Oponentní posudek doktorské disertační práce

Autor: **Ing. Khodr Ibrahim**

Název práce: **A study of high strength steel mechanical behaviour during cold roll forming**

Rozsah práce: 141 stran, 159 obrázků, 19 tabulek, 80 literárních pramenů.

Posouzení předložené práce:

Po krátkém úvodu, kde byl vyjádřen význam technologie válcování profilů z ocelových pasů, zejména pro automobilový průmysl, se disertant podrobně zabýval v kapitolách 2 a 3 problematikou plošného tváření, zejména anizotropií vlastností tvářených materiálů při ohýbání.

V kapitole 4 „Cold roll forming" podrobně popisuje technologii válcování ocelových profilů za studena, včetně tvářecích stanic a faktorů, které ovlivňují počet průchodů na tvářecí lince a vzdálenosti mezi jednotlivými stanicemi. Vlivem zbytkových pnutí dochází k odpružení i podélné deformaci vyválcovaného profilu.

Kapitola 5 „Engineering software for roll forming" zpracovala současné poznatky o simulačních programech pro návrh tvářecí linky. Většina software vychází z mezného pnutí na hranách pásu při návrhu postupných deformačních kroků. To umožňuje optimálně navrhnout tvářecí linku včetně jednotlivých stanic. Základním problémem při použití simulací na bázi konečných prvků je jejich přesnost a odchylky reálného výrobku od navrženého tvaru profilu. Při použití velkého množství prvků se značně prodlužuje doba výpočtů.

V kapitole 6 „Material behaviour during cold roll forming" je studován vliv příčných ohybových a zbytkových deformací na odpružení s využitím elastických a viskoplastických modelů.

Kapitola 7 je věnována experimentální části disertace. V její úvodní části jsou uvedeny cíle práce, kterými je stanovení faktorů pro korekci odchylek mezi výsledky simulací a experimentů u jednotlivých ocelí, zejména s ohledem na odpružení. Zkoušeno bylo 5 ocelí s 3 různými sestavami rotačních tvářecích nástrojů, které měly poloměr zaoblení 2-4 tloušťky zkoušených ocelí. Celkový rozsah experimentů byl značný.

Připomínky k předložené práci:

1. Zvolené materiály pro experimenty jsou dostatečně definovány. Chemické složení použitých ocelí je uvedeno až v tab.7.15 na straně 120.
2. U převzatých obrázků a tabulek by měl být uveden zdroj.
3. Chybí kapitola věnovaná diskusi výsledků.
4. Není vhodné používat v části textu 1. osobu jednotného čísla
5. Značení v tab. 7.1-7.4 (Mpa, Gpa).

Zhodnocení:

a) Předložená disertační práce přináší řadu nových poznatků o problematice válcování profilů z ocelových pasů vysokopevnostních ocelí.
b) Postup zvolený k řešení problematiky i zvolené metody řešení jsou v souladu se současným stavem poznání. Cíl disertační práce byl splněn.
c) Výsledky disertační práce jsou přínosem pro hlubší poznání vztahů mezi parametry válcovacích stolic a mechanickými charakteristikami zkoušených ocelí.

d) Předložená práce je uspořádána ve studijní části systematicky a přehledně. Experimentální program je velmi rozsáhlý, zahrnuje široké spektrum zkoušených ocelí a modifikací tvaru válcovacích stanic.
e) Disertant k předložené disertační práci nepřiložil seznam publikací, které mají prezentovat výsledky jeho prací v časopisech a na mezinárodních konferencích či na konferencích v ČR.
f) Doporučuji předloženou disertační práci k přijetí. Dále doporučuji po vyjasnění připomínek k disertaci udělit Ing. Khodrovi Ibrahimovi akademický titul „Ph.D."

V Praze, dne 7.1.2021

Prof. Ing. Jan Suchánek, CSc.

Dipl. Ing. (FH) Wolfgang Buhl, MBA

Elisabethgasse 9
A3400 Klosterneuburg, Austria
Cell: +43 660 7138850
email: wolfgang.buhl@gmx.at

UNIVERSITY OF WEST BOHEMIA
FACULTY OF MECHANICAL ENGINEERING

16 January 2021

Evaluation of Mr. Ing. Khodr Ibrahim´s PhD thesis

In this letter, I give my assessment of the PhD thesis by Mr. Ing. Khodr Ibrahim, titled "A study of high strength steel mechanical behaviour during cold rollforming".

The thesis presents original research results of mechanical behaviour of high strength steel during cold rollforming. To compare the experimental work with FEA simulation results and acquire a relation of the deviation between the simulation and the real forming process was the main target of this huge amount of studies and such an analysis has never been done before.

Mr. Ibrahim found out that longitudinal stress can be reduced by using smaller forming radii, but on the other hand smaller radii are increasing transversal strain, so this causes a contradiction in terms. Knowing this helps tremendously to understand the process better and to push tooling designs closer to the feasible limit.

The second part of the study compares simulation results with experimental work, this is equally important to the roll forming industry. The big gap between simulation and real forming process especially in string back behavior shows us that there is a huge amount of scientific work left to improve Software and Materialinputdata. Especially if we come to the highest grades of the UHSS, correlation doesn´t exist at all between simulation and reality iwith the nowadays existing FEA-tools.

Another very important information would be a correlation study between calculated stain and real strain during real forming process. Also when it is very difficult and time consumin to get the real strain out of the real forming process, it would bei worth proving if the strain levels we are seeing in the simulation are correlating with reality.

Finally my conclusion is that the PhD thesis of Mr. Ing. Khodr Ibrahim presents original research results of large importance and I recommend without hesitation the PhD to be defended.

Sincerely,

Dipl. Ing. (FH) Wolfgang Buhl, MBA

doc. RNDr. Mária Behúlová, CSc., Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Ulica Jána Bottu č. 2781/25, 917 24 Trnava, Slovak Republic

REVIEW REPORT ON THE DOCTORAL THESIS

1. PhD. student:	Ing. Khodr Ibrahim
2. Topic of PhD Thesis:	**A study of high strength steel mechanical behaviour during cold roll forming**
3. Study programme:	P2031 Mechanical engineering
4. Field of study:	3911V016 Materials engineering and technology
5. University, faculty:	University of West Bohemia in Pilsen Faculty of Mechanical Engineering
6. Supervisor:	doc. Ing. Ludmila Kučerová, PhD.
7. Consultant specialist:	Dr. Ing. Hana Jirková
8. Reviewer:	doc. RNDr. Mária Behúlová, CSc.
9. Workplace of the reviewer:	Slovak University of Technology in Bratislava Faculty of Materials Science and Technology in Trnava Institute of Applied Informatics, Automation and Mechatronics

Relevance of the dissertation thesis for the study field:

Dissertation thesis of Ing. Khodr Ibrahim deals with numerical simulation and experimental study of mechanical behaviour of steels during their cold roll forming with the focus on the high-strength steels. Owing to current trends in automotive industry, especially requirements on the reduction of car weight and passenger safety increase, I consider the topic of the thesis as a very actual. Application of AHSS in car bodies has undoubtedly many advantages but the spring-back during forming processes represents the real problem depending on several parameters. Understanding the material behaviour of newly developed high-strength steels during cold roll forming is necessary for accurate prediction of spring-back effects and for a comprehensive design of entire forming process.

Problem solution and methodology applied to achieve the objectives

The doctoral thesis is written on 141 pages altogether, it contains 159 figures and 16 tables. References used for the elaboration of the PhD. thesis include 80 literature sources and demonstrate a sufficient overview of the candidate in the investigated field of research. The list should additionally contain also the standards for the applied experimental tests. The PhD. thesis is divided to the theoretical part covering 6 chapters (including the Introduction) and experimental part (Chapter 7) representing approximately 60 % of the thesis. The numbered Chapter 8 contains references. In the theoretical part, the basic principles of sheet metal forming are introduced with a focus on cold rolling of sheets made from different materials. The approaches to flower pattern and rolls design are discussed. Significant attention is paid to the numerical simulation of cold rolling processes and the analysis of the state-of-art in this field especially regarding the prediction of spring-back.

In the experimental part, results of an extensive experimental program are presented. Mechanical behaviour of five different steels was studied during three different processes of cold roll forming. In the first step, mechanical properties of experimental materials were measured using the tensile testing. Subsequently, these material properties were applied to develop simulation models of the investigated forming processes. The COPRA FEA simulation software was used to analyse longitudinal

and transversal strain formed during the roll forming. Additionally, the equivalent plastic strains were computed and compared when using three different toolings. For the spring-back evaluation, an open profile with the hat shape and the final angles of 100° was chosen. The spring-back deviations between the nominal profiles from CAD data, the simulation results and the physically roll formed parts, respectively, were compared. Finally, microstructural and micro-crack analysis was performed to confirm the possibility of cold forming high-strength steels such as MS1500 and MS1700 without the micro-cracks formation.

The experimental part is extensive and provides a large number of valuable results obtained from numerical simulations as well as experimental measurements. However, due to the fact that the PhD. thesis does not contain a separate chapter or section with clearly defined objectives of the work and methods of achieving them, it is difficult to orientate in the flood of data and results and to focus on the essential information. The chemical composition of the materials used in the study is introduced almost at the end of the thesis. Further important data are provided only by description in the text, so it is difficult to find them. Generally, the engineering approach involves concise and clear expression using figures and tables. For example in this case, geometrical parameters included in Eq. 6.1 to 6.7 or the main dimensions of geometrical model used for simulation could be defined simple in figures. The description of the developed simulation model to analyse the longitudinal and transversal strains during cold roll forming is incomplete (e. g. the applied element type or boundary conditions are not specified) and therefore non-reproducible. The simulation model should be verified, it is not sufficient to rely on the software validation. Nevertheless, the presented results seem to be reliable, clearly processed, interpreted and discussed on the basis of comparison with experimental measurements.

Achieved results of the doctoral thesis and the specific original contribution of the candidate:

The scientific impact and relevance of the achieved results for the praxis lies mainly in the demonstration of the possibility of the save cold roll forming of profiles of high-strength martensitic steels with the ultimate strength up to 1700 MPa using a tight inner radius up to a sheet thickness ratio of 2. This principal result is supported by other important findings regarding the mechanical behaviour of five material grades during the three different roll forming processes especially in connection to spring-back effects and their prediction. The results were obtained by a suitable combination of scientific methods, using numerical simulation of roll forming and experimental investigation of the material behaviour in the forming process.

I consider the main goal of the thesis stated in the annotation to be fulfilled. The abstract of the thesis is prepared at the required level and provides important information on the investigated issues and the achieved results.

Formal and language level of the thesis:

The doctoral thesis is prepared carefully. Apart from some inaccuracies, the terminology used is in accordance with the study field of Materials Engineering and Technology. The concept of the dissertation thesis, its content, stylistic, linguistic and formal aspects are at the required level and correspond to the scope of the problem. I have reservations about the graphical level of some figures and graphs that are too small, labelling or description in figures is sometimes difficult to read. Several figures are placed before their description in the text. The readability of the thesis is affected also by the use of different symbols for the same quantities. From this point of view, the nomenclature is missing.

Publication of the candidate:

The list of publications is not part of the abstract. According to SCOPUS and WOS databases, Ing. Khodr Ibrahim published 10 papers during the years from 2015 to 2017. Most publications deal with the problem investigated in PhD. thesis only marginally. There are a total of 7 citations for the published research papers in the SCOPUS database.

Comments and recommendations:

1. At the beginning of the defence of PhD. thesis present the motivation and the main objectives of your research, please.
2. In the thesis, the candidate uses different symbols to denote the same quantities (e.g. for a force/load, the symbols „*F*" and „*P*" are used, symbol „*F*" in Fig. 7.52 or 7.56 represents the stress, thickness is denoted „*t*" and also „*T*").
3. The equations are written in a non-uniform style. For example, the „X", „x" or point (.) characters are used as a multiplication sign. Some equations (mostly with compound fractions) are difficult to read (Eq. 2.7, 3.1, 3.5, 6.1).
4. Figures taken from the literature should be cited.
5. Figures should be large enough. The figures with unreadable captions lose the meaningful value and significance (Fig. 7.34 - 7.45, 7.61).
6. A comparison of the measured angles with the nominal angles from CAD (Fig. 7.67-7.72) would be better presented by bar graphs. In all figures, I recommend using the same line (bar) color for the given material.
7. The statement that „*Tensile test were done with grain*" or „*against the grain*" (p. 56) is not correct (also Fig. 7.6 -7.9, Tables 7.4 – 7.9).
8. The unit of stress or presure is correctly written MPa (GPa), not Mpa or Gpa (Tables 7.1 – 7.9).
9. The designation of the materials used as A, B, C, D and E in Table 7.12 (p. 95) is unreasonable and confusing. The explanation and assignment of the letters to the corresponding materials with the original designation is even on the page 98.
10. No data are provided for the shaft stiffness calculations (Section 7.5.4.1).
11. The modifications of material model for simulation of spring-back (p. 118) were probably based on the trial and error principle to achieve a better „coincidence" of computed and experimentaly obtained results. Based on such method, it cannot be claimed that *„By reducing the deviation gap, it will make simulations more reliable and we will be able to use the simulation results with higher confidence."*

Questions and subjects for discussion:

1. What was your motivation to choose just selected grades of steels for the research? Can you explain the distinct behaviour of the sample 5 made of the mild steel during the uniaxial tensile test (Fig. 7.5)? What material model was applied in numerical simulations to approximate measured stress-strain curves?
2. Can you present in detail the FE model applied for numerical analysis of cold roll forming? What type of element was used to generate the FE mesh? Specify the boundary conditions! Why do you consider the simulation model to be asymmetric?
3. What are the reasons for the development of non-symmetrical transversal strain distribution during cold roll forming of mild steel (Fig. 7.36) or MS1700 steel (Fig. 7.50)?
4. In the framework of numerical simulation, you studied also the influence of the mesh density on the computed results, specifically on the width strains. Can you explain the philosophy of the mesh refinement? What was the aspect ratio for elements in the original and refined mesh? Why did you not use more elements along the sheet thickness? Do you think that the exploited mesh refinement was sufficient for evaluation of the influence of the mesh density on the accuracy of strain calculation?
5. Can you explain the definition of boundary conditions according to Fig. 7.62 and Fig. 7.63?
6. Based on the results of PhD. thesis and your experience, is it possible to suggest a uniform methodology for the prediction of spring-back of different materials?

Final evaluation and statement:

The submitted PhD. thesis entitled "A study of high strength steel mechanical behaviour during cold roll forming" fulfills the requirements for a dissertation thesis, and therefore I recommend the acceptance of PhD. thesis in accordance with Act no. 111/1998 Coll. §47 for defence.

After a successful defence of the dissertation thesis, I propose Ing. Khodr Ibrahim was awarded the academic title of PhD. (philosophiae doctor) in the field of Materials Engineering and Technology.

Trnava, 26.01.2021

doc. RNDr. Mária Behúlová, CSc.
reviewer of PhD. thesis