UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

DESIGN LIMIT CURVES FOR CYCLIC LOADED STRUCTURAL ELEMENTS MADE OF HIGH STRENGTH STEELS

Booklet of PhD Theses

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1. INTRODUCTION

1.1 PRELUDE

In our days, the engineering structures give a hard challenge to the designers. The accelerated world brings new kind of base materials in every year, and with these, new kind of approaches. Amongst the wide range of modern base materials, the metals, especially the steels still have a main role. This can be explainable with the wide range of application [1]. Nowadays, the main tendency is the strengthening of the base materials. The recent high strength steels (HSS) require special manufacturing methods, which leads to complex microstructures, hence, the designers faces many challenges [2]. The different regulations cannot keep up with these constant changes. One example for this is the thermomechanically rolled steels standard out of the hot rolled steels standard group (MSZ EN 10025-4), where the highest category is only *460 MPa* guaranteed yield strength, while there are *960 MPa* steels as well in this category. From the same group, the quenched and tempered steel standard (MSZ EN 10025-6 [3]) includes the *960 MPa* category, but *1300 MPa* steels already exist. In the Eurocode 3, which is the standard for the steel structures designing [4], the maximum strength is only *460 MPa* [5], and *700 MPa* with additional restrictions in the 12th chapter [6][7].

One of the most crucial challenges is the welding of the high strength steels. Because of the irreversible effect of the heat input, the gained softened or hardened areas cannot be change after the welding [8]. The other determining area is the selection of the filler metal, because manufacturers cannot produce enough high strength filler metal for these steels. So in the case of the HSS materials we cannot fulfil the classical coupling method requirements, where the base material and the filler metal yield strength values are nearly the same [9].

Besides the weldability, the other major issue is the fatigue properties of these steels and welded steel structures. In the case of the newest steels, the exact fatigue properties are not known, or just partially. When static tensile loading affect the structure, the high strength properties can be utilize fully, but in the case of buckling, the high strength steels are not so beneficial. When cyclic loading occur, the behaviour of these steels become indefinite, furthermore we must investigate the behaviour under cyclic loading conditions separately [10]. In the case of high strength steels the main phenomena is the high cycle fatigue (HCF), but in special circumstances the low cycle fatigue (LCF) also can be occur, and in the case of the welded joints we must investigate the fatigue crack growth (FCG) properties as well [11].

1.2 THE PURPOSE OF DISSERTATION

In Hungary, amongst the high strength steels in the heavy plate thickness region, the quenched and tempered (Q+T) steels are widely used, in addition the thermomechanically rolled steels (TM) gain more usage. This justified that I chose the S690QL and S960M base materials according to the MSZ EN ISO 10025-6. Since the weldability of these steels is a complex task, I chose the following aims for my research work:

- determination of the optimal welding parameters in the case of both steels;
- examination of the filler metal choice effect (weldability and mechanical properties), with *matching* and *overmatching* filler metals in the case of S690QL steel category, and with *matching* and *undermatching* filler metals in the case of S960M steel category.

In the field of cyclic loading condition, I chose the examination of the welding parameters and the filler material choice effect on the characterisation of the fatigue properties.

- In case of low cycle fatigue, the aim were the characterisation of the two base materials, and also the effect of the *matching*, *undermatching* and *overmatching* filler metal choice on the fatigue properties of the welded joints.
- In case of high cycle fatigue, I chose the examination of the filler material choice (*mismatch* effect) for the S690QL base material, while in case of S960M steel, I chose the examination of the heat input effect (low, average, high heat input with matching filler metal).
- In case of fatigue crack growth, I chose the examination of the base materials and the welded joints with different filler metals were chosen.
- The final aim was the determination of the fatigue design limit curves, in all three cases, for the base materials and their welded joints too.

2. METHODOLOGY

In the first part of my *theoretical research* I give a short summary about the different strengthening methods, especially in case of the quenched and tempered and the thermomechanically rolled steels, with the different type of manufacturing methods, alloying elements and the welding properties. Both of the examined steels have a really fine grained microstructure, but their production methods are different [12]. The Q+T steels were produced with quenching and high temperature tempering. At the same time the carbon content is not so high, so the main strength increasing method can be originated from the fine, lath-like martensitic microstructure and from the dislocation density than the solved carbon content [1][13]. The TM steels combine the heat treatment and the metal forming. During this process, the rolling temperature was decreased from *1100-1200 °C* to *850-900 °C,* and usually two or more steps were used. The procedure can be finished with air or water cooling [14]. The gained microstructure is a complex bainit matrix with martenzit and cementite. Therefore, the evolved non-equilibrium microstructure in both steels requires a complex welding technology [15]. In addition, because of the smaller microstructure and lower alloying content the TM steels have beneficial mechanical and toughness properties; on the other hand, the material thickness is less than the Q+T steels [16].

The weldability, and with that the heat affected zone structure is more favourable in the TM steels, but both materials require attention during welding [17]. I summarize the different calculation methods of the preheating temperature, and also the welding technology determination methods apply the critical cooling time $t_{8.8/5}$ parameter. I summarize the different welding technology of the examined steels, the cold cracking sensitivity, and with these the possible welding parameters. Analysing the filler metal choice problem, it can be stated, that the *960 MPa* category is a limit, over this strength only *matching* and *undermatching* filler metals exist. Most of the literature advise to use *matching* or *undermatching* filler metal, but in special cases the *overmatching* filler metal can be beneficial as well [18].

Since flawless welded joints do not exist, it is important to examine the different aspects of the failures, especially in case of the welded joints [19][20]. It is important to note, that with the increasing of the base materials strength, the fatigue properties are not necessarily increasing as well [21][22]. The modern high strength steels require a different design approach, but the different regulations and standards cannot keep up with these constant changes, so their data not always up to date [23]. These regulations frequently leave out of consideration the different manufacturing methods, and totally neglect the effect of the filler metal choice.

The *experimental research* can be divided into two parts. In the first part, I investigated the weldability of the selected materials (Table 1). I determinate the optimal welding parameters, furthermore I studied the filler metal choice. In the second part, I examined the fatigue properties of these base materials and their welded joints.

Table 1. The markings of the investigated materials

Steel marking			**Plate thickness, mm**
Standard	**Manufacturer**	**Dissertation**	
S690QL	RUUKKI Optim 700QL	R700Q	30
S690QL	SSAB Weldox 700E	W700Q	15
S960M	VOESTALPINE Alform 960M	A960M	15
S960QL	SSAB Weldox 960E	W960Q	15

The weldability and filler metal choice experiments were performed by gas metal arc welding process (MSZ EN ISO 4063: 135) in the Welding Laboratory at the Institute of Materials Science and Technology. For the experiments REHM MegaPuls 500 and DAIHEIN Vartsroj Welbee P500L welding machines were used, with M21 (*82% Ar + 18%* CO_2) shielding gas according to the MSZ EN ISO 14175 standard. For the stability of the welding process welding car was used, with the exception of the root layer. The measurements of the experimental plates were *300 mm x 125 mm*, with a starter and a run plate, according to the MSZ EN ISO 15614-1 standard.

According to the results of the welding experiments, it can be stated that the actual optimal parameter window is different in every base material, so there can be no universal parameter window, because of the very different weldability properties of the base materials. According to my own experiments, the ideal cooling time was between *5 s* and *10 s*, with *150 °C* minimum preheating temperature and *180 °C* maximum interpass temperature for the S700Q base material. In case of the S960M base material, the optimal cooling time was between *5 s* and *20 s*, with no preheating temperature and over *200 °C* maximum interpass temperature. However, in case of larger plate thicknesses *50-80 °C* preheating temperature can be beneficial.

For the experiments of the filler metal choice, I used different kind of filler metals (Table 2). According to the results, the *overmatching* filler metal improves the mechanical properties, but on the other hand, decreases the toughness properties of the joint, with additional increased toughness areas in the heat affected zone.

Table 2. The base material-filler material pairing during the experiments

Base material	**Filler metal**	**Matching condition**
R700Q	NiMoCr	matching
W700Q	Union X85	matching
W700Q	Union X90	overmatching
A960M	Union X96	matching
A960M	Union X90	undermatching

In case of the *overmatching* filler metal, the average value of the hardness also increases, and in the heat affected zone decreases in some areas, but these changes were not significant. With mixed welded joints (partially *matching*, partially *overmatching* filler metals) the properties benefit from both the filler metals, so in case of the root layers *matching*, while in case of the other layers *overmatching* filler metal can be beneficial [24]. In case of *undermatching* filler metal, the mechanical properties are decreasing, but the toughness properties are not changing significantly. Examine the hardness test results, it can be stated that the *undermatching* filler material does not cause significant changes in their values. It is important to note, that in the heat affected zone, depend on the joint preparation (mainly the angle), heavily softened areas can be occur, because of the multiple heat treatment of the succeeding layers [25].

After the welding experiments, I examined the fatigue properties of the base materials and the welded joints. The low cycle fatigue (LCF) experiments were controlled by total strain amplitude, with $R = -1$ stress ratio, rectangle loading wave form and on cylindrical test specimens. The 10% reduction of maximal force at the tensile side was set as a damage criteria [26][27]. According to the results, the elastic deformation is the significant in case of A960M material. Additionally, the plastic strain amplitude results show a larger deviation; therefore the plastic deformation is less appraisable because of the really fine microstructure. Studiing the W700Q test results, it can be stated that the welding technology affect the fatigue properties unfavourable. The *matching* filler metal results were worse than the base material results, and the *overmatching* results were worse than the *matching* results. Therefore, the higher strength, but lower deformation capability filler metal has a negative effect on the low cycle fatigue properties. The parameters of the LCF design limit curves can be seen in Table 3.

Table 3. The parameters of the LCF design limit curves

Material designation	**Elastic deformation**			**Plastic deformation**			**Cyclic yield curve**		
	σ_f'	**b**	**R**	**ε_f'**	**c**	**R**	**K**	**n**	**R**
W700Q BM	721	-0.037	0.89	0.265	-0.589	0.99	822.85	0.070	0.97
W700Q M	865	-0.066	0.97	0.0776	-0.488	0.98	1204.5	0.134	0.97
W700Q OM	1092	-0.105	0.97	0.275	-0.745	0.91	1075.6	0.106	0.80
A960M BM	1236	-0.061	0.99	0.232	-0.698	0.86	1242.9	0.068	0.90

For the strain amplitude – cycles to failure functions, the table contains the parameters of elastic deformation (σ_f', b) and plastic deformation (ε_f', c) curves; and also it contains the parameters of the stress amplitude – plastic strain amplitude functions (K, n). The correlation indexes (R) were determined in each case.

The high cycle fatigue (HCF) experiments were controlled by constant load amplitude, with $R = 0.1$ stress ratio, sinusoidal loading wave form and on flat test specimens [28]. In every examined case, the properties of the welded joints were under the base materials properties. In case of W700Q, with smaller cycle numbers (under $2*10^5$ cycles) the *overmatching* welded joints properties were worse than the *matching* joints, but in higher cycle numbers region the *overmatching* welded joints succeeded the *matching* joints high cycle properties. This can be explaining with the brittle property of the overmatching filler metal, which favours the crack initiation. In case of A960M, with the heat input increases the fatigue limit increases as well, at the same time the mechanical properties remain the same. This may be explaining with the coarse grained microstructure and the difficult crack propagation. The *undermatching* filler metal (with average heat input) has better fatigue limit properties, than the *matching* filler metal with low and average heat input, and has the same properties as the *matching* joint with large heat input, and as the base material. In the lifetime region, the *undermatching* welded joints have the better qualities. The parameters of the HCF design limit curves were summarized in Table 4.

The m and $lg(a)$ values are the parameters of the Basquin equation, the N_k value is the number of cycles for the knee point of the S-N curve, the $\Delta\sigma_D$ is the fatigue limit, and the $\Delta\sigma_{1E07}$ is the stress value belonging to $1*10^7$ *cycles* in the cases, when the horizontal (endurance limit) part of the curves cannot be determined.

Table 4. The parameters of the HCF design limit curves

Base material	**Manufacturing, orientation**	**m, –**	**lg(a), –**	**N_k, ciklus**	**$\Delta\sigma_D$, MPa**	**$\Delta\sigma_{1E07}$, MPa**
R700Q	BM h/v	51.282	151.109	–	–	646
	M k/3W	4.826	17.476	9.850E+05	239	–
	M k/1W	50.251	141.26	–	–	470
W700Q	BM h/k	12.453	39.650	1.68E+06	483	–
	M k/1W	9.960	32.469	–	–	–
	OM k/1W	31.25	90.415	–	–	467
A960M	BM h/k	11.494	37.885	5.122E+06	513	–
	M k/1W 5-6 s	8.130	27.893	4.270E+06	412	–
	M k/1W 10-11 s	16.129	49.413	2.681E+06	462	–
	M k/1W 15-17 s	15.385	47.838	9.693E+05	525	–
	UM k/1W	41.667	119.723	–	–	507

The fatigue crack growth (FCG) experiments were executed under mode I loading condition, with $R = 0.1$ stress ratio, using sinusoidal loading wave form and TPB test specimens. The crack propagation was detected with optical method, using *100x* magnification [29][30]. In case of W700Q and A960M base materials in L-T and T-L orientations the results are significantly same, but in T-S orientation the results are significantly different. The welded joints results are significantly different from the base materials results, in all directions and in all *mismatch* conditions. The average value of the Paris-Erdogan equation exponent (n) in case of the welded joints is over the base material exponent value. In three cases, the FCG resistance were the same in both examined orientations (21W and 23W), only in the A960M *matching* case was different. The ΔK_{fc} value in 23W orientation (thickness direction) is lower with all welded joints, than the 21W orientation. The ΔK_{fc} values of W700Q welded joints are usually over the base material value, on the other hand, the ΔK_{fc} value of A960M welded joints are usually under the base material value. In case of W700Q steel the *matching* condition is more beneficial than the *overmatching* filler metal, while the A960M material has better FCG properties with *undermatching* filler metal. The parameters of the FCG design limit curves can be seen in Table 5.

Table 5. The parameters of the FCG design limit curves

Designation	**Orientation**	**n**	**C**	**ΔK_{fc}**
		mm/cycles, $MPam^{1/2}$		**$MPam^{1/2}$**
W700Q BM	T-L and L-T	*1.70*	*8.09 E-07*	*101*
	T-S	1.50	2.06 E-06	75
W700Q M	T-L/21W	*4.10*	*1.12 E-11*	*105*
	T-S/23W	2.30	4.93 E-08	80
W700Q OM	T-L/21W	1.85	4.02 E-07	*96*
	T-S/23W	*1.90*	*3.19 E-07*	61
A960M BM	T-L and L-T	*1.82*	*4.63 E-07*	*116*
	T-S	1.75	6.41 E-07	87
A960M M	T-L/21W	1.90	3.19 E-07	*114*
	T-S/23W	*2.75*	*6.06 E-09*	82
A960M UM	T-L/21W	*2.40*	*3.10 E-08*	*115*
	T-S/23W	2.15	9.93 E-08	67

During the evaluation of the experimental data, concerning to the statistical approach, the design limit curves were determined as function of the orientations, in case of the base materials and the welded joints. If the orientation of the crack is known, than the regarding data can be used, but if the orientation is unknown, than the lower data must be used. Hence, the higher values highlighted with italic letters. (In case, when the crack place – base material (BM) or welded joint – and the *mismatch* condition – *matching* (M), *undermatching* (UM), *overmatching* (OM) – is known.) In the table, the ΔK_{th} values are missing, that means in the ΔK_{th} region, in the small crack growth rate range, the given curves are open. We can use literary data, and/or the function between ΔK_{th} and R. In case of welded joints, with or without the ΔK_{th} value, with the consideration of the residual stresses, the given value can be modified, or determinate. With compressive residual stress field the ΔK_{th} value can be increased, while with tensile residual stress field the ΔK_{th} must be decreased.

3. NEW SCIENTIFIC RESULTS – THESES

T1. Among the examined steels the thermomechanically rolled A960M steel has better welding qualities; therefore the welding technology used in the industry – both the designing and the weldability sides – is simpler. I justify this, with the comparison of the welding parameters, determined by theoretical and practical ways in case of the W700Q and the A960M steel (1) (8) (16) (18).

T2. In case of the W700Q steel, the base material has the best low cycle fatigue resistance; also the *matching* filler metal has better qualities, than the *overmatching* filler metal. I justify this statement, with both the given low cycle fatigue test results and the determined strain amplitude – cycles to failure functions (9) (11) (14) (24) (26).

T3. The high cycle fatigue resistance of A960M thermomechanically rolled steel in case of *matching* condition depends on the heat input, in case of *undermatching* condition is better than the joint with higher heat input and *matching* filler metal, and basically the same as the base material and the *matching* condition with higher heat input. With the increases of the heat input the fatigue limit increases as well, while the mechanical properties are remain the same. I justify this, with the high cycle fatigue test results and the determined design limit curves, according to the staircase method (1) (2) (3) (17).

T4. The fatigue crack growth resistance of the W700Q and the A960M steels in the rolling (longitudinal) and the transversal directions are significantly same, but in the thickness direction significantly different; hence both steel sensitive to the thickness oriented cracks. The fatigue crack growth resistance of the welded joints of these steels is significantly different on the longitudinal and the thickness directions, without reference to the *mismatch* condition. I justify this, with the fatigue crack growth test results executed by statistical approach and their comparisons, and this can be used for integrity calculations (2) (5) (7) (14) (15).

T5. The W700Q steel has better fatigue crack growth resistance in *matching* condition, than in *overmatchin*g condition; while the A960M steel has better resistance using the *undermatching* condition. I justify this, with the fatigue crack growth tests results accomplished by statistical approach and the determined fatigue crack propagation design limit curves (2) (19).

4. INDUSTRIAL UTILIZATION AND FURTHER DEVELOPMENT

In our days the knowledge of the engineers, designers, welding engineers are limited on the high strength steels and their behaviour under cyclic loading conditions. The different standards and prescriptions include the weldability of these steels with the extension of the conventional steel properties; therefore neglect the dissimilar properties of the high strength steels. At the same time, these steels have fundamentally different welding and fatigue properties. Furthermore the different type of these steels required different approach, depend on the strength category. Therefore, the research work aimed the determination of the weldability and the fatigue properties of these steels for industrial applications.

The determined welding parameter windows useful for the welding engineers, for the determination of the optimal welding characteristics, therefore the possible defects during the welding process can be minimized. The shape of the welded joint is significant, because in special cases, in the root layer heat affected zone, heavily softened areas can be formed, since the heat input of the succeeding layers. This can be preventing with smaller penetration and the changes of the joint shape angle.

The filler metal choice experimental results can be used by the practising welding engineers too. Since, my experiments cover both the S700 and the S960 steel categories, the results can be used in these cases. Where the loading condition of the welded joints is static, *overmatching* filler metals can be used with W700Q material, at the same time, the *matching/overmatching* mixed joints have better properties, because the root layer has the larger deformation capability *matching* filler metal, and the other layers have the larger strength *overmatching* filler metal. In case of the A960M base material, the *undermatching* condition has lower mechanical properties; on the other hand, the toughness properties remain the same.

In case of the low cycle fatigue tests, there are no significant difference between the results of the W700Q and A960M steels, although in case of the thermomechanically rolled steel, the elastic strain amplitude of the base material constantly over the amplitude of the quenched and tempered base material and the welded joint. In the examined region, the elastic strain amplitude is the determinant with the A960M steel base material. The results of the W700Q welded joints show, that the welding process causes a negative effect on the low cycle fatigue properties, furthermore the *overmatching* filler metal has worse properties, than the *matching* condition.

The high cycle fatigue tests show, that the *overmatching* filler metal has benefits with the S700 category, when the loading is smaller, while under higher loading the *matching* condition is the better option. Furthermore, in case of S960 category it can be seen, that the higher strength does not mean higher high cycle fatigue resistance. With the increases of the heat input the fatigue limit is increases as well, at the same time the mechanical properties are decrease. Therefore, in case of static loading condition lower heat input must be used (this means higher discipline of the welding parameters and circumstances), while in case of high cycle loading condition higher heat input can be beneficial (with the remark, that too high heat input decreases the mechanical properties dangerously).

Using the results of the fatigue crack growth experiments, I determined the design limit curves for the examined S700Q and W960M base materials and their welded joints with different *mismatch* conditions. These curves – either in general or in specific form – can be used for the integrity assessment of welded joints, the prediction of lifetime and/or remaining lifetime, and for comparative calculations.

5. LIST OF THE PUBLICATIONS RELATED TO THE TOPIC OF THE DISSERTATION

IN ENGLISH

(1) Dobosy, Á., Gáspár, M., Jámbor P.: *Weldability of S960M thermo-mechanically treated advanced high strength steel*. YPIC2017 3rd Young Welding Professionals International Conference, Halle (Saale), Germany, 2017 August 16-18, pp. 1-6.

(2) Lukács, J., Dobosy, Á.: *Matching effect on fatigue crack growth behaviour of high strength steels GMA welded joints*. 70th IIW Annual Assembly and International Conference, Commission XIII Fatigue of welded components and structures, 2017 June 25-30, Shanghai, China, IIW-DOC XIII-2692-17, p. 19

(3) Dobosy, Á., Gáspár, M., Lukács, J.: *High cycle fatigue investigations on high strength steels and their GMA welded joints*. Vehicle and Automotive Engineering, Proceedings of the JK2016, Miskolc, Hungary, Springer, 2017, pp. 453-467 (DOI: 10.1007/978-3-319-51189-4_39)

(4) Dobosy, Á., Lukács, J.: *The effect of the filler material choice on the high cycle fatigue resistance of high strength steel welded joints*. Materials Science Forum Vol. 885, Trans Tech Publications, 2017, pp. 111-116. (doi:10.4028/www.scientific.net/MSF.885.111)

(5) Lukács, J., Dobosy, Á., Gáspár, M.: *Fatigue crack propagation limit curves for high strength steels and their welded joints, and the applicability of these curves for ECA calculations*, IIW 2016 International Conference, The Total Life Cycle of Welded Components, Melbourne, Australia, 2016 July 14-15 (poster presentation)

(6) Dobosy, Á., Lukács, J.: *The effect of the welding parameters on the properties of the thermomechanically rolled high strength steels*. XXX. microCAD International Multidisciplinary Scientific Conference, Miskolc, 2016 April 21-22. D2_3 (ISBN: 978-963-358-113-1)

(7) Gáspár, M., Dobosy, Á., Lukács, J., Sas, I.: *Behaviour of undermatched AHS steel welded joints under static and cyclic loading conditions*. 68th IIW Annual Assembly and International Conference, Commission XIII Fatigue of welded components and structures, Helsinki, 2015 July 02-03, IIW-DOC IIW2015-15/1804, p. 16

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(9) Dobosy, Á., Nagy, Gy., Lukács, J.: *Low cycle fatigue resistance of quenched and tempered high strength steels*. Production Processes and Systems, Vol. 7. No. 1., Miskolc, 2014. pp. 31-40. (ISSN 1786-7983)

(10) Dobosy, Á., Lukács, J.: *Fatigue resistance of the welded joints of high strength steels*. YPIC 2014, Young Welding Professionals International Conference, Budapest, 2014 September 17-20, pp. 7-16. (ISBN: 978-963-12-0084-3)

(11) Dobosy, Á., Nagy, Gy., Lukács, J.: *LCF experimennts on different yield strength steels and their welded joints*. XXVIII. microCAD International Multidisciplinary Scientific Conference, Miskolc, 2014 April 10-11, D1 (ISBN: 978-963-358-051-6)

(12) Dobosy, Á., Lukács, J.: *Welding and fatigue of quenched and tempered high strength steels*. International Engineering Symposium at Bánki, Budapest, 2013 November 19, CD supplement

(13) Dobosy, Á., Gáspár, M.: *Welding of quenched and tempered high strength steels with heavy plate thickness*. XXVII. microCAD International Multidisciplinary Scientific Conference, Miskolc, 2013 March 21, Paper M7 (ISBN: 978 963 358 018)

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(14) Dobosy, Á., Gáspár, M.: *Nagyszilárdságú acélok hegesztési hozaganyagai*. 19. Hegesztési Felelősök Országos Tanácskozása, Hajdúszoboszló, 2017 September 14-15, CD supplement

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(16) Dobosy, Á., Gáspár, M.: *A termomechanikus és a nemesített nagyszilárdságú acélok hegeszthetőségének összehasonlítása*. 18. Hegesztési Felelősök Országos Tanácskozása, Hajdúszoboszló, 2016 September 15-16, CD supplement

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