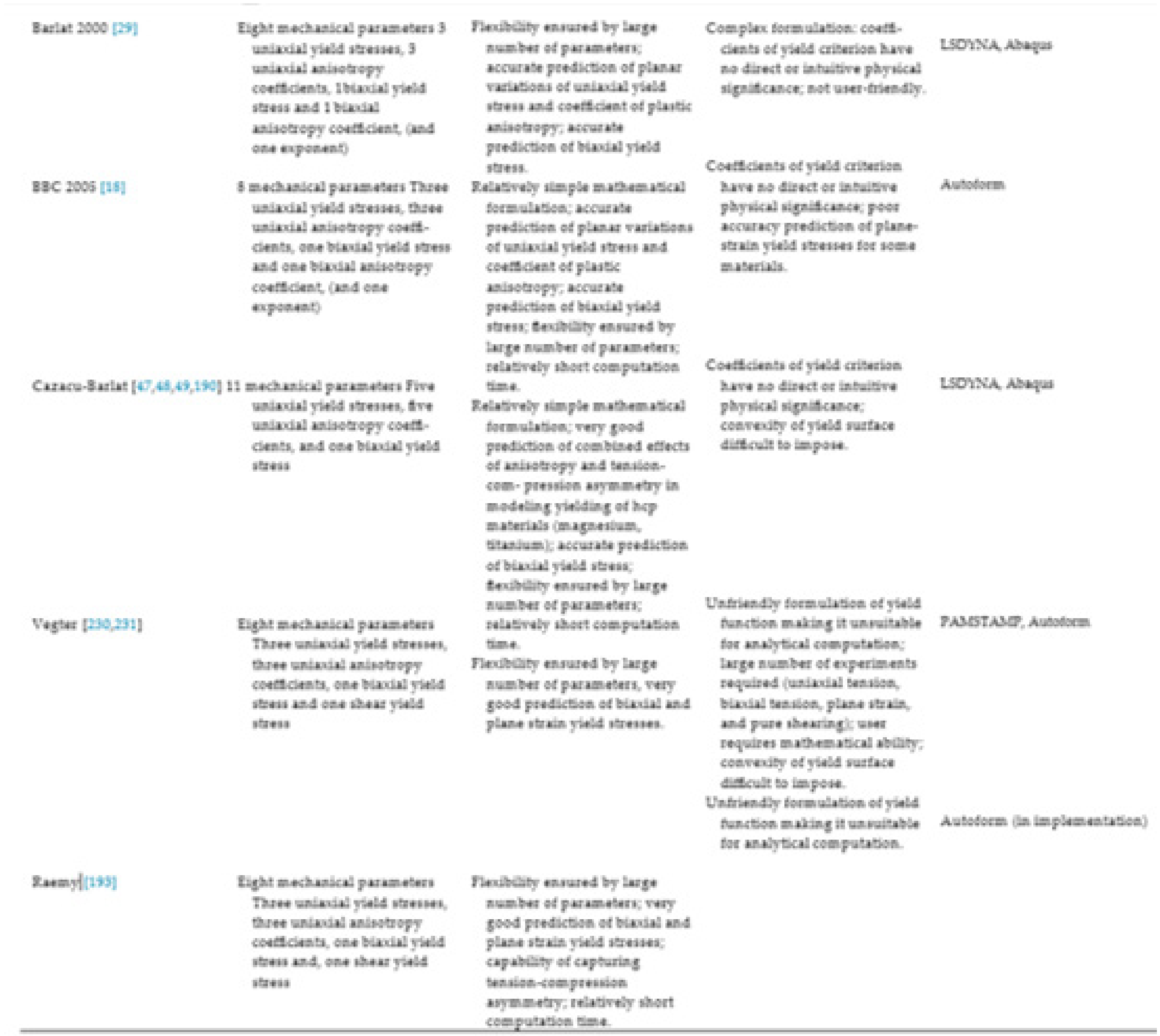
- Capability of giving accurate predictions of the yield locus and planar distribution of the uniaxial yield stress and the uniaxial coefficient of plastic anisotropy
- Computational efficiency and ease of implementation in numerical simulation codes
- Flexibility of the yield criterion
- Degree of generality
- Number of mechanical parameters needed by the identification procedure
- Robustness of the identification procedure
- Experimental difficulties caused by the determination of the mechanical parameters involved in the identification procedure
- User-friendliness of the yield criterion
- Acceptance of the yield criterion in the scientific/industrial community.

The most accurate predictions are usually ensured by the yield criteria having an identification procedure based on both uniaxial and biaxial tension experimental data. Regarding the experimental data obtained by uniaxial tensile tests, the identification should use the yield stresses and the coefficients of plastic anisotropy corresponding to at least three planar directions (0°, 45°, and 90°). Fig. 6 presents a comparison between finite FE using different yield criteria and experimental data for the minor strain distribution in bulge forming (AA6016-T4).

Table 1

Synthesis of the most commonly used anisotropic yield criteria in the commercial FE codes.

Anisotropic yield criterion	Mechanical parameters used in identification	Advantages	Drawbacks	Commercial FE codes using the yield criterion.
Hill 1948 [95]	Four mechanical parametersOne uniaxial yield stress and three uniaxial anisotropy coefficients (or three uniaxial yield stresses and one uniaxial anisotropy coefficient)	Simple mathematical formulation: a small number of mechanical parameters needed for identification; basic assumptions easy to understand; gives relatively good prediction for materials with moderate variations of mechanical parameters; efficient in terms of computation time; corresponding material parameters have direct physical meaning.	Unable to capture anisotropic behavior of aluminum sheets to desired accuracy; can only be applied to materials forming four 'ears' in axisymmetric deep drawing processes; cannot capture simultaneously planar variation of uniaxial yield stress and uniaxial coefficient of anisotropy; poor prediction of biaxial and plane strain yield stresses.	PAMSTAMP, Autoform, LSDYNA, Abaqus, MARC
Barlat 1989 [28]	Three mechanical parameters One uniaxial yield stress and two uniaxial anisotropy coefficients (and one integer exponent)	Simple mathematical formulation: reduced number of mechanical parameters used for the identification; relatively easy identification; relatively good prediction of yield locus for aluminum alloys exhibiting moderate anisotropy; relatively short computation time.	Coefficients of yield criterion have no direct or intuitive physical significance; cannot capture simultaneously planar variations of uniaxial yield stress and uniaxial coefficient of plastic anisotropy; does not give accurate predictions of biaxial mechanical parameters.	LSDYNA, Abaqus



Barlat 2000 [29]	Eight mechanical parameters 3 uniaxial yield stresses, 3 uniaxial anisotropy coefficients, 1biaxial yield stress and 1 biaxial anisotropy coefficient, (and one exponent)	Flexibility ensured by large number of parameters; accurate prediction of planar variations of uniaxial yield stress and coefficient of plastic anisotropy; accurate prediction of biaxial yield stress.	Complex formulation: coefficients of yield criterion have no direct or intuitive physical significance; not user-friendly.	LSDYNA, Abaqus
BBC 2005 [18]	8 mechanical parameters Three uniaxial yield stresses, three uniaxial anisotropy coefficients, one biaxial yield stress and one biaxial anisotropy coefficient, (and one exponent)	Relatively simple mathematical formulation; accurate prediction of planar variations of uniaxial yield stress and coefficient of plastic anisotropy; accurate prediction of biaxial yield stress; flexibility ensured by large number of parameters; relatively short computation time.	Coefficients of yield criterion have no direct or intuitive physical significance; poor accuracy prediction of plane-strain yield stresses for some materials.	Autoform
Cazacu-Barlat [47,48,49,190]	11 mechanical parameters Five uniaxial yield stresses, five uniaxial anisotropy coefficients, and one biaxial yield stress	Relatively simple mathematical formulation; very good prediction of combined effects of anisotropy and tension-com- pression asymmetry in modeling yielding of hcp materials (magnesium, titanium); accurate prediction of biaxial yield stress; flexibility ensured by large number of parameters; relatively short computation time.	Coefficients of yield criterion have no direct or intuitive physical significance; convexity of yield surface difficult to impose.	LSDYNA, Abaqus
Vegter [230,231]	Eight mechanical parameters Three uniaxial yield stresses, three uniaxial anisotropy coefficients, one biaxial yield stress and one shear yield stress	Flexibility ensured by large number of parameters, very good prediction of biaxial and plane strain yield stresses.	Unfriendly formulation of yield function making it unsuitable for analytical computation; large number of experiments required (uniaxial tension, biaxial tension, plane strain, and pure shearing); user requires mathematical ability; convexity of yield surface difficult to impose.	PAMSTAMP, Autoform
Raemy[193]	Eight mechanical parameters Three uniaxial yield stresses, three uniaxial anisotropy coefficients, one biaxial yield stress and, one shear yield stress	Flexibility ensured by large number of parameters; very good prediction of biaxial and plane strain yield stresses; capability of capturing tension-compression asymmetry; relatively short computation time.	Unfriendly formulation of yield function making it unsuitable for analytical computation.	Autoform (in implementation)

The high accuracy of the minor strain distribution is notable when the BBC 2005 yield criterion is identified using the following seven mechanical parameters (BBC 2005 7 in Fig. 6): three uniaxial yield stresses, three anisotropy coefficients associated with the 0°, 45°, and 90° directions, and one biaxial yield stress. When only mechanical parameters obtained from uniaxial tensile tests are used, e.g., the BBC 2005-4 (one uniaxial yield stress and three anisotropy coefficients) or BBC 2005-6 (three uniaxial yield stresses and three anisotropy coefficients), the quality of the numerical predictions is poorer

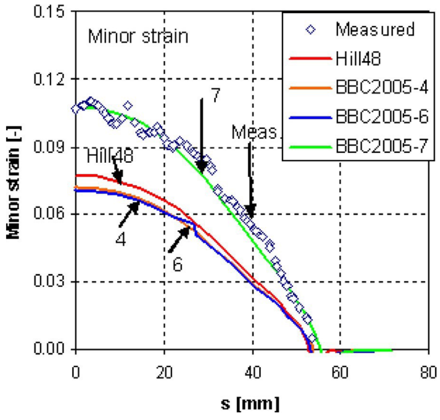


Fig. 6. Measured and computed minor strains for a DC04-IF steel sheet subjected to bulge forming (s is the distance from the center). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than that of the predictions provided by the Hill 1948 yield criterion. One may thus conclude that simply using an advanced yield criterion such as Barlat 2000, BBC 2005, or Vegter does not ensure accurate numerical predictions unless an adequate amount of experimental data is used for the identification (the usage of the biaxial yield stress is particularly essential from this viewpoint).

Fig. 7 shows a comparison between the minor strain distribution obtained by numerical simulation and the experimental data corre- sponding to a DP 500 steel sheet subjected to a bulge test. The best predictions are provided by the BBC 2005 yield criterion [18,21,189] identified with the experimental value of the biaxial yield stress (Sb=300 MPa in Fig. 7). If the values of the biaxial yield stress used for identifying the BBC 2005 yield criterion are different from the experi- mental value, the quality of the numerical predictions is comparable to or even poorer than that when the Hill 1948 yield criterion is used. It is thus essential to identify the yield criterion with accurate values of the mechanical parameters (especially the biaxial yield stress).

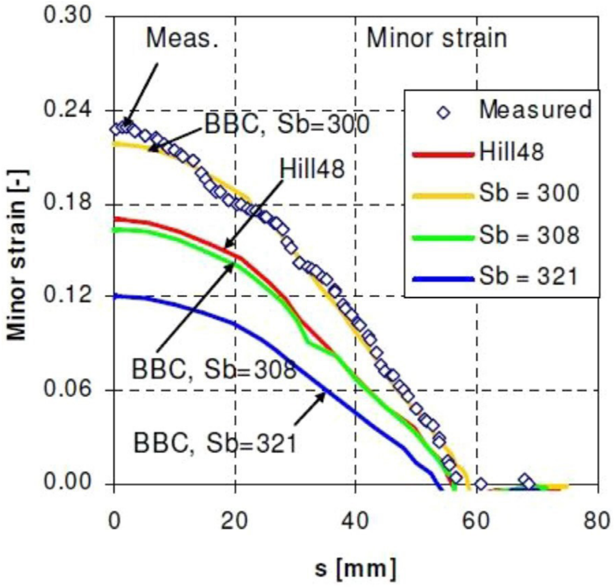


Fig. 7. Sensitivity analysis of the biaxial yield stress for DP 500 alloy (s is the distance from the center).

The yield criteria that use a larger number of mechanical parame- ters in the identification (13 or even more Yld 2004 [31], BBC 2008 [22,63] and so forth) can provide highly accurate descriptions of the anisotropic behavior. Their capability to capture the occurrence of six or eight ears in the case of deep drawing of cylindrical cups [77] is

especially notable. Fig. 8 presents a comparison between the predic- tions of three advanced yield criteria (BBC 2008 identified with 8 mechanical parameters, BBC 2008 identified with 16 mechanical parameters, and Yld 2004 identified with 18 mechanical parameters) and the experimental data corresponding to the earing profile of a cylindrical cup made of AA2090-T3 aluminum alloy [234]. One may note that BBC 2008 identified with only 8 mechanical parameters cannot give accurate predictions, while BBC 2008 identified with 16 mechanical parameters and Yld 2004 identified with 18 mechanical parameters can reproduce both the number of ears and their circum- ferential distribution. As a consequence, to obtain accurate predic- tions of the plastic behavior of highly anisotropic sheet metals (AA2090-T3 aluminum alloy in this case), advanced yield criteria identified with a large number of mechanical parameters should be used (in general, more than 8 mechanical parameters including the biaxial yield stress and biaxial anisotropy coefficient).

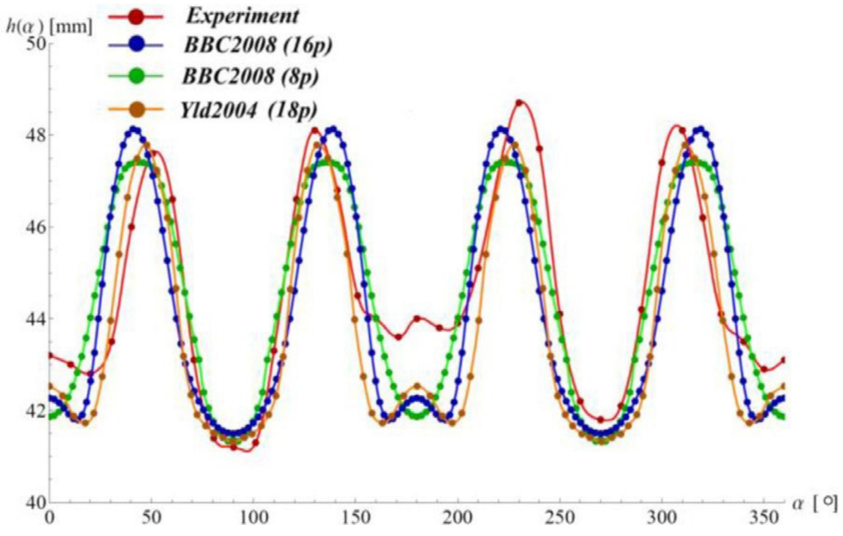


Fig. 8. Experimental vs numerically predicted earing for AA2090-T3 aluminum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During the last few years, several researchers have used CP mod- els to calibrate the phenomenological yield criteria of Yld 2000 [29], BBC 2005 [18], and BBC 2008 [63] using the virtual laboratory con- cept. Gawad et al. [78] proposed a new hierarchical multiscale frame- work (HMS) that allows the evolution of plastic anisotropy during sheet forming processes to be taken into account. The evolution of crystallographic texture is predicted by the ALAMEL CP model devel- oped by the van Houtte group [111]. The BBC 2008 phenomenological yield function is systematically recalibrated to data provided by the CP virtual experiment framework (VEF). A detailed presentation of this technique is given by Banabic et al. [24]. Raabe's group developed the virtual laboratory DAMASK using CP simulations to calibrate the initial yield surface used in the simulation of sheet metal forming [262,269], as shown in Fig. 9 and Fig. 10.

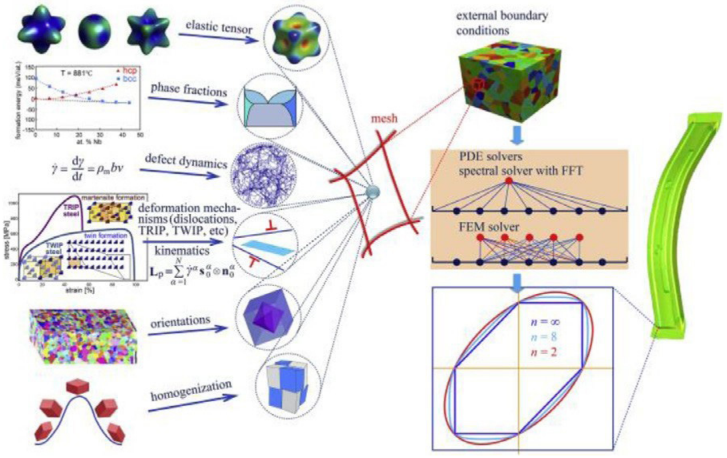
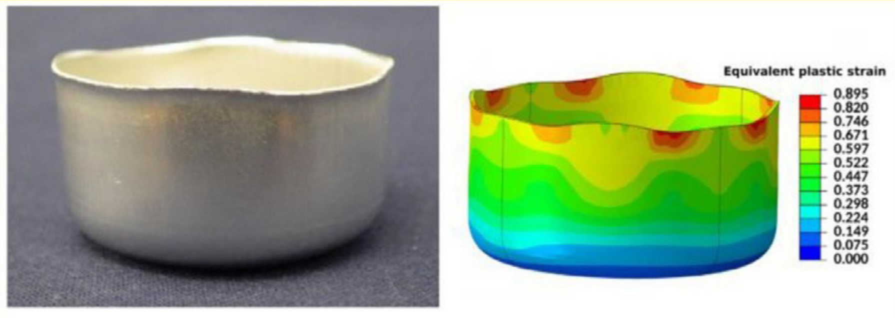


Fig. 9. Yield surface fitting by DAMASK. [262].

The advanced anisotropic yield criteria coupled with advanced anisotropic hardening models (Yoshida Uemori (Y U) 2002 [259], HAH 2011 [32], HAH 2020 [35]) can give accurate predictions for complex parts belonging to car structures, such as the decklid inner panel of a GM automobile shown in [21]. Fig. 11 presents springback



(a) (b)

Fig. 10. Cylindrical deep-drawn cup of AA3104-H19 aluminum alloy (a); distribution of the equivalent plastic strain for the deep-drawn cup predicted by the modified yield function using CP-based virtual tests (b). [136]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

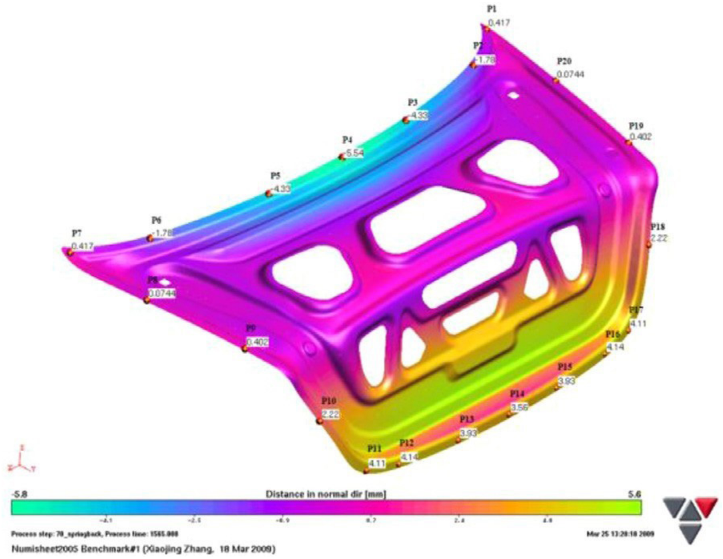


Fig. 11. Results of springback simulation. [21].

predictions provided by the BBC 2005 yield criterion in combination with the Y U hardening model [259] for such a part made of AA6111-T4 aluminum alloy.

The large variety of anisotropic yield criteria developed in the last three decades such as [18,29,49,78,193,230,260] can be confusing for users of FE programs. Therefore, in the above, we have presented the main factors that must be taken into account when choosing the yield criterion. For a yield criterion, there is a conflict among its accuracy and flexibility, its user-friendliness and robustness, and its CPU time consumption and cost. The conflict is illustrated in Fig. 12. The more accurate and flexible the yield criterion, the larger the number of coefficients included in its expression, and the longer the time needed for its identification. In general, such a yield criterion is not user-friendly and has low robustness. The identification cost of a yield criterion can be reduced by keeping a balance between its flexi- bility and robustness, by using robust identification algorithms, and by performing virtual experiments to determine material parameters that cannot be obtained from simple mechanical tests (e.g., the yield stress in the thickness direction) (see Fig. 12).

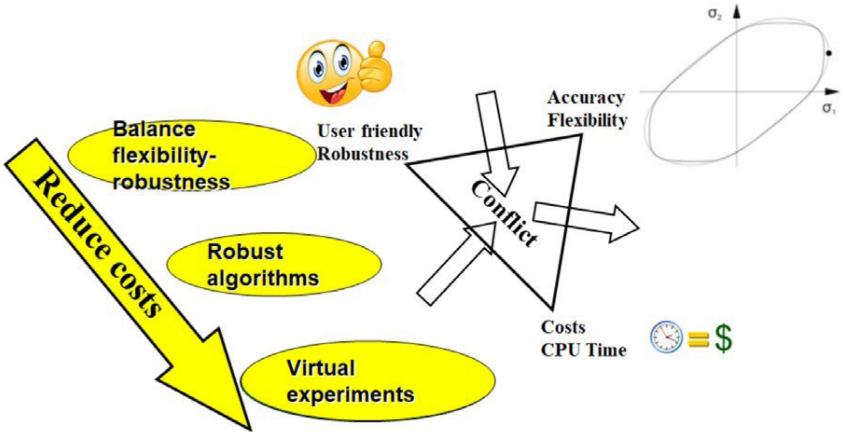


Fig. 12. Conflict between accuracy, robustness, and cost.

2.4. Hardening laws

From ancient times, metalsmithing has been a process of trans- forming metals in objects. By repeated loading and heating, the metal is shaped and also strengthened through a mysterious process called work hardening. However, we have only recently acquired some understanding of the science behind work hardening owing to the modern investigation technologies that allow the development of phenomenological models to account for dislocation dynamics. Hard- ening mechanisms such as solid solution strengthening, precipitation hardening, and martensitic transformation introduce crystal lattice defects that act as barriers to dislocation slip. Solving the mystery of dislocation dynamics has just begun. Bulatov et al. [261] developed in situ computational microscopy showing how dislocations movement is limited in certain strain conditions triggering new deformation mechanisms such as illustrated in Fig. 13.

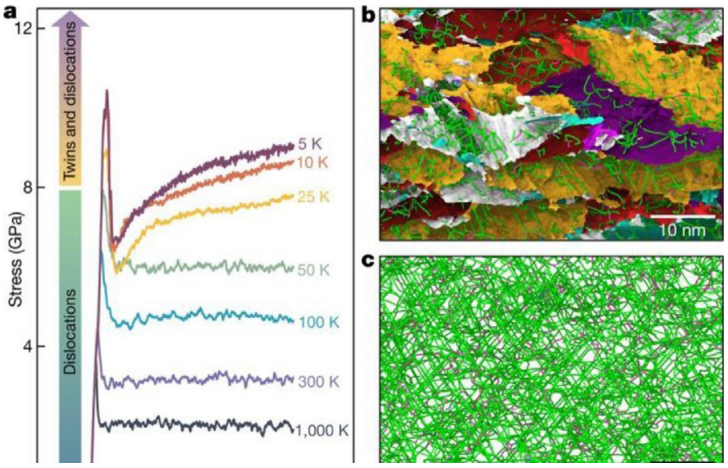


Fig. 13. Molecular dynamic simulation of the response to compression as a function of strain rate. [261].

Advanced atomistic modeling provides substitutes for"in-situ"experiments of understanding the influence of the strain rates on for- mation different forming mechanism. These deformation mechanisms were theoretically explained but never confirmed until atomistic simulations and computation power advanced so that to model polycrys- tals. For example, Bulatov's team simulations were able to study the deformation mechanisms in Ta under high strain and low strains dur- ing compression tests. It was shown that by compression of Ta, the dis- locations are extended, merged and together moved toward preventing failure.

The atomistic models determined the threshold from dislocation movement and twinning. Moreover, these simulations revealed also twisting of region of materials leading to crystal orientation, defining conditions under which this mechanism appear. Under low strains applied in a compression test of Ta, the dislocations are synchronous with the applied forces so that the crystal reach a steady state, which will be maintained avoiding transition to twinning, and consequently allowing the dislocations to continue to move preventing material to fail. The only the existence of this mechanism in pure materials leads to indefinitely maintain the same strength. This can explain the secret of manufacturing the famous Japanese swords. These findings allow better control of the loading path and heating during forming to achieve higher formability for more complex com- ponents. Bridging the scales of these findings from the microscale level (atomic) to the mesoscale level (CP) and the macroscale level (behavior or material) enables a new wave of digital manufacturing called meta- morphic manufacturing [272]. Metamorphic manufacturing allows the incremental forming of materials through multiple possibilities of the loading path, postponing the necking and failure of the material. Thus, under new circumstances, it is important for two aspects of materials to be numerically simulated with high fidelity: (1) the hardening of materials under multiple path changes and (2) the formability of mate- rials beyond the known limits.

1. ***Hardening:*** The effect of hardening model to springback is shown in Fig. 14 [60]. The Yoshida Uemori (Y U) [259] and homoge- neous yield-function-based anisotropic hardening models (HAH) [32,35] are typical models that can predict the Bauschinger effect, transient hardening, and permanent softening. Simulation of a double-stage U-draw bending of an advanced high-strength steel (AHSS) sheet was modeled using HAH with the scope of spring- back prediction. For this simulation, finite difference meth- od (FDM)-based stress update algorithm was used. The results shown a high computational efficiency of this simulation, comparable with analytical methods. Following this study, a key recommenda- tion is that for, materials exhibiting a clear Bauschinger effect but insignificant texture anisotropy (e.g., MP980), the selection of suit- able yield criteria (e.g., Hill48 [95]) and the consideration of elastic modulus degradation combined with the Y U model can signifi- cantly increase the accuracy of springback prediction. Contrary, for materials that exhibit small Bauschinger effect but have signifi- cant texture anisotropy (e.g., AA6022-T4), the use of a yield crite- rion that accounts for anisotropy (e.g., YLD2000 2D [29]) is more important for improving the accuracy of springback prediction.

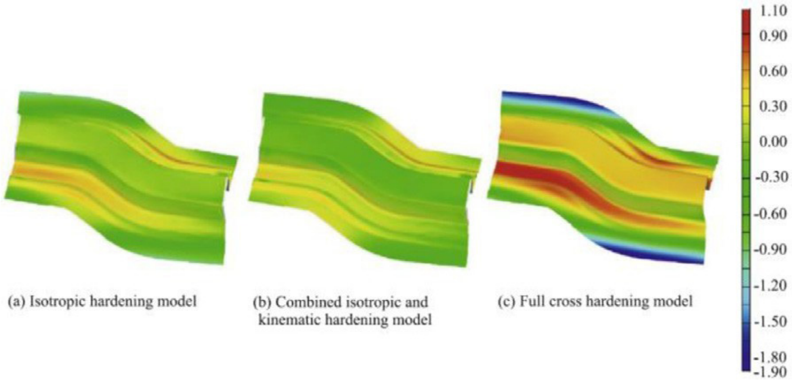

(a) Isotropic hardening model
(b) Combined isotropic and kinematic hardening model
(c) Full cross hardening model

Fig. 14. Predicted springback for S-Rail for the full cross hardening model. The refer- ence geometry was simulated after the forming stage. The geometry twists along the x-axis. [60]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Formability: There is a growing tendency of using incremental mod- els based on the forming limit curve (FLC) to consider the effects of nonlinear strain paths for failure evaluation, therefore contributing to more precise design assesments.

However, as demonstrated in this paper, some of these FLC-based incremental models can be promptly reproduced by using already existing damage-based incre- mental models. In fact, damage-based models seem to be more gen- eral than many of the FLC-based incremental models because they allow the use of nonlinear damage accumulation, the definition of different failure curves for different fracture mechanisms, the consid- eration of coupling between stress and damage, the use of regulariza- tion tools against spurious mesh dependence, and several other features. This is expected to a certain extent in ductile metal sheet because, in forming simulations, one is more interested in predicting localized necking as the indicator of the forming limit of a given part. In crash applications, it is important to correctly predict fracture, for which most tensile stress states appear after localized necking, and, for this purpose, damage-based models are more suitable, will be as discussed in 'Damage models' section.

2.5. Flow rule

The flow rule is expressed as [96]

$$d\varepsilon_{ij}^{p} = h\frac{\partial g(\sigma)}{\partial \sigma_{ij}}df. \qquad (3)$$

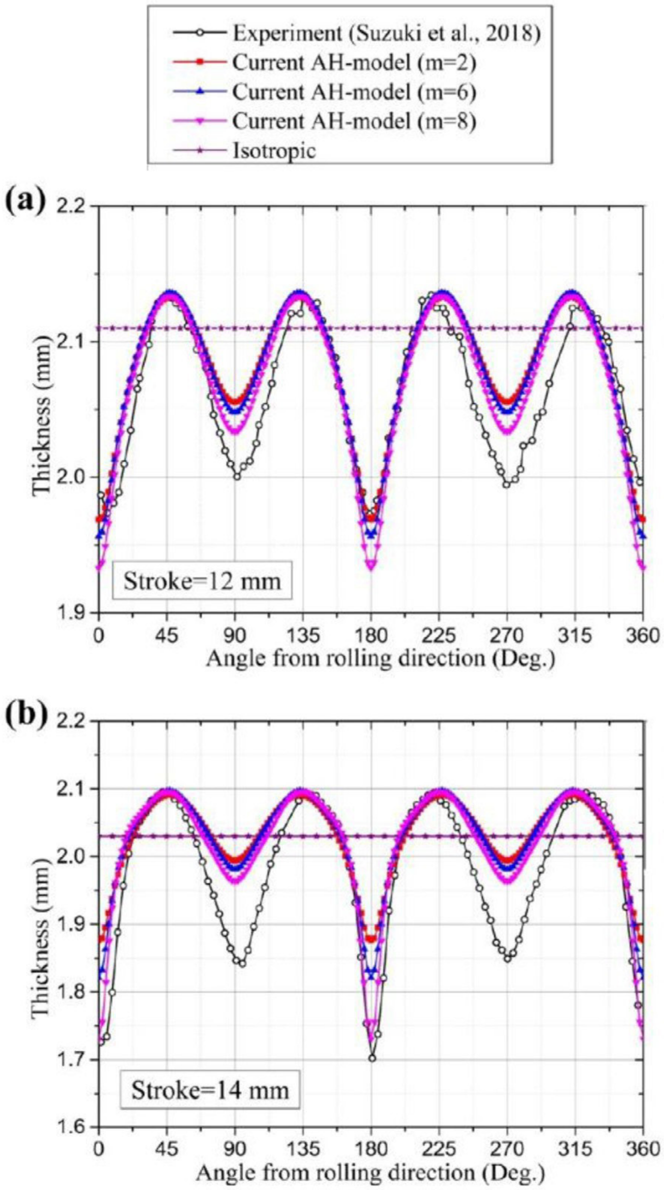


Fig. 15. Thickness distributions along the hole edge of a JSH590R sheet, predicted using the non-associated anisotropic hardening model with different exponents, along with the distribution for the isotropic case and the experimentally measured results: (a) 12 mm and (b) 14 mm punch strokes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Most of plasticity modeling utilizes an associated flow rule, in which the plastic potential function g s is identical with the yield function f s . This assumption is correct for isotropic metallic materi- als, but it cannot always be applied to materials with anisotropic characteristics. To begin with, there are two types of anisotropy: stress anisotropy, represented by the strength variation in the tensile test direction versus the rolling direction (RD), and deformation anisotropy, represented by the Lankford value, represented by the ratio of in-plane stress of tensile direction vs thickness strain. In the simplest case of the plane strain condition and Hill48 yield function f ðsÞ, two tensile tests in the RD and transverse (TD) are performed to obtain s0 and s90, respectively, an equibiaxial test (bulge test) is per- formed to measure sB, and an in-plane shear test is performed to measure ts to determine the coefficient of yield function f ðsÞ. The Lankford value must be used to determine the coefficients of plastic potential g s (not f s).

The non-associated flow rule is general, and the associated flow rule is just one part of the non-associated flow rule. The number of investigations of the non-associated flow rule is gradually increasing [213]. Fig. 15 shows the results of the analysis of the thickness distri- bution in a hole expansion test [216,250]. The application of the non- associated flow rule will become much more relevant in future.

The accuracy of the numerical simulation depends on the accuracy of the modeling. The progress of numerical simulation is driving the inves- tigations in the modeling of plasticity to realize more accurate but sim- pler numerical simulations of metal forming in the future.

3. Recent modeling of observed physics for simulation of metal forming

3.1. Modeling of damage

Damage and the associated failure of components are critical in many engineering applications. Today, the social demand drives research and development of lightweight components to reduce the CO2 footprint of transportation [46]. As presented in a comprehensive review [221], nowadays, the design of lightweight components is damage-driven, and consequently, damage criteria are used for decision making in the prediction of component failure. As shown by Tek- kaya et al. [221], advances in microscopic analysis have provided a better understanding of the damage mechanisms in metals leading to failure. These mechanisms involve three phases: (1) nucleation of voids, (2) growth of the voids under subsequent loading, (3) coales- cence of the voids (internal necking and shearing). Different formula- tions have been used to model each phase of the damage, and these formulations are called damage models. The predictions of the mod- els over the load up to failure are integrated to represent failure crite- ria. A synthesis of the damage models and failure criteria is presented in Table 2, which shows the evolution of the formulations to adapt to the development of lightweight materials characterized by high anisotropy and hardening [172].

Through these models, advanced damage modeling reveals invisi- ble phenomena. However, there are still challenges in modeling com- ponent failure with high precision. Examples include the following:

(1) In the GTN model, voids do not grow under pure shear; however, failure can occur under pure shear through two mechanisms, namely, void locking due to the presence of hard inclusions and the nucle- ation of new voids at high plastic strain levels. (2) The models are mesh-size-dependent, leading to the variation of nucleation and internal necking localization. (3) Models have high computation cost. The high-precision prediction of damage evolution in the metal form- ing of complex components during their design has an unprece- dented role in creating digital twins of the forming processes and their cost-effective manufacturing (Fig. 16). Fracture initiation is more frequently simulated by multiscale modeling taking the micro- structure morphology into account [185] as shown in Fig. 17.

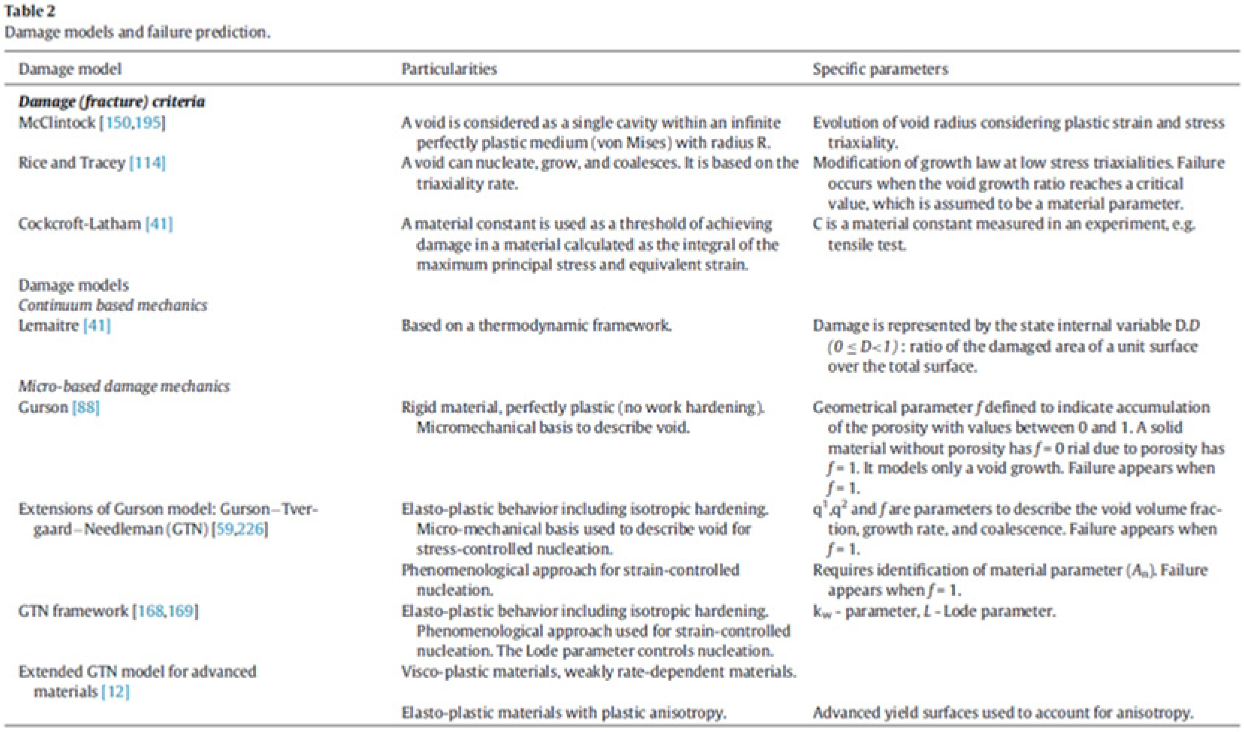


Table 2
Damage models and failure prediction.

Damage model	Particularities	Specific parameters
Damage (fracture) criteria		
McClintock [150,195]	A void is considered as a single cavity within an infinite perfectly plastic medium (von Mises) with radius R.	Evolution of void radius considering plastic strain and stress triaxiality.
Rice and Tracey [114]	A void can nucleate, grow, and coalesces. It is based on the triaxiality rate.	Modification of growth law at low stress triaxialities. Failure occurs when the void growth ratio reaches a critical value, which is assumed to be a material parameter.
Cockcroft-Latham [41]	A material constant is used as a threshold of achieving damage in a material calculated as the integral of the maximum principal stress and equivalent strain.	C is a material constant measured in an experiment, e.g. tensile test.
Damage models		
Continuum based mechanics		
Lemaitre [41]	Based on a thermodynamic framework.	Damage is represented by the state internal variable D.D $(0 \leq D < 1)$: ratio of the damaged area of a unit surface over the total surface.
Micro-based damage mechanics		
Gurson [88]	Rigid material, perfectly plastic (no work hardening). Micromechanical basis to describe void.	Geometrical parameter f defined to indicate accumulation of the porosity with values between 0 and 1. A solid material without porosity has $f = 0$ rial due to porosity has $f = 1$. It models only a void growth. Failure appears when $f = 1$.
Extensions of Gurson model: Gurson–Tvergaard–Needleman (GTN) [59,226]	Elasto-plastic behavior including isotropic hardening. Micro-mechanical basis used to describe void for stress-controlled nucleation.	q^1,q^2 and f are parameters to describe the void volume fraction, growth rate, and coalescence. Failure appears when $f = 1$.
	Phenomenological approach for strain-controlled nucleation.	Requires identification of material parameter (A_n). Failure appears when $f = 1$.
GTN framework [168,169]	Elasto-plastic behavior including isotropic hardening. Phenomenological approach used for strain-controlled nucleation. The Lode parameter controls nucleation.	k_w - parameter, L - Lode parameter.
Extended GTN model for advanced materials [12]	Visco-plastic materials, weakly rate-dependent materials.	
	Elasto-plastic materials with plastic anisotropy.	Advanced yield surfaces used to account for anisotropy.

3.2. Modeling of friction

The modeling of friction is an old topic, but it still remains an important field of research in observed physics. Past investigations are dedicated to understanding friction or interface phenomena to model friction [171,239].

3.2.1. Friction models in sheet metal forming

In addition to the constitutive equations, the models used to describe the frictional interactions between a blank and forming tools play an essential role in ensuring the accuracy of simulation. Fig. 18 shows a diagram of the tribological system in which the main factors offering friction in sheet metal forming processes are presented [224].

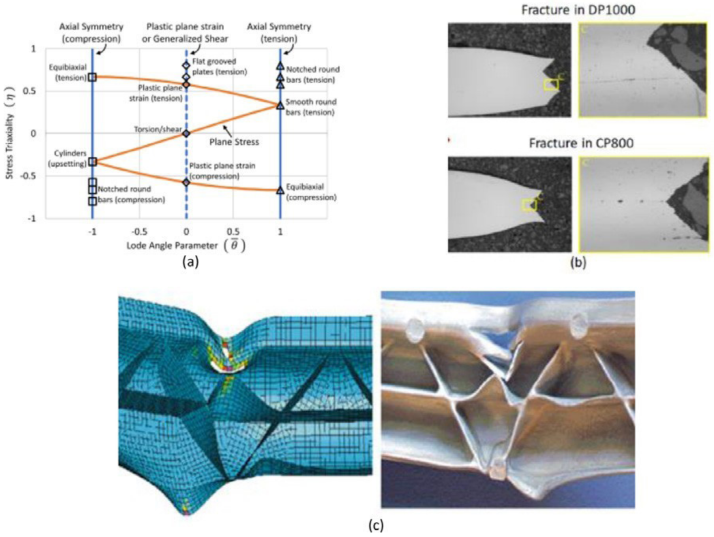


Fig. 16. Illustration of damage prediction: (a) prediction of necking - stress triaxiality and Lode angle parameter [161], (b) multiphase metals exhibiting a complex fracture surface, which can be modelled using the GTN model with the lode-parameter-controlled nucleation of voids [92] and, (c) modeling three-point bending test of magne- sium interior door using Gurson model. [270]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

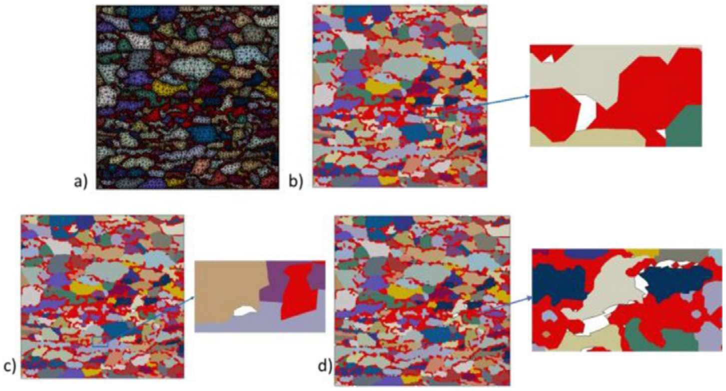


Fig. 17. Fracture initiation and evolution in DP steel calculated with the developed RCAFE model: a) initial FE mesh, b) martensite fracture initiation, and propagation, c) ferrite fracture initiation, and d) ferrite fracture propagation

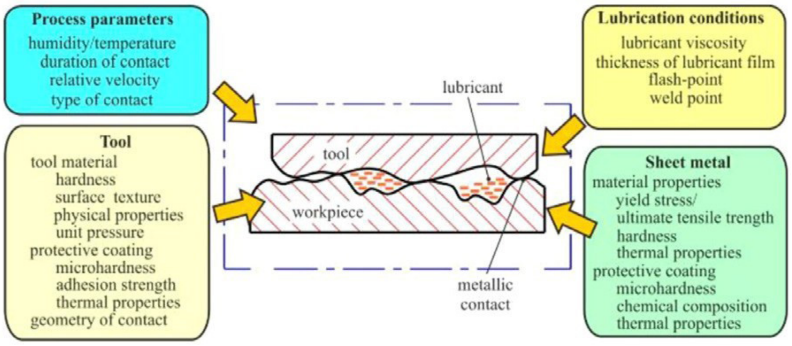


Fig. 18. Scheme of a tribological system in sheet metal forming. [224].

These factors are process parameters (temperature, duration of contact, relative velocity, and type of contact), forming tools (tool material properties, tool coating properties, and geometry of contact), lubrication conditions (thickness and viscosity of the lubricant layer, and flash and weld points), and mechanical and coating properties of sheet metal [224].

According to Coulomb's law, the frictional force between two bod- ies in relative motion is proportional to the normal force acting on the bodies. The proportionality coefficient is the coefficient of friction, which is usually assumed to be constant. This is the simplest and most widely used model in the FE programs used for sheet metal forming simulation. Since the friction coefficient is considered con- stant (an imprecise approximation in the case of metal forming pro- cesses [200]), the accuracy of predictions obtained by simulation is low. Over time, more advanced models, that consider several param- eters of the tribo-system and thus have higher accuracy have been developed. The modeling of the friction phenomena that occur at the part tool interface in metal forming processes has been attempted since the 1950s with the intensification of effort after the 1970s. Dif- ferent approaches have been introduced to improve Coulomb theory including adhesion theory [105], a theoretical model of the real con- tact area at high pressures [240], a model of plastic waves as a mecha- nism for friction [242], frictional contact with hardening [212], and multiscale friction modeling [102], and so forth. Systematic research on the development of friction models was conducted by groups coordinated by Wanheim and Bay [241,242], Wilson [179,246,247,248], and so forth. Schey [200] presented in detail the friction models existing at that time [201]. Schey performed a synthe- sis of the friction laws used in the simulation of metal forming pro- cesses. Recently, such a synthesis has been published by Nielsen and Bay [173]. A significant improvement in the accuracy of simulations, especially in the case of complex-shaped parts in car bodies, was achieved by using advanced friction models [102-104,238].

]. The mod- els based on multiscale friction modeling developed by Hol et al. [102-104,] predict the dependence of the friction coefficient on the contact pressure, sliding velocity, plastic strain, and temperature.

Fig. 19 shows the distributions of contact pressure and friction coefficient for a cruciform test piece [102]. Using the proposed model, Hol et al. accurately predicted the distributions of the contact pres- sure and friction coefficient in the deformed part, which allowed real- istic predictions of both the draw-in evolution of the part during the deformation and the distribution of the part thickness.

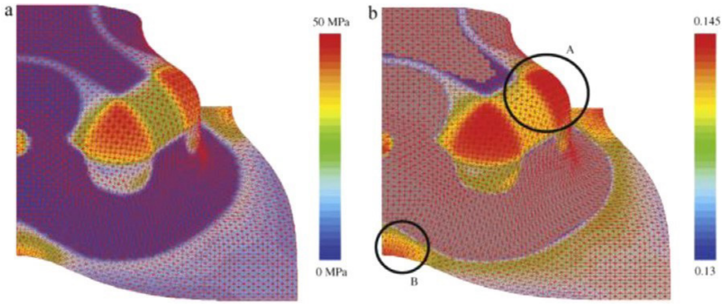


Fig. 19. Development of contact pressure (a) and coefficient of friction (b) for normal loading only (gray regions represent the non-contact areas). [102].

These results allowed the proposed model to move from labora- tory-scale studies to implementation in commercial FE codes for use in industrial practice. Sigvant et al. [207] implemented the friction model developed by Hol et al. [103,104] in a commercial program and tested it for a complex car body part (rear door inner for Volvo X90). Using this model, the simulations successfully captured the roughness variation on the upper and lower surfaces of the binder, punch, and die, as well as the variation of strain rate sensitivity. Fig. 20 shows a sensitivity analysis of the major strain with the roughness Ra of the upper and lower binder surfaces. The variation of the friction coefficient as a function of contact pressure is shown in Fig. 21 [207].

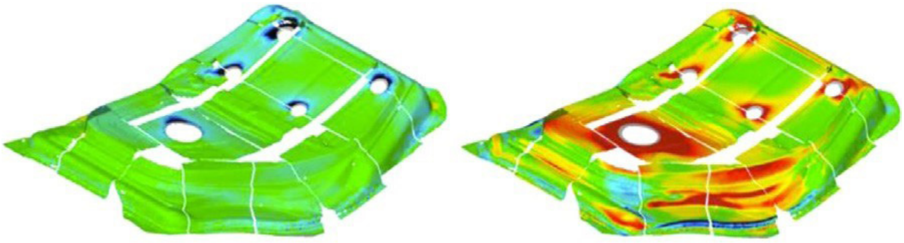


Fig. 20. Difference in major strain for reduction in roughness Ra of binder surface from 0.45 μm to 0.35 μm (left) and for increase in Ra from 0.45 μm to 0.75 μm (right). [207]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

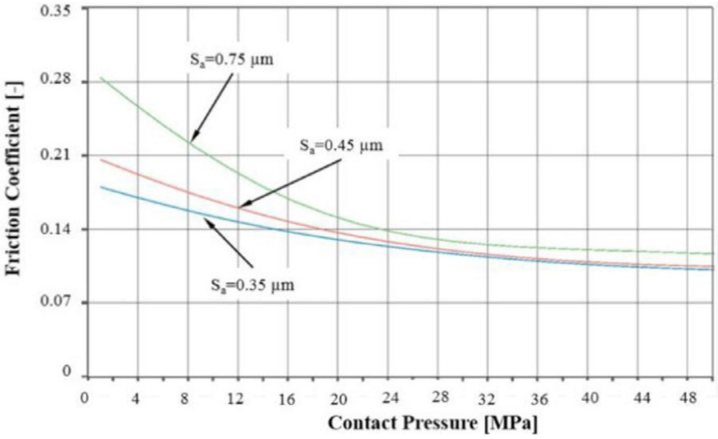


Fig. 21. Friction coefficient as a function of contact pressure for different Sa- values of binder surface. [207].

3.2.2. Friction models in bulk metal forming

In bulk metal forming, extremely high contact pressures (up to a few times the yield strength of the workpiece material) are gener- ated, and large surface and sub-surface modifications are often encountered, which cannot be seen owing to the closed dies. Also, the relative sliding distance between a tool and a workpiece is com- paratively short, and under these circumstances, the "run-in" behav- ior of the interface is also important. That is, it is important to characterize not only the steady-state behavior but also the evolution of the frictional resistance to a steady state. Our understanding of the friction in bulk metal forming is limited by the accessibility to the working area and the speed of the forming process. Moreover, according to the development lightweight materials and forming, heating was added to enable formability and decrease the forming forces [162].

The most common friction models used in the FE simulation of bulk forming are presented in comprehensive review papers [141,173,218]. The most common friction models used in the FE modeling of bulk forming are the Coulomb friction, constant friction, general friction, absolute constant friction stress, and empirical fric- tion models [37,103,127,178,186]. Model parameters are usually cali- brated using a ring compression test or an upsetting test [217]. The normal pressure and friction area ratio are calibrated against mea- sured curves. Calibration curves of the friction area ratio are more sensitive to friction at the tool work material interface than those of the normal pressure. Although ring compression experiments are easy to conduct and are widely used, they lack the capability of pro- viding direct information about the dependence of the frictional resistance of an interface between a tool and a material on the con- tact pressure, and relative sliding distance, and speed. Consequently, Nielsen et al. [173] developed a mathematical model that accurately describes the friction in tube drawing. This model, named the plastic wave model, was developed using either the upper bound theorem or the sliding lines theorem. This model was used by Baillet and Boyer [13] to design a macroscopic friction law for forging processes.

This model is based on a phenomenological approach that models the asperities of the tool and material surfaces resulting from machining. At the interface, because of friction and plastic strain, heat is also gen- erated at the tool workpiece interface. The plastic wave model was extended to a mixed lubrication regime [6], enabling the hydrostatic pressure of the lubricant entrapped between the asperities to be taken into account. The thermal contact resistance (TCR) defined at the interface between the tool and the material is variable during forming. Through FE modeling, the TCR is predicted by the model and correlated with the contact pressure. Thus, by prediction the thermal field during forming, contact pressure can be seen.

As shown in Fig. 22(a), in the model developed by Vidal-Salee et al. [232], the asperities of the tool workpiece interface are modeled in triangles and using parallel springs. Thus, the modification of the con- tact between asperities at the tool workpiece interface during form- ing is accounted for and a variable TCR is predicted. The effect of the TCR on the upsetting of a cylindrical billet of AA 6082 and backward extrusion are presented in Figs. 22(b) and (c), respectively.

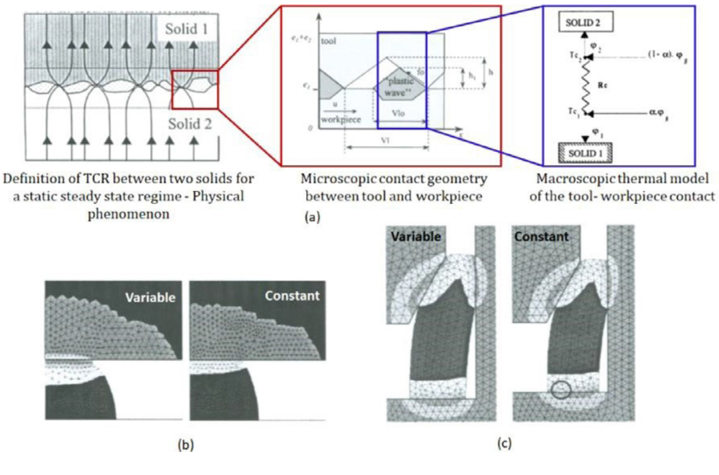


Fig. 22. Role of the variables in temperature prediction for variable and constant TCR (thermal contact resistance) values (a); (b) upsetting of a cylindrical billet between two flat dies and (c) backward extrusion. [232]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To summarize this section, advanced friction models can capture the effects of the most significant parameters of a tribological system. The comments on the conflict among the accuracy and flexibility of a model, its ease of use and robustness, and the cost and CPU time are similar to those presented earlier for the anisotropic yield criteria.

4. Numerical methods in simulation

Computational materials science (CMS) involves and enables the visualization of concepts and phenomena occurring in materials that are otherwise difficult to describe or even imagine. This is why this area of research is one of the driving forces towards the digitalization of metal forming. Among its various features, this field of research allows materials to be designed and tested efficiently, often reducing the number of time-consuming and expensive experimental trials. Therefore, CMS extends and complements the capabilities of labora- tory and industrial-scale investigations, allowing a comprehensive approach to research and process designs.

4.1. Mesh-based simulation

The mesh-based techniques mentioned earlier are still the pri- mary choice to obtain a numerical solution of complex partial differ- ential equations describing physical phenomena in metal forming. As presented, the accuracy of the results depends to a large extent on geometrical aspects of the investigated computational domain, the properties of the material being evaluated, and finally, the defined initial and boundary conditions.

The geometrical aspects in the metal forming area are particularly important, as the geometry of the entire investigated system, com- prising the sample and dies, and so forth, is often very sophisticated. To recreate these continuum-type systems within the numerical algorithm of mesh-based techniques, the discretization of the computational domain into the set of finite subdomains is crucial.

The discretization approaches vary depending on the type of mesh- based technique selected for the investigation. In the finite boundary or finite volume method, the meshing process involves the generation of boundary elements or finite volumes, respectively. In the most pop- ular mesh-based technique, namely FEM, the investigated geometry is divided into a set of elements. FEM has been used in metal forming since the 1970s, especially after the flow formulation was proposed by Kobayashi [123,128] as widely described in [124].

Most of the time, the investigated systems are highly complex and vary in unpredictable ways using continuous functions across the entire domain. However, it is expected that such a system can be numerically approximated by discretization into finite elements (shell, solid, and membrane). In general, the finer the discretization level, the higher the accuracy of the obtained results. However, at the same time, the computation time increases significantly and often exceeds acceptable limits. Therefore, the control of the discretization level is one to decrease the simulation time of metal forming operations.

Over the years, two approaches that link the mesh with the mate- rial and its flow have been used: the Lagrangian and Eulerian approaches (Fig. 23).

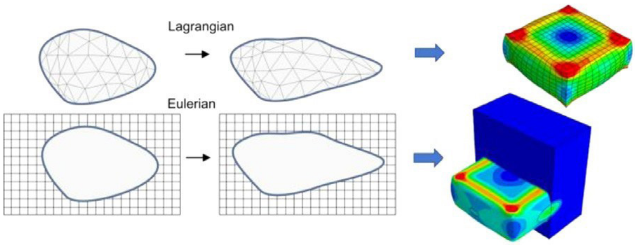


Fig. 23. Lagrangian vs Eulerian FE meshes and corresponding simulation of the rivet- ing operation.

The former is called a material description, with mesh nodes directly connected to material points and their movement precisely tracked during deformation. The coordinates of material points are time-invariant, and the material does not pass between subsequent elements. The advantage of the approach is related to the fact that boundary nodes during the simulation remain at the boundary of the sample. As a result, boundary conditions are easily applied. This approach also accounts for the history of deformation and allows changes in material properties to be followed [187]. However, at the same time, as the deformation proceeds, mesh distortion and mesh degeneration can occur, affecting the quality of results and often leading the non-convergence of the solution. As a result, often unphysical artifacts occur in the solution, affecting its appropriate interpretation. To overcome this limitation, remeshing operations have been developed [40,79]. In metal forming operations character- ized by significant deformations, such as extrusion, a remeshing operation is required in each iteration, which leads to long computa- tion time and may also affect the geometrical description of the computational domain. To minimize the error of the numerical solu- tion while maintaining an acceptable computation time, a series of dedicated algorithms for fully automatic adaptive finite FE refine- ment/coarsening have been developed, as shown in Fig. 24 [57,89]. Adaptation is initiated on the basis of various error indicators [267]. The classical approach assumes modifications in the number of finite elements (h-adaptation) or the redistribution of their position with- out changes in their number [r-adaptation] [148,155]. Another class of methods that was developed assumes modifications in the approximation level of finite elements (p-refinement) [10]. These approaches can be used separately or under a combined scheme, e.g., hp- adaptation [175]. Modifications of the FE mesh in the Lagrangian approach are also required for the efficient modeling of fracture in metal forming. Approaches such as the partition of unity method (PUM) [11], generalized finite element method (GFEM) [214], or extended finite element method (XFEM shown in Fig. 25) [158] incor- porate discontinuous functions into the solution space, allowing the modeling of fracture propagation without loss of the volume of the material.

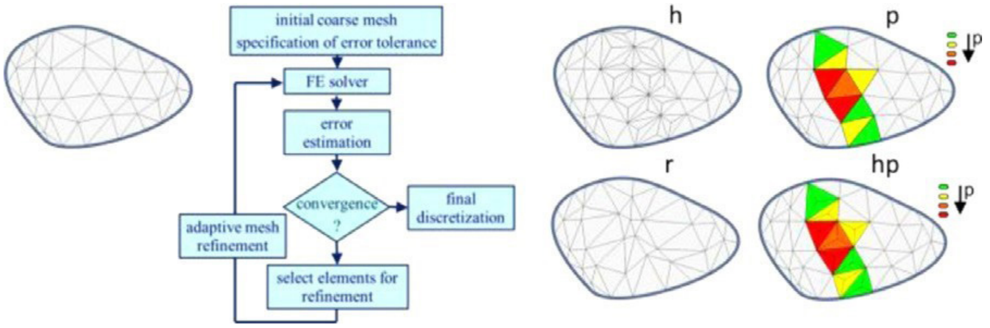


Fig. 24. Examples of FE mesh adaptation techniques.

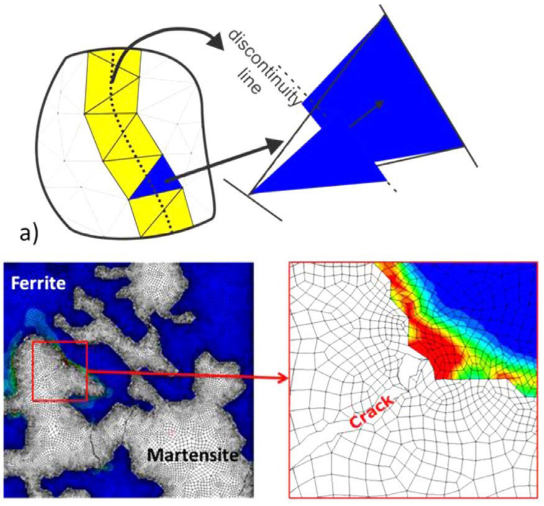


Fig. 25. a) Concept of the XFEM method and b) example of application to fracture modeling in dual-phase steel.

An alternative solution that can be used to overcome issues with mesh degeneration is the Eulerian approach, which identifies a cer- tain fixed location in the computational domain and follows the changes in its properties as the material passes through that location (Fig. 25(b)). Nodes are fixed and coincide with spatial points, not material points as in the Lagrangian approach. Therefore, the material flows through the defined mesh, which makes the process of assign- ing boundary conditions a complicated task. However, at the same time, there is no mesh degeneration because the mesh is fixed in the computational domain, which is also larger than the investigated material geometry. The advantages of both methods were combined in [174] and have since been explored, mainly for fluid dynamics and metal forming applications, under various combinations leading to methods such as the arbitrary Lagrangian Eulerian (ALE) and cou- pled Eulerian Lagrangian (CEL) methods [38,69,117].

When the computational domain is discretized, appropriate prop- erties (e.g., thermal, mechanical, and rheological) should then be assigned to its components to predict the evolution of physical phe- nomena occurring in metal forming (Fig. 26). These properties are determined from a series of experimental laboratory tests [5], acquired from open access [184] and commercial databases [204], or calculated online by thermochemical calculations [86,199].

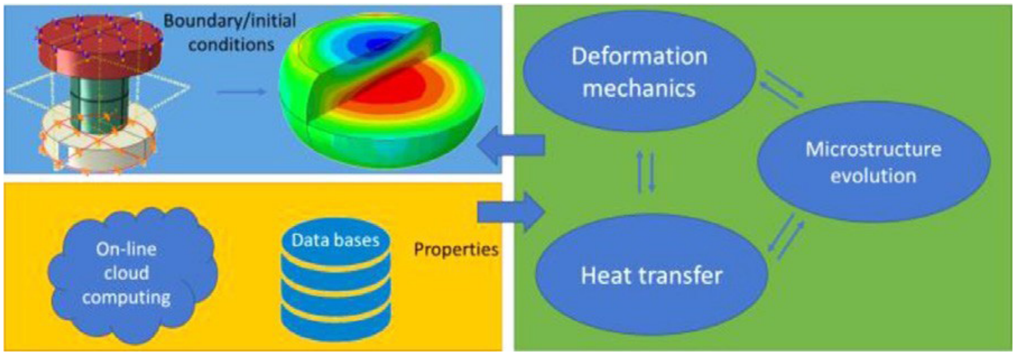


Fig. 26. Physical phenomena occurring in metal forming and their relation to property databases.

Finally, to obtain accurate results from FE simulations, appropriate boundaries and initial conditions should be defined, as shown in Fig. 26. This step is directly related to the type of metal forming simu- lation and can significantly vary from one case study to another [187]. Therefore, in this case, both experience and engineering knowledge play a crucial role.

The complexity of numerical simulations by FEM has increased since it was first used. This is directly related to the growth of com- puting power (HPC computing [67], grid computing [74], cloud com- puting [45], and hybrid computing [149]), and also to the in-depth understanding of the complexity of the physical phenomena being replicated [229]. However, finding the balance between accuracy and acceptable computation time is still a challenge. Various solutions, such as model order reduction [191] (e.g., 3D 2D), self-consistent clustering analysis [137], the approximation of the deformation pro- cess with a stationary solution [235], mesh adaptation [175], and the application of mass scaling or load factoring, have been proposed [188,208] (Fig. 27). The last two approaches are applied to dynamic explicit calculations and strain-rate-insensitive materials, respec- tively. In recent years the FEM was also successfully incorporated directly into the computer-aided design (CAD) based on the NURBS (Non-Uniform Rational B-spline) curves [118]. Such concept of iso- geometric analysis (IGA) is of a practical character, especially for industrial applications, as the time from the design stage to the analy- sis stage is significantly reduced. The concept, advantages, limitations and possible alternative solutions are summarized in [170].

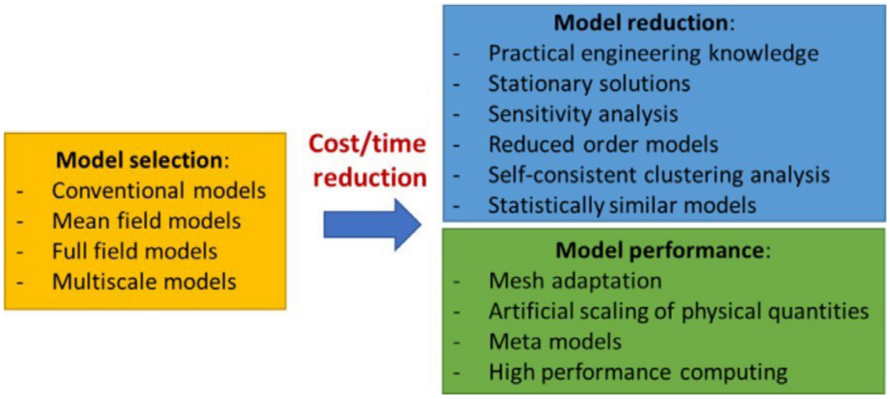


Fig. 27. Concepts in computational models cost reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Along with FEM, alternative approaches for the analysis are also applied in the metal forming area, particularly the boundary element method (BEM) [51,154] and finite volume method (FVM) [36,42]. The BEM generally discretizes the boundary of the investigated system. Therefore, it is often more efficient than other methods, including FEM, in terms of computational resources for problems where there is a small surface/volume ratio, such as sheet forming [52]. However, the BEM has also been applied to study bulk forming, e.g., extrusion or rolling [53]. The FVM is based on a formulation consisting of flux conservation equations, which are averaged across elements called controlled volumes. This method is especially efficient for the simula- tion of metal forming processes characterized by large velocities and deformation degrees, such as extrusion [36].

The presented mesh-based techniques are often used in the metal forming area as the basis for advanced and multidisciplinary multi- scale solutions.

4.2. Mesh-free simulation

A class of problems for which the above-mentioned mesh-based methods are difficult, or even impossible, to apply can be identified in the metal forming area. In particular, large deformations leading to severe geometrical changes, explosive forming with fast-moving free surfaces or fracture, and defragmentation belong to this class. In the mesh-based techniques, the required discretization, often of adaptive nature, leads to excessive computation time and also a decrease in accuracy due to frequent interpolations during remeshing. Therefore, the main concept of the mesh-free methods (meshless methods) is to use a cloud of nodes instead of elements during the approximation (Fig. 28(a)). These nodes are associated with material points, and they store field variables and move with the material during calcula- tions. In this case, the density and distribution of nodes directly depend on the required accuracy of the solution, as well as the avail- able computational power. As there are no direct connections between the nodes, mesh distortion is eliminated, which is crucial when large deformations are considered. The refinement and de- refinement of nodes can also be easily controlled.

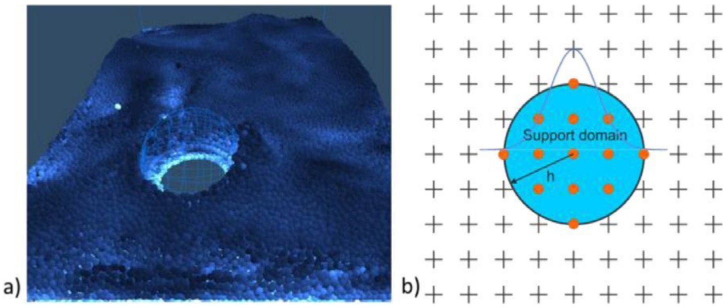


Fig. 28. Support domain of the j- th particle.

These nodes have a spatial distance called the smoothing length h, over which their properties are 'smoothed' by a kernel function Wij:

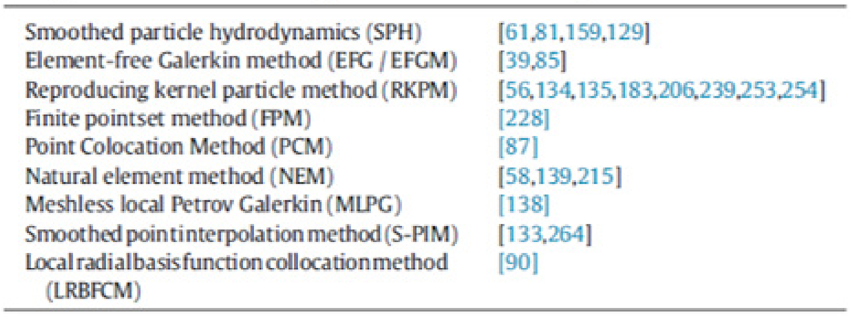
$$\langle f(x) \rangle \cong \sum_{j=1}^{N} f(x_j) W_{ij}(x - x_j, h) V_j, \qquad (4)$$

where <> - kernel approximation, Wij - kernel function, h - smoothing length, and Vj volume associated with the j- th particle [81,160].

Using the equation, a physical quantity of the investigated node is obtained by the summation of the appropriate properties of all the neighboring particles from the support domain defined by h (Fig. 28(b)).

One of the first developed mesh-free methods was the smoothed particle hydrodynamics (SPH) proposed in [81] and widely described in [132]. However, in addition to SPH, there is a wide range of meth- ods based on a similar concept that have been developed and applied in metal forming and metal cutting, as shown in Table 3.

Table 3
Examples of various mesh-free approaches in metal forming.



Smoothed particle hydrodynamics (SPH)	[61,81,159,129]
Element-free Galerkin method (EFG / EFGM)	[39,85]
Reproducing kernel particle method (RKPM)	[56,134,135,183,206,239,253,254]
Finite pointset method (FPM)	[228]
Point Colocation Method (PCM)	[87]
Natural element method (NEM)	[58,139,215]
Meshless local Petrov Galerkin (MLPG)	[138]
Smoothed point interpolation method (S-PIM)	[133,264]
Local radial basis function collocation method (LRBFCM)	[90]

The mesh-free methods are also becoming increasingly available in commercial computer-aided engineering (CAE) codes such as Aba- qus and LSDYNA [83]. As a result, the application of these methods to practical metal forming research in the areas of bulk [61] and sheet forming [159] as well as joining has increased over the last decade (Fig. 29). Despite the advan- tages mentioned in this section, the mesh- free methods are still often considered more expensive from a numerical point of view than their mesh-based counterparts. In gen- eral, the solution in some cases may be numerically unstable. Also, imposing the essential boundary conditions is more demanding. However, there are approaches in the scientific literature trying to face these challenges [65].

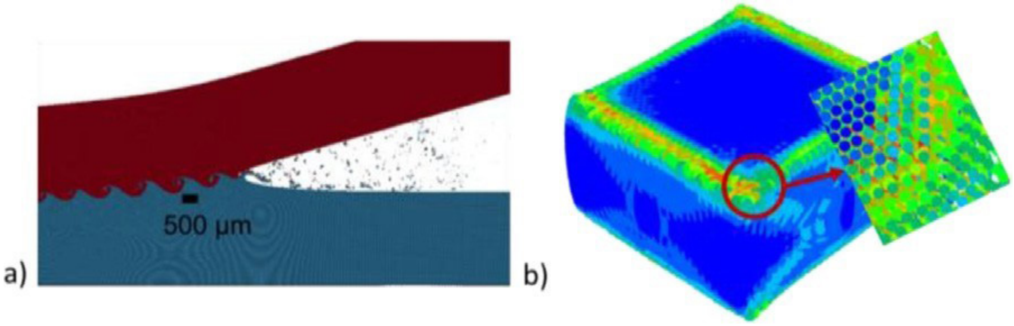


Fig. 29. Example of SPH application in a) joining and b) bulk forming

5. Multiscale simulation methods

5.1. Basis of multiscale simulation

Multiscale simulations deal with resolving physical problems hav- ing important features controlling a particular phenomenon at multi- ple scales [107]. Both the length and temporal scales can be distinguished during an investigation (Fig. 30). The former describes the physical dimensions characteristic of a particular scale, while the latter deals with the physical time specific to the particular phenome- non. The temporal scale is often unified across different length scales to ensure physically relevant results. This, however, makes the model computationally expensive. Appropriate data bridging techniques across the length and temporal scales have to be determined [187] to create an efficient and robust multiscale model for metal forming [220]. The basic principles of the modeling technique, as well as the classification of models, can be found in the fundamental works of Allix [4] and Fish [73]. Examples of applications to industrial case studies were widely discussed in [107,187].

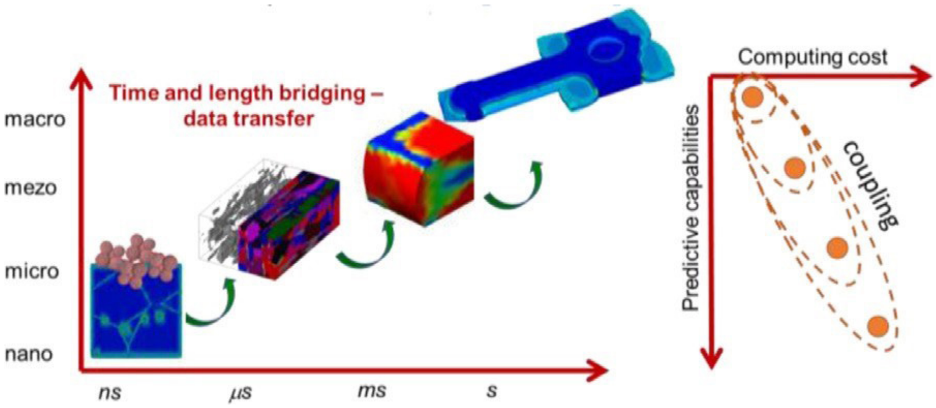


Fig. 30. Concept of length and time scales in multiscale models.

Two multiscale concepts can be identified in the literature related to metal forming simulations (Fig. 31). The first assumes that the lower-scale models are directly linked with each upper-scale com- puting node. If FEM method is considered as a case study of macro- scale simulations, then each FE node is linked with the numerical model dealing with the complete computa- tional domain of a lower scale. The lower-scale model should satisfy the condition of a repre- sentative volume element (RVE) [97] and scale separation criterion [180] (Fig. 31).

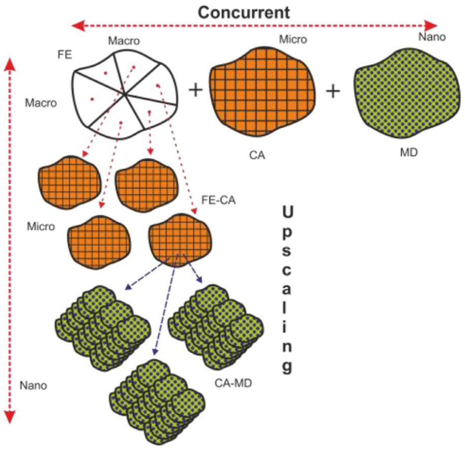


Fig. 31. Concept of the upscaling and concurrent class of multiscale models.

These approaches can have more than two scales, e.g., macro- mezo micro nano. In this situation, the model complexity increases significantly, because each node in the lower length scale model, e.g., the microscale is again associated with the complete computational domain of the nanoscale, and so forth. Although this provides enormous predictive capabilities, in many industrial appli- cations, it is impractical owing to long computation time. To reduce the simulation time, reduced-order modeling (ROM) techniques are typically applied to each scale (e.g., simplification of the computa- tional domain Fig. 32) or high-performance computing must be employed within heterogenous computer ecosystems (e.g., grid environments, GPGPU clusters, and cloud computing).

The alternative is to use the second class of multiscale models, the concurrent approach. This concept assumes that the same computational region of the material is described by a superposition of different numerical techniques, each dealing with phenomena characteristic of a particular scale. Approaches that combine the two concepts in the single numerical model have also been proposed [142].

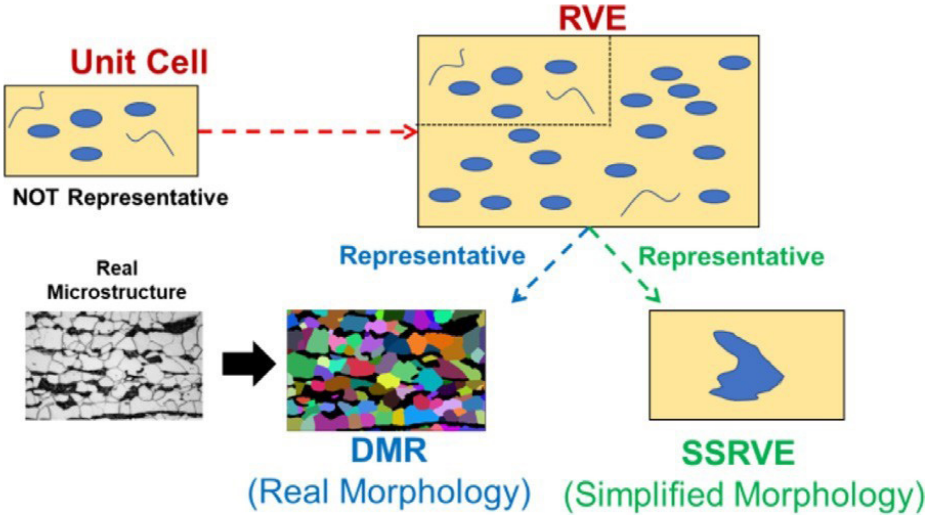


Fig. 32. Concept of the digital material representation model as a direct representative volume element and a statistically similar volume element.

Multiscale models are particularly valuable for the investigation of small-scale phenomena and their relation to macroscopic material behavior. Such microscale phenomena are often difficult or even impossible to observe experimentally. Therefore, to provide reliable and non-trivial results, models for various scales should be created according to four major steps [187]:

- Formulation of the mathematical background incorporating knowledge about the investigated phenomenon.
- Identification of model parameters to adjust the predictions to the investigated material. Inverse analysis combined with a series of laboratory tests is often used for this task.
- Validation and robustness analysis. The model should be evaluated in terms of extent to which it can replicate a particular phenome- non. The reliability of each model, as well as data transfer mecha- nisms, should be confirmed.
- Verification of the model with experimental trials.
- After the successful verification stage at subsequent scales, the model can be used to simulate metal forming operations within its applicability limits [233].

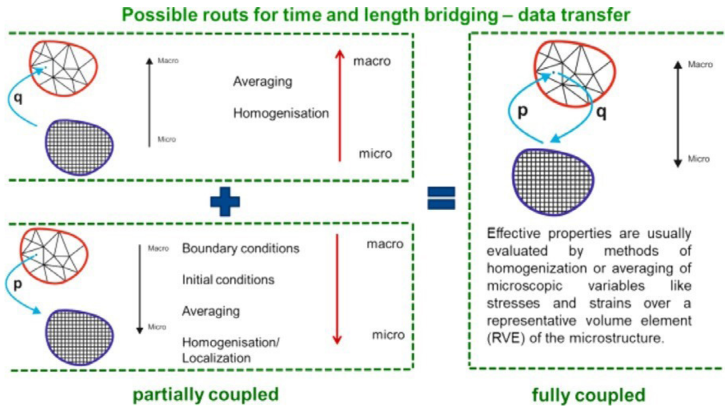
As mentioned, multiscale models involve numerical investigation across various length and time scales; therefore, the selection of appropriate data transfer mechanisms for a particular application is crucial.

5.2. Scale interaction techniques

There are two main concepts of scale interactions. The first is based on strong coupling, which combines the description of two or more scales into a comprehensive system of equations with a sound mathematical formulation (partial differential equations) [72]. Such models are usually solved with a single numerical method. Their lim- itation is related to predicting phenomena of a stochastic nature. The other approach is based on weak coupling, where only selected data are transferred between the scales. These models are more flexible, from both mathematical and numerical viewpoints, which makes their development and adaptation flexible. In this case, the complete two-way coupling (fully coupled) and one-way coupling (partially coupled) approaches are most frequently used (Fig. 33) [187].

In complete two-way coupling, data from upper-scale models are used as an element of the constitutive equations and initial and boundary conditions for lower-scale models. At the same time, in each time step after microscale calculations, data obtained from the lower scale are transferred to update the upper-scale models. The two-way coupling provides accurate results, taking into account interactions between multiphysics phenomena at various scales, but it is often computationally unacceptable for practical studies. There- fore, one-way coupling is more frequently used when the enrichment of classical macroscale metal forming simulations is required. Despite the introduction of simplifications due to unidirectional data transfer (upper ! lower scale or lower ! upper), this approach ensures valu- able results and also has acceptable computation time for practical application in the metal forming area.

The data from the upper-scale is transferred to lower-scale as a boundary condition, initial condition, averaged data or data obtained by numerical homogenization (localization). The latter two are also used for the information exchanges between micro- and macroscales.



Effective properties are usually evaluated by methods of homogenization or averaging of microscopic variables like stresses and strains over a representative volume element (RVE) of the microstructure.

Fig. 33. Data transfer schemes.

5.3. Evolution of multiscale phenomena

As mentioned earlier, industrial macroscale problems are usually addressed by the classical mesh-based or mesh-free methods. To describe evolving phenomena, e.g., microstructure evolution during deformation at both room and elevated temperatures, this class of approaches usually incorporates analytical or more advanced mean-field models that describe statistical quantities of the computational domain [80]. As a result, comprehensive results from the microscale can be obtained, extending the engineering knowledge of the material response during a particular metal forming process [257]. However, when the averaged data or data obtained by numerical homogenization (localiza- tion) is transferred from lower-scale, the complexity of lower scales is significantly simplified, which results in a homogeneous response neglecting, for example, the morphology of the microstructural features. In the case of modern multiphase materials, these approaches may not be sufficient for an understanding of the physical back- ground and consequences of phenomena occurring at lower-length scales. Therefore, more advanced models based on the RVE concept mentioned earlier, are introduced [196]. Solutions based on the crys- tal plasticity (CP), phasefield (PF), levelset (LS), Monte Carlo method (MC), cellular automata (CA), or Vertex are available and often used. These approaches can take into account lower scale morphological features in an explicit manner and therefore are called full-field mod- els [80]. The predictive capabilities of such simulations supported by full-field multiscale approaches for microstructure evolution are enormous and help to visualize phenomena that are often difficult or even impossible to visualize by experimental observations (Fig. 34).

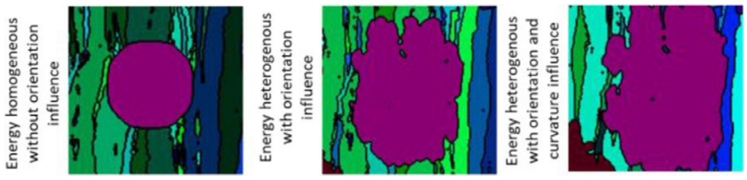


Fig. 34. Evolution of CA microstructure during static recrystallization with consider- ation of various physical factors.

Unfortunately, even with the above-mentioned techniques, com- putation time are excessive. That is why full-field approaches are used for scientific investigations rather than process optimization and, needless to say, online process control. At the same time, new knowledge acquired by such full-field simulations can be used to develop simplified mean-field approaches for practical applications [143] without the necessity of a large set of experimental investiga- tions (Fig. 35). Similarly, the full-field models can generate a sufficient amount of accurate data for machine learning solutions [163], which can significantly reduce the computation time [153].

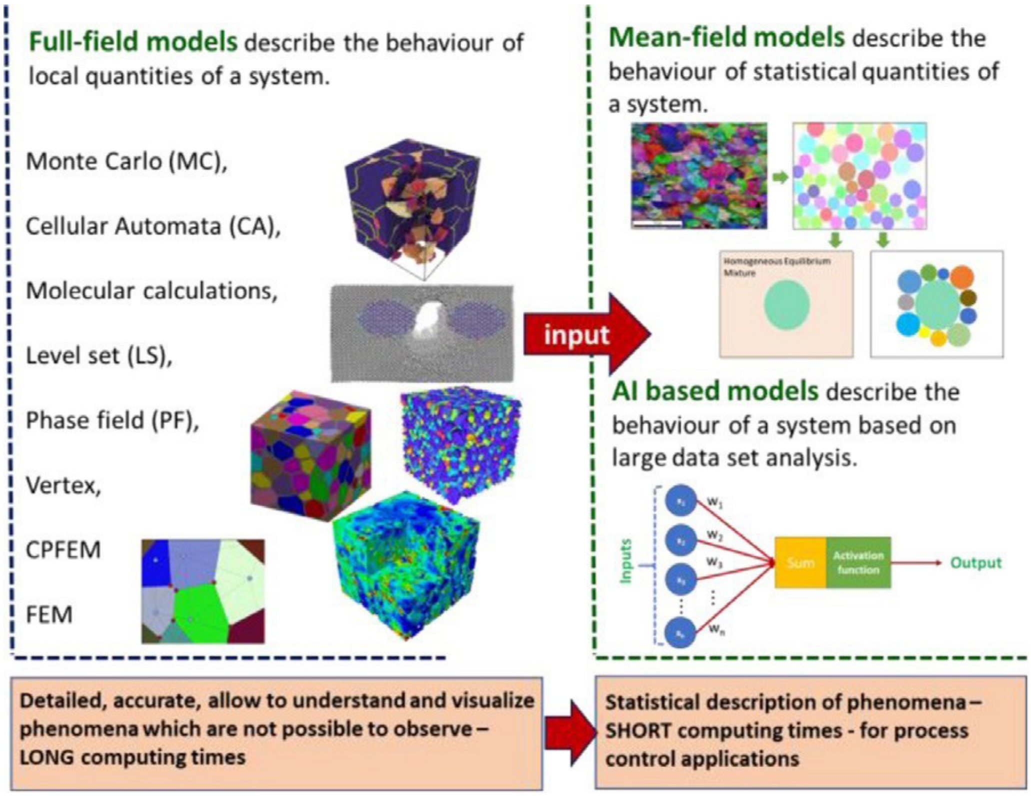


Fig. 35. Interactions between full-field and statistical models (based on research pre- sented in [143,151,163,188]).

6. Forming simulations in the past and towards a digitized society

6.1. Visualization of large plastic deformation

Materials under metal forming undergo large plastic deformation [124]. A possible means of obtaining a solution for such deformation is to use a mesh-free simulation, which is discussed in Section 4.2.

The progress in the remeshing technique has led to the applica- tion of FE simulations with a structured mesh to practical forming processes [176]. Adaptive meshing methods such as the r-method [148,155], p-method [10], and h-method [175] have been introduced to obtain plastic deformation for practical metal forming processes. An example of the analysis of large plastic deformation in rib-web forming using rigid-plastic formulations is shown in Fig. 36 [176]. Current metal forming simulations cannot be realized without the implementation of the remeshing technique with the numerical treatment of the complex surface geometry of the die and workpiece. Many state-of-the-art metal forming simulations have incorporated the remeshing technique. This technique has been applied to the analysis of metal forming using rigid-plastic FE formulations as it only requires the reproduction of the equivalent plastic strain before and after remeshing.

Another important point in promoting the analysis of large plastic deformation is the introduction of explicit dynamic analysis with a forward time integration scheme with lumped mass matrix. In fact, the simulation of metal forming has been significantly promoted by the introduction of a dynamic explicit analysis scheme, especially in sheet forming processes with complex and transient contact with the dies and blank. The governing equation of a continuum is the equilib- rium equation in the static state (Eq. (1) in Section 1) with u_ i ¼ 0 and gi ¼ 0, which is used to analyze the result in Fig. 36. The body force can be neglected as gi ¼ 0 in metal forming simulation, but the accel- eration u_ i can be calculated from the left of Eq. (1) if we use the momentum equation as the dynamic equilibrium equation for for- ward time integration to calculate the increment in the displacement of Dui u_ iDt at each node. The incremental time Dt must be suffi- ciently small to satisfy the Courant condition, and then a simple for- ward differential scheme can be adopted to solve Eq. (1). By converting the mass matrices to a concentrated mass system, the rapid computation of plastic deformation can be realized [106].

Numerical methods have attained remarkable progress, and the previously discussed schemes, such as the remeshing method and the dynamic description of deforming bodies, have been imple- mented in commercial software. Most people simulate metal forming can now conduct complex 3D simulations of metal forming without difficulty. However, engineers and researchers of metal forming are not satisfied with the present ability of the software. In other words they require more powerful software to visualize the large plastic deformation of metal inside dies, the stress field of dies and tools, and the progress of microstructure evolution associated with large plastic deformation. These demands will motivate more innovative simulations, and further innovations in the modeling of plasticity, the physical modeling of damage and friction, numerical methods, and multiscale analysis are strongly required. If Moore's law continues to be satisfied in the future, more complex simulations with complex modeling will become possible and play an increasingly important role in visualization in metal forming.

Many state-of-the-art simulation results have been obtained, such as in forging [75], stamping [152], and extrusion [126], aiming at developing new forming processes. Large-scale simulations are uti- lized for the research and development of forming technology, and the scale of the computation and the complexity of geometries will continue to increase in the future. The current demand for metal forming simulation cannot be fully satisfied at present and in the future. We need to promote larger-scale and more precise simula- tions of metal forming to assist the research and development of metal forming through visualizing invisible phenomena.

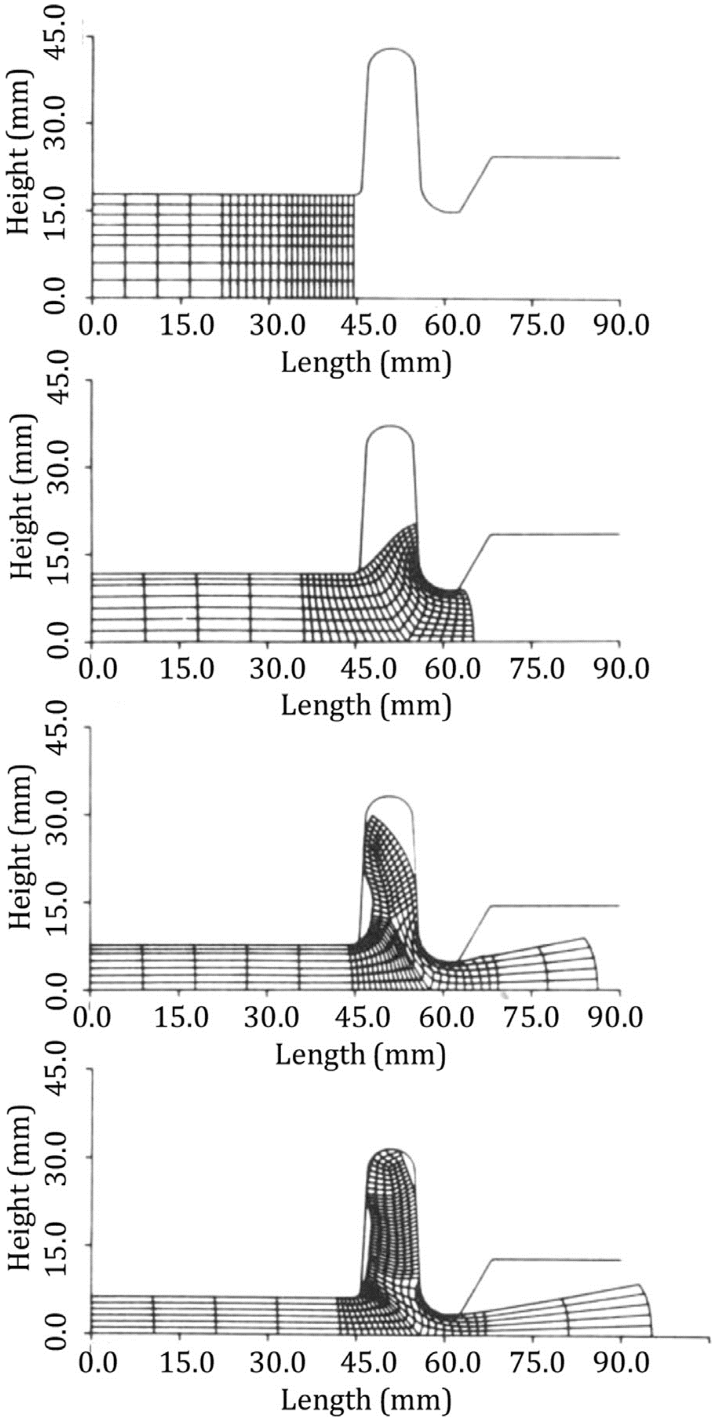


Fig. 36. Predicted metal flow in rib-web forming.

Large-scale simulations will be more precise and will more accu- rately visualize invisible phenomena, such as the localized metal flow inside dies and the contact pressure distribution at the interface between materials and dies, and between segmented die parts. How- ever, the accuracy and applicability of practical industrial problems involving the simulation of metal forming are governed by the modeling of various phenomena. The simulation of metal forming certainly enhances the importance of modeling phenomena, such as plasticity and anisotropy, hardening, the flow rule, friction, damage, and so forth.

6.2. Visualization for emerging advanced forming techniques

Development of the lightweight metals pivoted the approach that numerical simulations are just a tool for optimization of conventional forming processes to a designing platform of the next generation of the forming processes. Advanced lightweight materials are characterized by lower formability and higher susceptibility to cracking. Thus, numerical simulations are an enabler of understanding invisible phenomena which are associated with superposing conditions of pressure, temperature, change of the deformation path, electric, magnetic, vibration effects [46], and more examples illustrated in Table 4. Revolutionary multiscale investigation methods (digital image correlation, transmission electron microscopy, synchrotron analysis, etc.) have increased our understanding of the invisible phenomena, which are influencing the formability of materials under superposed conditions. Examples of such phenomena include (1) the hardening of materials based on dislocation movement (2) the strengthening of materials under extreme conditions, and (3) initiating and evolving damage under complex conditions. Understanding and controlling these phenomena from the atomic level to the component level will enable the use of customized forming processes with different materials, components, and functionalities. In an infinite number of combinations of the superposed conditions, physics-based models are complemented by data-driven models, in an attempt to find how formability can be enhanced and can surpass the forming limit diagram (FLD) predictions [164]. For example, new integrated simulation platforms are being developed for hybrid forming processes, as can be seen in the state-of-the-art application of particle mesh-free simulations [129] in Fig. 29 [159]. The visualization of large plastic deformation gives us valuable information on how to improve the novel forming process. But do we have enough information to go beyond the limits of the forming processes and reinvent them to address better the lightweight materials development? We are pessimistic about this possibility. However, if we change the question to 'Will simulation be able to calculate the optimum number of forming operations to form a part?', then we are more optimistic. A vision of how the authors see the further developments is presented in the next sections.

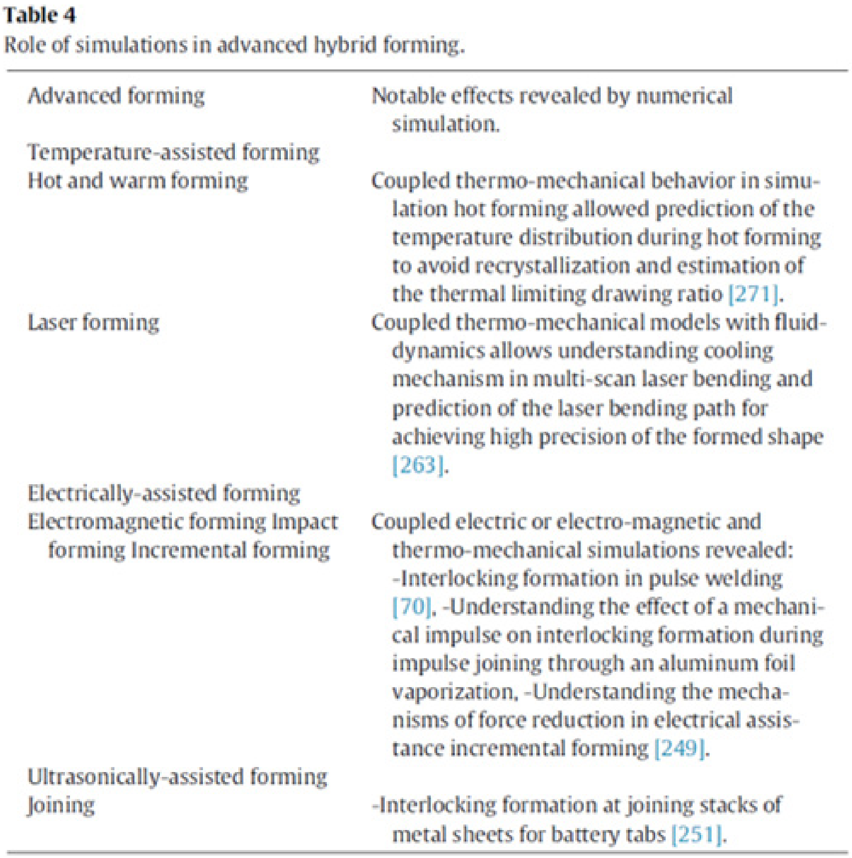


Table 4
Role of simulations in advanced hybrid forming.

Advanced forming	Notable effects revealed by numerical simulation.
Temperature-assisted forming	
Hot and warm forming	Coupled thermo-mechanical behavior in simulation hot forming allowed prediction of the temperature distribution during hot forming to avoid recrystallization and estimation of the thermal limiting drawing ratio [271].
Laser forming	Coupled thermo-mechanical models with fluid-dynamics allows understanding cooling mechanism in multi-scan laser bending and prediction of the laser bending path for achieving high precision of the formed shape [263].
Electrically-assisted forming	
Electromagnetic forming Impact forming Incremental forming	Coupled electric or electro-magnetic and thermo-mechanical simulations revealed: -Interlocking formation in pulse welding [70]. -Understanding the effect of a mechanical impulse on interlocking formation during impulse joining through an aluminum foil vaporization, -Understanding the mechanisms of force reduction in electrical assistance incremental forming [249].
Ultrasonically-assisted forming	
Joining	-Interlocking formation at joining stacks of metal sheets for battery tabs [251].

6.3. Simulation of metal forming in digital twins

The above-mentioned achievements in simulation software, mean and full-field numerical modeling, discrete numerical analysis, and multiscale and multiphysics modeling techniques lay the foundation for the intensively developed concept of digital twins [130] (Fig. 37).

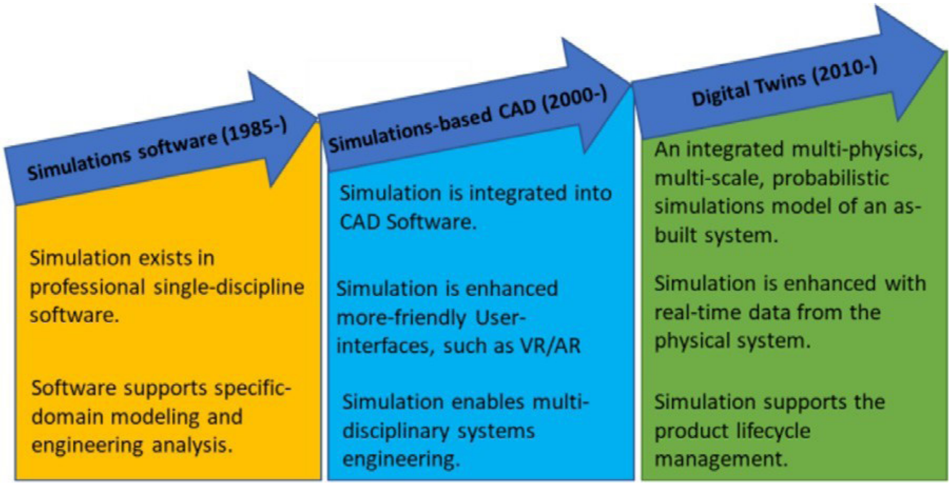


Fig. 37. Evolution of numerical simulations towards the concept of digital twin, based on [130].

There is no unique definition of a digital twin, and often it covers a wide range of approaches. However, in general, a digital twin is con- sidered as an integrated multiphysics and multiscale model of a par- ticular product, process, or entire manufacturing chain that can numerically replicate the physical behavior [219]. The concept is often supported by a real-time-updated data set from sensors storing information within a cloud or fog environment [211]. If two-way cou- pling is considered, then direct feedback from the model to the physi- cal system is also possible [130]. This technology was considered in [76] as a breakthrough overcoming limitations on the modeling and engineering analysis capabilities of simulation by integrating the IoT approach. In this area, other similar approaches are also used, such as digital shadows based on mathematical modeling to describe the investigated system [202], and digital surrogates defined as an inte- grated model that represents, connects, and synchronizes part of or the entire physical system or process taking into account data from that system [203]. From the metal forming viewpoint, three major components shuold be considered during the development of digital twins: the forming equipment, the formed component, and the form- ing process [101].

Developments in digital twins based on simulation and sensor areas are also driving the progress of the human interface of the sim- ulation, which is categorized as the first contact and is composed of pre- and post-processing systems of simulation software. The visuali- zation of numerical results is essential for engineers and researchers to understand the results of simulations. Visualization software enforces the human-machine interface, connecting the physical domain, or realworld, with the virtual domain, or simulation results, as illustrated in Fig. 38 [205]. The result in Fig. 38 represents the state-of-the-art in the area of digital twins, but challenges still remaining, such as (1) the rapid computation of large plastic defor- mation on-line and (2) the augmented reality that accurately incites the senses of researchers and engineers [252]. Haptic metal spinning [198] (Fig. 39) could be a good example of how the interface should be between the physical and real domains. Such a human robot interaction is one of the basic ideas of future factories.

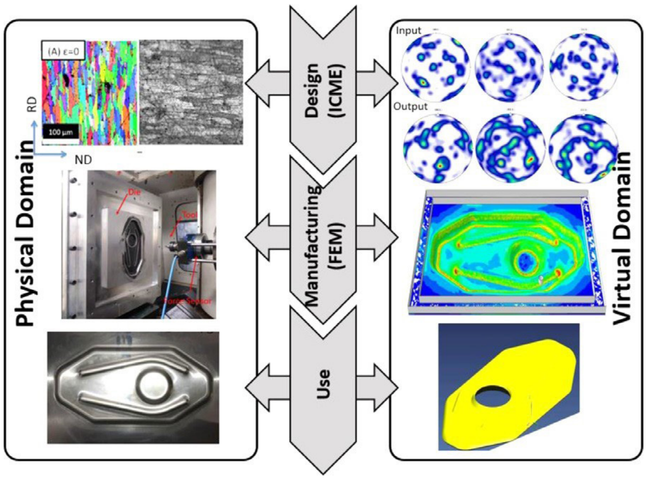


Fig. 38. Digital twin of incremental forming of Boeing fuel cover. [205].

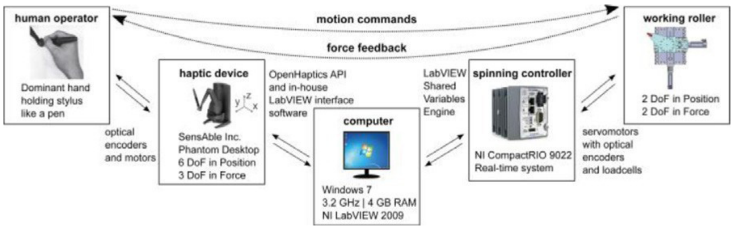


Fig. 39. Haptic metal spinning.

The simulation of metal forming for a control system is a step on the way to realizing digital twins. The simulation takes a long time to complete, so the requirement of a short computation time, for example 0.1 s, in on-line control systems prevents the application of current FE simulations. A longer computation time would be a serious issue in the direct use of FE simulation in a digital twin. To overcome this issue, FE-simulated data and results must be stored in storage instead of computed every time, or a rapid computing method based on a phenomenological model must be used for the control system or digital twin [177] (Fig. 40).

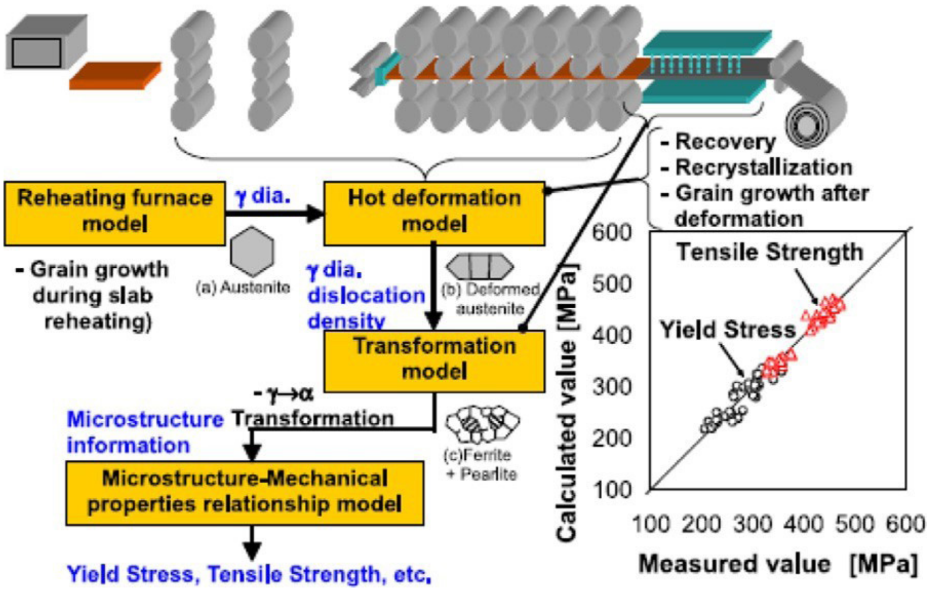


Fig. 40. Rapid simulation model in control system to predict mechanical properties of strip.

This concept has recently been extended towards a digital twin based on augmented reality with thousands of precalculated FE results used for the online visualization of a forming operation (Fig. 41). Augmented and virtual reality technologies are also more often being introduced as parts of digital twins [227]. Virtual reality maps a system with its components, surroundings, and events into a virtually generated environment. This approach can replicate compo- nents of the real world [237] or generate additional elements that enrich real environments [84]. In both cases, the user is introduced to a synthetic world, as shown in Fig. 42.

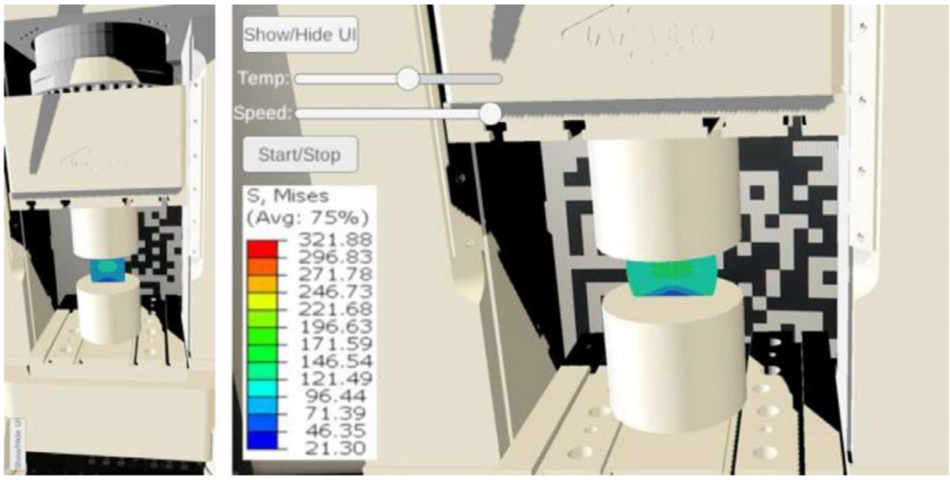


Fig. 41. Augmented reality-based digital twin with online visualization of forming simulations.

Augmented reality, unlike virtual reality, is a technology that overlays computer-generated information in realtime over data from the user's real-world environment [66]. Usually, the information is overlaid with the use of a tablet or specialized glasses on which 3D objects are displayed. Many applications of this technology are in the area of equipment maintenance [181] or training [209] (Fig. 43). Progress in these areas is also a driving force for the development of dedicated programming platforms facilitating the generation of dedi- cated solutions, e.g., ARCore, ARKit, Vuforia, and Wikitude.

Fig. 42. Virtual reality system of the forging press workplace located at AGH University of Science and Technology, Poland.

Fig. 43. Augmented reality system of the forging press operation training at AGH Uni- versity of Science and Technology, Poland.

6.4. Simulation of metal forming and data science

6.4.1. Stochastic simulation

Although the performance of numerical simulation programs is increasing (mainly caused by the refinement of the theoretical mod- els and algorithms used), the differences between the numerically and experimentally obtained results are often significant. One of the main sources of such discrepancies lies in the fact that the current theoretical models do not take into account the variation of the input quantities during the process and the variation of the material char- acteristics given as input quantities. Experiments have shown that

(1) these quantities exhibit pronounced variation during forming and

(2) their values show considerable dispersion. To improve the perfor- mance of numerical simulation programs, it is necessary to take into account the variation of input parameters and also to use statistical methods that allow these characteristics of variability and dispersion to be considered into the numerical simulation of metal forming. This approach has been explored by researchers in recent years [2,8,20,62,110,120,147,166,245]. Systematic research on the effect of material variation on the stretchability of sheet metal forming was conducted by Wiebenga [244,245]. Fig. 44 shows the effects of the variability of mechanical parameters on the experimental and numerically predicted force displacement curves for DX54D+Z form- ing steel. Use of stochastic simulation will increase the level of confi- dence (the so-called level of robustness) of the technological design.

6.4.2. Machine learning

Basic equations of plasticity (yield criterion description, flow rules, and hardening laws) are not trivial, especially for the modeling of material behavior such as the anisotropy of materials, distortional hardening, and the material response through complex strain paths. Machine learning, (ML), as mentioned in Section 5, is an alternative to an analytical description of these equations.

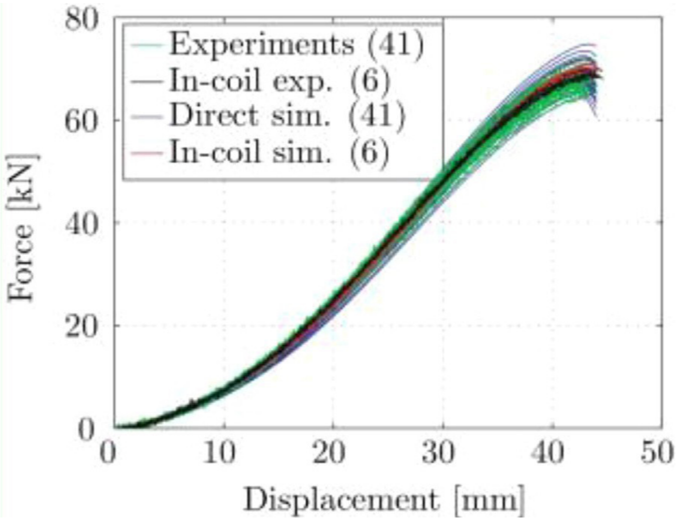


Fig. 44. Comparison of the experimentally measured force-displacement data and the result of numerical prediction by direct simulation. [245].

A data expert acts as a guide and he/she learns the algorithm what conclusions he/she should draw. The algo- rithm is instructed by a data set that is already labeled and has a pre- defined output. Deep learning is a subset of ML in which multilayered neural networks learn from vast amounts of data. Using these methods, the scientists can generate constitutive equations of plasticity based on data provided by different methods (e.g., FEM or RVE) [163]. There are practical uses of ML shown to work as an effi- cient bridge between a few number of experimental measurements and the accurate parameter values of a learned phenomenological model [122].

Different data analytics methods have applied within the field of continuum material mechanics, motivating the development of accu- rate and comprehensive databases and ensuring their accessibility [116]. The data analytics methods used in continuum mechanics are presented in Fig. 45. ML- and DL- based frameworks have been pro- posed over the last decade for modeling constitutive models [121,131,182] or predicting the occurrence of defects [68] in sheet metal forming processes. Gorji et al. [82] applied an ML-based model to reproduce predictions of an anisotropic Yld2000 2d model with HAH. Abueidda et al. [1] used learning methods for the modeling of path-plasticity and thermo-viscoplasticity.

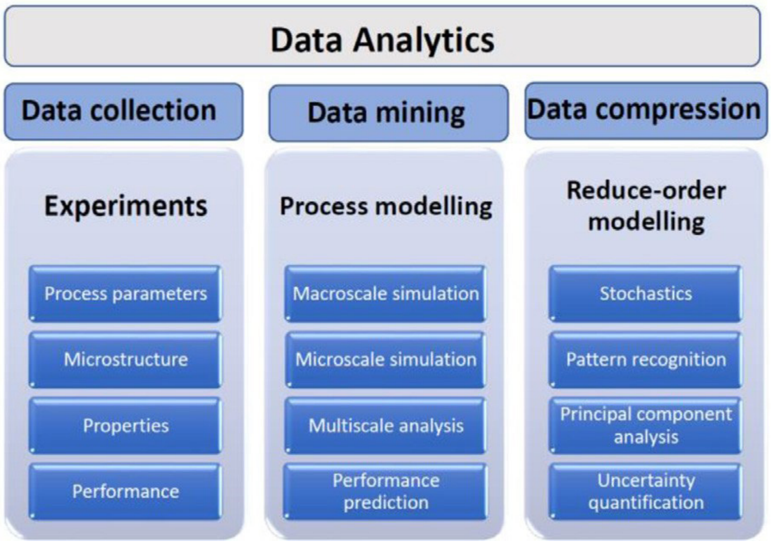


Fig. 45. Data analytics methods used in continuum material mechanics.

Mozaffar et al. [163] studied the predictive capabilities of the model by evaluating the yield locus evolution, when an RVE experi- ences different deformation paths. As a result, a correlation was found between the yield locus and hardening laws without any explicit mathematical relations between effective plastic strain and effective stress as in classical plasticity. The method is an alternative to HAH models developed in the last decade. Inal's team [165] devel- oped an ML-based framework to predict the local strain distribution, the evolution of plastic anisotropy, and the failure during tensile loading of an aluminum alloy produced by SLM. A schematic repre- sentation of the proposed ML framework is presented in Fig. 46 [165]. The ML method was used successfully to predict microstruc- ture property performance relationships for engineering materials with intricate heterogeneous microstructures. The results encourage the use of ML methods for the design of materials with defined func- tional properties and the optimization of forming processes.

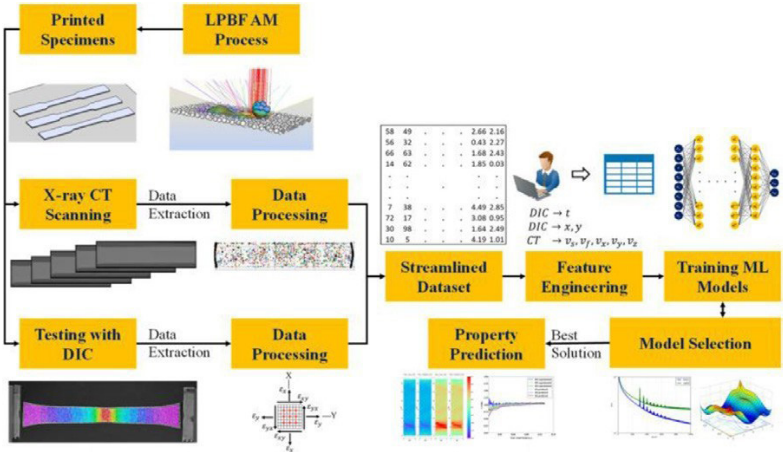


Fig. 46. Schematic representation of the proposed ML framework. [165].

6.5. Simulations for digitized society by platform integration

Cloud-based technologies use interconnected remote servers hosted on the Internet to store, manage, and process information. This technology is increasingly used for the FE simulation of sheet metal forming processes.

Zhou et al. [265] and Wang et al. [236] proposed a knowledge- based cloud FE (KBC-FE) simulation technique to enhance the capa- bility of commercial simulation software packages (e.g., PAMSTAMP, AUTOFORM) and to reduce the gap between scientific models and their implementations. The structure of the platform is presented in Fig. 47. Different functional modules such as Formability, Microstruc- ture, Tool life, and Tool design have been developed to work indepen- dently in the cloud system. The FE simulation software runs the simulation and exchanges the data with individual modules in differ- ent locations in the Internet. In this manner, the user's costs are sig- nificantly reduced as it is only necessary to pay for the time of use of simulation program and the modules, rather than purchase them. The Material Modeling Committee of the Japan Association for Nonlinear CAE (JANCAE) has recently developed a unified usersu- broutine (UMMDp, Unified Material Model Driver for Plasticity) [273], which can be used with all FE software [125]. The key feature of UMMDp is that the program prepares a unified interface routine for several commercial FE codes (Abaqus, ANSYS, ADINA, LS-DYNA, Marc and Radioss see Fig. 48).

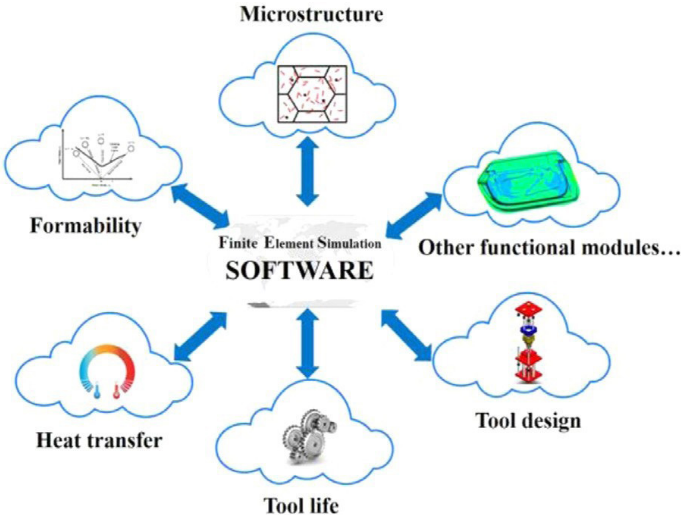


Fig. 47. Schematic chart of knowledge-based cloud FE simulation of sheet metal form- ing processes. [265].

The main anisotropic yield criteria (Hill, Gotoh, Barlat, Banabic, Cazacu, Vegter, and Karafillis-Boyce) and hardening laws (Swift, Voce, Ludwick, Prager, Chaboche, Armstrong, and Yoshida Uemori) are implemented in UMMDp. UMMDp is now being made available for public use. The main advantage of the UMMDp platform is that it is independent and it is possible for users to create material model even if they do not understand how to write in advanced FE code.

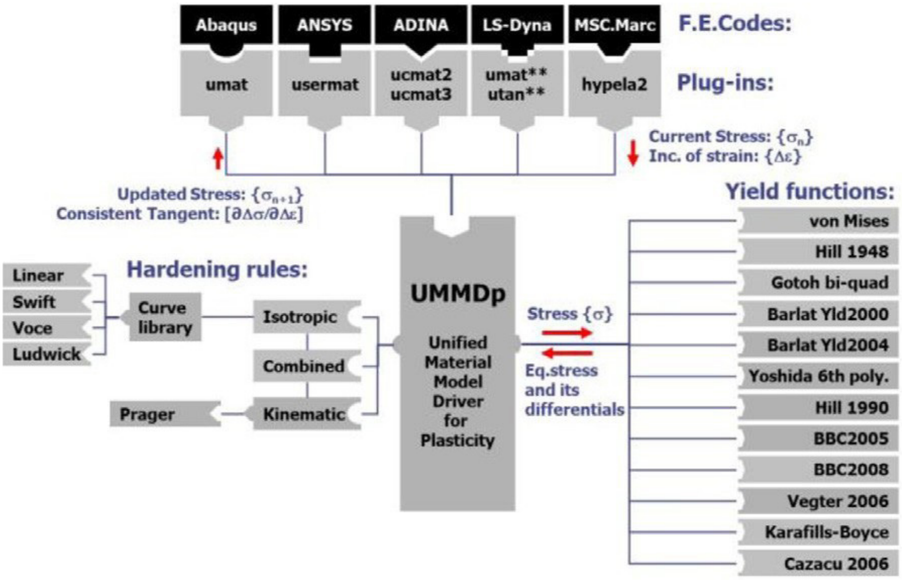


Fig. 48. Implementation of constitutive models in UMMDp. [273].

The DAMASK platform, developed by Raabe's group using CP sim- ulations to calibrate the initial yield surface used in the simulation of sheet metal forming [153,196,262,269], has already been presented in the Section 2. In designing a product, engineers use different tools for design and simulation of metal forming. A sensitive issue is that of the trans- fer of data between the different applications used. This data is usu- ally entered manually, which lengthens the simulation process and increases the risk of errors. To overcome this problem, companies that develop simulation programs have developed data entry auto- mation programs that allow the automatic execution of hundreds or thousands of simulations.

Such instruments are extremely useful in, for example, stochastic simulations. For this purpose, Dassault Sys- tems has recently developed a tool, Isight, which provides a compo- nent library for integrating and running simulation programs. [268].

7. Conclusion

Simulation is an important element in cyber-physical manufacturing space. It has been applied over a hundred years and has played an important role in the research and development of forming processes. It is now one of the main components of the digital design and manufacturing of industrial products. For example, the platform design of cars is conducted in digital space, enabling the most efficient use of high-strength steels and other structural materials to realize lightweight and stiff multimaterial bodies by performing stamping simulations, forging simulations, and analyses of vibrations and crashworthiness. The design of commercial cars becomes more charming and stereo- graphic thanks to the digital design of stamping dies using FEM with augmented reality of reproducing highlight (reflection) lines [3]. At present, simulations are applied to reveal phenomena such as high- speed deformation in novel forming processes. Such processes cannot be understood without the use of metal forming simulations.

The simulation of metal forming will be increasingly important in the cyber-physical world as a tool for visualizing invisible phenom- ena such as deformation inside dies and internal stress distributions of a workpiece and die. Several important inventions and develop- ments have driven metal forming simulations:

- governing equations (modeled physics/theoretical basis),
- exact numerical representations of governing equations,
- static and dynamic equilibria,
- explicit and implicit time integration scheme,
- digital representation of deforming bodies,
- large plastic deformation,
- automated meshing,
- optimized meshing and remeshing,
- simulations without using structured mesh,
- simulations at submicron scale
- computer material science,
- bridging scales by exchanging parameters,
- computer resource revolution,
- high-performance computers,
- personal computers,
- explosive increase in memory,
- commercialization of metal forming software to enable self-con- tained development,
- material testing/measurement,
- modeling of observed physics,
- damage,
- interface phenomena,
- plasticity models.

Is the current situation of simulation sufficiently advanced for metal forming science? If so, simulations are already capable of resolving the future issues pointed out in Section 6. These include the visualization of large plastic deformation and emerging advanced forming techniques, the simulation of metal forming in digital twins, the simulation of metal forming in combination with data science, and simulations for a digitized society by plat- form integration. However, advanced methods are still far from reflecting reality. Many problems are failing to be solved at pres- ent, so future innovation is expected, as previously pointed out. Making full use of the simulation of metal forming in the digi- tized era is a major remaining issue that must be continuously investigated in the future.

Finally, we point out another important issue that must be emphasized. Several of the important inventions and developments that have driven the simulation of metal forming, which were previ- ously highlighted in the bullet points, have intentionally started from a 'theoretical basis' of modeled physics (governing equations) and ended at 'observed physics', as was shown in Fig. 4. The governing equation is the modeled physics, but the anisotropic response of the sheet metal still remains in the area of observed physics. Much fur- ther investigation of this 'observed physics', which is not perfectly modeled in the governing equation, is required. We would like to stress the importance of investigating this 'observed physics', which younger researchers may be unaware of because we are surrounded by so many commercial software packages and supporting techni- cians teaching how to operate them. In fact, we do not even under- stand anisotropy well at present. Anisotropic yield criteria must be modeled more precisely by considering microscopic phenomena. Furthermore, in general, yield criteria having an identification proce- dure based on both uniaxial and biaxial traction experiments can provide more accurate predictions than yield criteria identified with only uniaxial traction data. When only uniaxial experiments can be performed, the identification should rely at least on the yield stresses and coefficients of plastic anisotropy corresponding to three planar directions (0°, 45°, and 90°). The yield criteria that require a larger number of mechanical parameters in the identification (13 or more Barlat 2004, BBC 2008, Vegter 2006 [231], etc.) can provide more accurate descriptions of the mechanical response of highly aniso- tropic sheet metals. Their capability of capturing the occurrence of six or eight ears in the case of cylindrical cups obtained by deep drawing is especially notable. The future research in this field will focus on developing models for materials exhibiting special proper- ties (e.g., superplastic behavior and shape memory). Allowing the evolution of the material coefficients involved in the expression of the yield criterion will make the description of nonlinear load effects on the yield surface possible. Stochastic modeling will also ensure robust predictions of the yield surface by considering the statistical variability of the mechanical parameters used for identification.

Coupling the phenomenological and crystal plasticity models will allow a better simulation of the parameter evolution in technological processes (temperature, strain rate, or strain path dependence, as well as structural evolution).

Simulation is a powerful tool for visualizing invisible phenom- ena to provide quantitative information on macroscopic phenom- ena, and it is becoming more accurate, more integrated, and more microscopic. However, although the simulation of metal forming has developed markedly, there are remaining gaps between simulation results and nature, i.e., real phenomena. For example, bifurcation-related problems such as instability in plas- tic deformation will take a longer time to analyze numerically and accurately. Research on modeling and simulation must be continued. We hope that progressive research on basic modeling will continue to realize simulations of metal forming in the digital era.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influ- ence the work reported in this paper.

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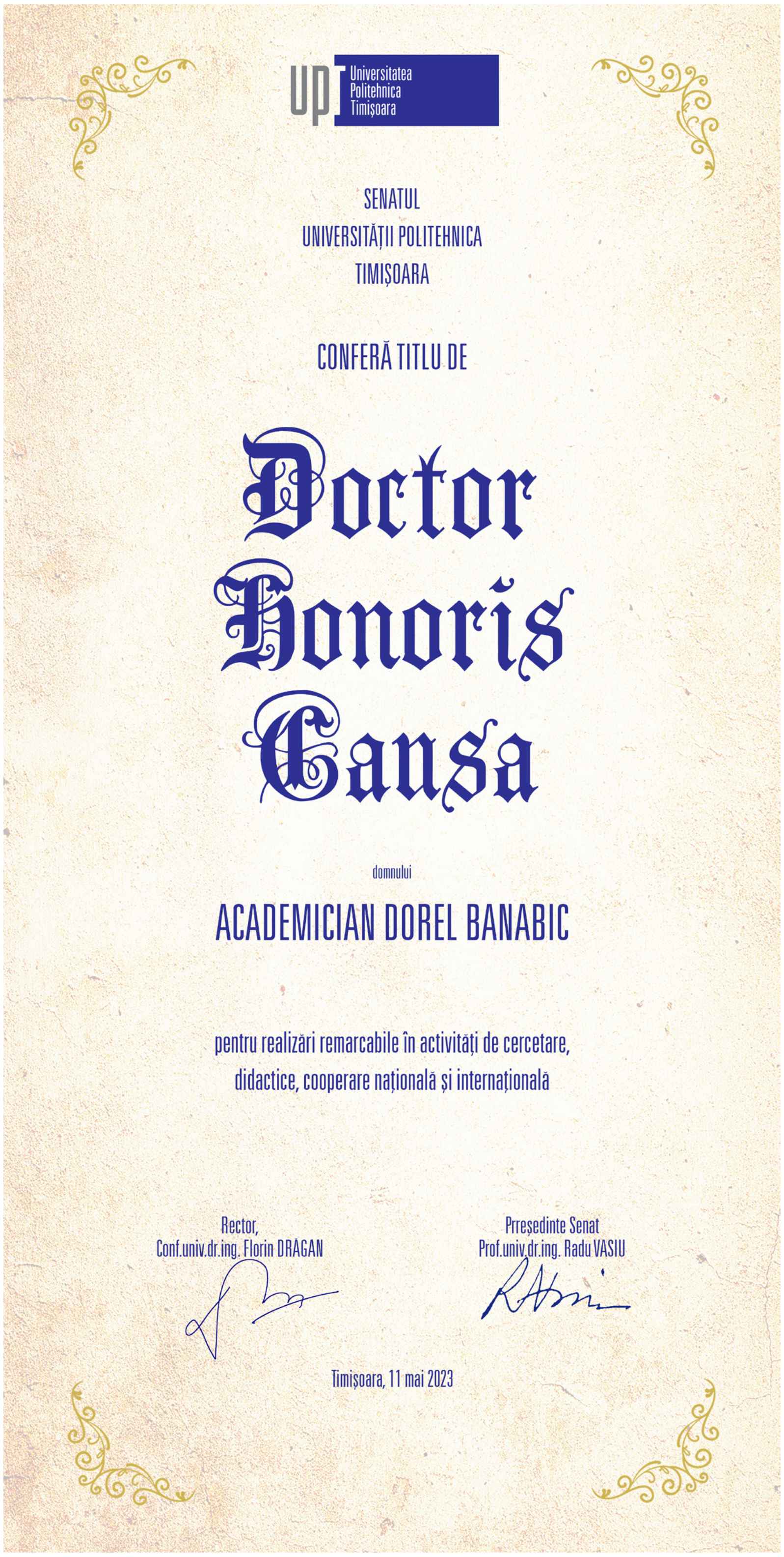

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pentru realizări remarcabile în activități de cercetare,
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Timișoara, 11 mai 2023